

SHOCK WAVE INDUCED SOLAR FLARES ASSOCIATED WITH CORONAL MASS EJECTIONS (CMEs)



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DECLARATION

I hereby declare that this PhD dissertation is my original work and has not been presented for a degree in any other university, and that all sources of material used for the dissertation have been duly acknowledged.

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Abstract

In this work, we have advanced shock wave induced stellar flare model (SWIF model) which describes the nature of energetic events on star, mainly solar atmosphere. The SWIF model, theoretical model, works for energetic events both at weak magnetic field region as well as strong magnetic field region of stellar atmosphere. This advanced physical SWIF model has two parts. The first part of the SWIF model which is independent of pre-existed magnetic field; we named it shock wave induced flare on stellar, solar, quiet region (SWIF-1SQR). The SWIF-1SQR model well describes Nano flares and micro flares as well as the impulsive flares theoretically. The second part of the SWIF model includes pre-existed force free magnetic field integrated with fast magnetic reconnection (FMR) theory. Thus, the second part of the SWIF model has been named as shock wave induced flare model on stellar, solar, active region (SWIF-2SAR model). The SWIF-2SAR model profoundly defines the impulsive flares and even small flares with high complexity nature of plasma dynamics.

The SWIF model enables us to predict the suddenly releasing of flare energy, formation of coronal mass ejections (CMEs) as well as electromagnetic wave burst from small local region on stellar atmosphere, specifically on the sun. Generally, the SWIF model articulates how flares, CMEs and observable electromagnetic wave burst are created on weak and strong magnetic field region of stellar atmosphere. The minimum electron current limit, which is occurred at small region for formation of flares and CMEs, is approximated by $J_e \approx en_e c_s$ that is the sonic electron current while the upper limit is $J_e \approx 10^3 en_e c_s$ at solar photosphere. Thus, the SWIF model predicts electron current limits which are responsible for solar flares and CMEs in the range of $J_e \approx 10^5 A$ to $J_e \approx 10^{12} A$ during flare formation. The corresponding electron induced magnetic field which provides flares and CMEs also anticipated as $B \approx 10^4 G$ to $B \approx 10^8 G$ in radius of $100 m$ collapsing spherical cavity. When this compacted magnetic field is well organized and exploded, a flare associated with CMEs and electromagnetic wave burst is looked.

Thus, the SWIF model predicts stellar fares and CMEs that are transpired ubiquitous where plasma flows with velocity greater than background acoustic velocity is noteworthy. On basis of SWIF model advancing, the flare electron runaway current is determined by strength of velocity shock potential (VSP). Here, we investigate that the VSP triggers stellar (solar) explosive events and that can be described by SWIF model, physical model.

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CHAPTER 1

1. INTRODUCTION

In this work, we investigate a new theoretical model, physical model, of stellar (Solar) flares incorporated with fast magnetic reconnection (FMR) theory associated with Coronal Mass Ejections (CMEs) at high conductivity and in-homogeneously magnetized stellar (Solar) atmosphere. To develop the new model, we start from observational evidences that are obtained from the solar atmosphere. The observational data are obtained from ground based and space born telescopes that are carefully analyzed by solar scientists. The observational evidences we used here, are obtained from NASA documentary resources, international journals and books. To formulate our stellar flare model we use secondary observable data as evidences. Some of the observational evidences that are obtained from secondary sources are explained in chapter 1 with their full references (i.e., literature review). These observational evidences obtained from sun enables us to raise a question, how solar flares can occur? Where solar flare and Coronal Mass Ejection are existed? How can magnetic reconnection be fast through high conductivity plasma? Those cited questions are answered in chapters 2, 3, and 4 at least in partial fulfillment of our infant solar flares theoretical model. Moreover, this new model gives a new sight on modeling solar explosive events, based on particle dynamics and particle-field interaction principle rather than pure magneto-hydrodynamics theory of large scale system. The first chapter of this thesis, chapter 1, incorporated the literature review which contains basic observational evidences and mandatory concepts of plasma physics, shock physics and physical behavior of the star (sun).

The second chapter (chapter 2) theorizes the dynamical nature of stellar (solar) surface so as to provide a preferable physical dynamics. And, answers that the solar flares and Coronal Mass Ejections (CMEs) are existed everywhere on the solar atmosphere. Mainly, small solar flares are created at weak magnetic field region of solar atmosphere independent of pre-existed magnetic field. The SWIF model includes two stellar (solar) flare models, SWIF-1SQR model and SWIF-2SAR model. The first SWIF-1SQR model is developed based on shock wave theory and dynamical nature of solar surface plasma at solar quiet region, for negligible effects of pre-existed magnetic field. This first model supports the existence of CMEs behind of flare; it may be unobservable flares at the deep photosphere. The third chapter (chapter 3) of this thesis

explains the further development of SWIF-1SQR model that is the second theoretical model of solar flares of strong magnetic field region.

The second model, SWIF-2SAR model well explains the intense solar flare followed by huge CMEs at solar active region. The second model, SWIF-2SAR model is strongly interconnected with the idea of fast magnetic reconnection (FMR) process through high conductivity plasma fluid on solar atmosphere. The FMR process is theorized in chapter 4. The main mechanism for formation of solar flares and FMR theory is formation of low density plasma region coupled with the occurrence of strong density gradients and fast propagating shock waves. This is well explained in chapters 2, 3 and 4. The flying Coronal Mass Ejecting (CMEs) from solar atmosphere may create flares and accelerated particles can be emanated. The oscillating magnetic flux tubes are a good sources of solar explosive events such as flares and CMEs, is described in chapter 4 in connection with FMR theory.

In the 5th chapter of this thesis, we validate our theoretical model by comparing with other known theoretical flare models and space experiments. In general form the Validation of the SWIF-1SQR model and SWIF-2SAR model is worthily explained the stellar (solar) explosive phenomena in clear and simple way, see chapter 5. The minimum electron current limit and maximum electron current limit is endorsed by comparing the predictable value of SWIF-1SQR and SWIF-2SAR models with the standard and observed value of solar atmospheric current. Validation of SWIF-1SQR and SWIF-2SAR models associated with CMEs also well explained at the end of respective chapters with the help of some predictable value of fast moving shock wave generated current.

The SWIF-1SQR and SWIF-2SAR models also explain predictable the radiation spectrum frequency of non-thermal accelerated particles. Generally, the SWIF model is constructed based on the observational evidences that are collected from the well know representative young star, group of G2 star, that is the sun. Those collected observational data have been carefully analyzed and interpreted by solar physicists, and are well organized, enables us to construct a model that explains the nature of stellar flares associated with coronal mass ejections (CMEs). The final chapter 6 gives conclusion and future work plane clue about the developing new theorized model of solar flares.

Objective of the research:

- ❖ To investigate the mechanism of stellar (solar) explosive events; flares and Coronal Mass ejections (CMEs) at rare density plasma medium, stellar (solar) atmosphere.
- ❖ Knowing the secret of stellar (solar) explosive events enables us to investigate protection methods from solar radiation hazards, the incoming radiation from space can cutoff electronic communications (i.e., disrupt satellite's function, electric power grid, dangerous for astronaut and space voyage).
- ❖ Predicting the occurrence time of stellar (solar) explosive events such as Flare radiation and CMEs, when and where they are created, enables us to predict the space weather condition

Methodology:

1. Identifying the problem : We have identified the problem after completing all courses and the seminar works
2. Collecting necessary materials: we have collected all necessary materials such as books, journals and soft wares from library, websites ...etc.
3. Formulation of the *SWIF model*: Using the collected materials we have formulated the *SWIF models* associated with Coronal Mass Ejections (*CMEs*) theoretically. This model is advanced based on the shock wave theory and dynamics of plasma fluid.
4. Validations of the *SWIF model*: After mathematical formulation, we have validated the *SWIF model* by comparing with the universally accepted solar observational evidences. Thus, the *SWIF model* explains the formation of stellar (solar) flares as well as Formation of CMEs integrated with fast magnetic reconnection (FMR) theory.

1.1. Historical Back Ground Studying of Solar Dynamics

On age of human history, people have tried to describe the beautiful, amazing and spectacular “ball of fire” that is the Sun on the sky. The beautiful star nourishes our planet we live there. The Sun is the brightest object in our surrounding and we detect with our naked eye and it provides enough light and heat energy that makes life on our planet possible. The Egyptians used to worship the Sun, and on the back of the golden chair of Tutankamen is an emblem that is very reminiscent of the shape of the corona. The Chinese thought an eclipse was the effect of a dragon swallowing up the Sun, and so they used to employ an astronomer to shoot the beast. The solar observation is dated back to ancient eclipse observations, which have been reported from Chinese, Indian, Greek, Egyptian ... etc [1 - 3].

The existence of features on the Sun was known from the records of sunspots observed by ancient astronomers with the naked eye; however, no systematic studies were made of such features until a telescope was invented in the early 17th century. The Italian scientist Galileo Galilei and the German mathematician Christoph Scheiner were among the first to make telescopic observations of sunspots [4, 5]. In the 1670s the British astronomer John Flamsteed and the French astronomer Gian Domenico Cassini calculated the distance to the Sun [6]. Sir Isaac Newton set forth the role of the Sun as the center of attraction of the known planetary system [7]. The sunspot cycle, a huge effect, was not discovered until 1843 by Samuel Heinrich Schwabe [8]. Rudolf Wolf, the Swiss astronomer confirmed Schwabe’s discovery by searching through previous reports of sunspots and established the period as 11 years [9]. Wolf also introduced what is termed the Zurich relative sunspot number, a value equal to the sum of the spots plus 10 times the number of groups, which is still used today [10]. Richard Christopher Carrington of Britain, who built a private observatory and discovered the differential rotation and the equator ward drift of activity during a sunspot cycle [11]. He also was the first to observe a solar flare [12]. Photographic monitoring began in 1860, and soon spectroscopy was applied to the Sun, so the elements present and their physical state could begin to be investigated. In the early part of the 19th century, Fraunhofer mapped the solar spectrum [13].

At the end of the 19th century, spectroscopy carried out during eclipses revealed the character of the atmosphere, but the million-degree coronal temperature was not established until observations of coronal spectral lines were made in 1940 by the German astrophysicist Walter

Grotrian [14]. Hale discovered the magnetic fields of sunspots by observing the splitting of their spectral lines into a number of components; this splitting, known as the *Zeeman Effect*, occurs in the presence of a strong magnetic field. By continuously studying the spots for two cycles, he discovered, with the American astronomer Seth Barnes Nicholson, the law of sunspot polarities [15]. Later, in 1953, the American father-and-son team of astronomers Harold and Horace Babcock, working with the same instruments, developed the magnetograph, with which the polar field was detected [16]. In the 1930s the French astronomer Bernard Lyot introduced the coronagraph, which made possible spectral observations of the corona when the Sun is not in eclipse, and the birefringent filter, which permitted two-dimensional monochromatic images [17]. With the Lyot filter, cinematography of the solar activity of magnetic and velocity fields became a reality. In the 1960s the American astronomer Robert Leighton modified Hale's spectroheliograph so that it could measure both velocities and magnetic fields and with it discovered solar oscillations. After 1950, new observatories were established in areas that were less cloudy. By 1960 astronomers realized that these sites not only had to be clear but that they also had to have stable air. By locating observatories near lakes and by employing electronic imaging and vacuum telescopes, astronomers were able to make new, higher-resolution observations. In 1969 the movement began with the Aerospace Corporation Observatory and the Big Bear Solar Observatory, both in California. Free of ground effects, these observatories achieved a new level of stable images and were soon followed by lake-sited solar observatories in India and China.

An entirely new dimension of solar studies was initiated by the space age. With one or two exceptions, all of the important spectral lines from the chromosphere and corona are in the ultraviolet, and since the photosphere is relatively weak in the ultraviolet, it is easy to disentangle the images of the upper layer from the powerful visible radiation of the photosphere. Moreover, satellites sampling the solar particles have the ability to monitor directly solar waves and particles that do not reach the ground. However, the task is not easy. Ultraviolet optics demanded special coatings and films, now charge-coupled devices, for observing. Special solar trackers were required to keep the image steady, and good telemetry was needed for the large data flow. For the corona, special coronagraphs were developed, with a series of occulting disks in front of an ultraclean lens. For X-rays, a high rate of photon detections per unit time was required to avoid early problems with pulse pile-up. The development of instruments to study the Sun also

benefited the creation of satellites that explored beyond the solar system [18]. The U.S. Orbiting Solar Observatory series of satellites (OSO 1–8, launched from 1962 to 1975) made the first observations of X-rays and gamma rays from solar flares [19]. They also were the first to observe gamma rays emitted from nuclear reactions in flares and to use an externally occulted coronagraph to view coronal mass ejections (CMEs).

A huge advance in resolution came with Skylab, a manned U.S. space station that used leftover hardware from the Apollo project. Skylab produced the first high-resolution images in the ultraviolet lines as well as the first X-ray images of the corona. The Skylab images displayed the coronal holes for the first time, and the timing of their disk passage showed their role as a source of high-speed solar wind streams and geomagnetic disturbances. The next important spacecraft was the U.S. Solar Maximum Mission (SMM), launched in 1980 [20]. New technological developments permitted greatly improved data, particularly on the solar-cycle dependence of the solar constant. Hard X-ray data could be obtained without saturation. In 1981 SMM's attitude control system malfunctioned, and the SMM mission was suspended until 1984 when it was repaired by the space shuttle *Challenger* [21]. Japan launched two very successful satellites, Hinotori and Yohkoh, in 1981 and 1991, respectively [22, 23]. Hinotori obtained the first measurements of a super-thermal (3×10^5 – 3×10^7 K) cloud produced by solar flares, which is the source of the soft X-ray burst accompanying all solar flares. Yohkoh produced continuous images of the corona in soft X-rays, detected and located hard X-ray bursts, and produced important soft X-ray spectra. The European Space Agency spacecraft Ulysses, launched in 1990, was the first space probe to travel in a polar orbit around the Sun. It discovered that the solar wind speed does not increase continuously toward the poles but rather levels off at high latitudes at 750 km/s.

Nowadays, there are several satellites actively observing the Sun. The U.S. satellites Solar and Heliospheric Observatory (SOHO) and Transition Region and Coronal Explorer (TRACE), launched in 1995 and 1998, respectively, have produced many important results. SOHO can observe the Sun continuously and among its many discoveries it has found that sunspots are shallow and that the solar wind flows outward by waves in vibrating magnetic field lines. TRACE is a powerful tool for exploring the chromosphere-corona interface and has found that much of the heating in the corona takes place at its base. The Japanese spacecraft Hinode,

launched in 2006, discovered magnetic waves in the solar chromosphere that drive the solar wind [24]. The two spacecraft of the U.S. Solar Terrestrial Relations Observatory (STEREO) mission, also launched in 2006, form a 90° angle with the Sun in order to make stereoscopic images of it. The U.S. satellite Solar Dynamics Observatory (SDO), launched in 2010, carries three instruments that observe the Sun every 10–50 seconds to study changes that previously launched satellites were not able to observe.

1.2. Observational Evidence on Solar Atmosphere

From observational evidences, we can understand that the solar atmosphere gives off electromagnetic energy in many wavelengths, including visible light, radio waves, ultraviolet, soft and *hard X-rays*, and more. The solar atmosphere also emits a stream of radiation in the form of charged particles that make up the plasma of the *solar wind* couples with force free solar magnetic field lines. Occasional outbursts from huge explosions on the Sun atmosphere (i.e., solar flares and CMEs) send space weather storms hurtling outward through our solar system to interstellar space. Consequently, based on the observational view points, the sun is a source of radiation energy and energetic particles during solar flares, source of solar winds, CMEs and other local solar activities. Nearly static phenomena such as prominences, faculae and static magnetic flux tubes are observed on solar surface for long time [25 - 27]. The intense solar radiation during flares and CMEs hits the magnetically enveloped our Earth planet repeatedly.

However, only visible light and radio wave length spectrum reaches the Earth surface. The Earth's magnetic field prevents the high frequency electromagnetic radiations and energetic particles from reaching Earth's surface. Living creatures are inhabited on Earth's surface and protected them from dangerous solar electromagnetic radiation spectrum. During the interaction between electromagnetic radiation and energetic particles with the Earth's magnetic field, several effects are produced (i.e., Earth's magnetic storm, aurora ... etc) at outer layer of Earth's atmosphere [28, 29]. When the Earth's upper layer of atmosphere is beaten by higher frequency electromagnetic radiation and energetic particles, there could be an increasing in ionosphere ionization process and disturbance of upper layer of Earth's atmosphere. Particle radiation spiraling down along our planet's magnetic field lines can damage satellites, disrupt communications systems, and even short out our electrical power systems. As these radiating particles collide with atoms in Earth's upper atmosphere, they sometimes produce the spectacular

light shown called auroras the Northern pole Lights and Southern pole Lights observable with our naked eyes about 80 km up to 250 km above north poles [30, 31].

Despite its apparently steady glow, the Sun is a churning mass of superhot plasma that regularly produces powerful flares, CMEs and storms that can knock out power and communication systems on Earth planet [32, 33]. The observable physical processes on the Sun give rise to an ample variety of structures on different spatial scales that in several cases are very small, with sizes probably below the resolution limit of existing telescopes [34]. Thus, the interpretation of solar phenomena requires the study of these structures, and consequently high spatial resolution observations are necessary to understand the physics of dynamic star (Sun). These observations must be complemented by an equally important high resolution spectroscopic analysis, including polar-metric measurements to determine the magnetic field strength. Solar images observed from the ground are degraded by the telescope and the Earth's atmosphere. The atmosphere is usually considered as an isotropic turbulent medium, and its influence on the image formation process is similar in effect to intercalating changeable and poor optics in the optical path. Image degradation by atmospheric turbulence is a very complicated process but is often described as the result of three separate contributions. These contributions are: A defocusing effect or loss of sharpness in the structures, Global displacements of the image to produce an agitation referred to as *image motion* and *Distortion* of the structures caused by differential image motion in different parts of the image [35]. The last two contributions may be present even in very sharp images. Observations made with telescopes operating outside the terrestrial atmosphere are not affected by seeing and, in addition, are not restricted to the relatively narrow spectral windows imposed by the selective transmissivity of the atmosphere. Furthermore, access to instruments in space for maintenance, repair and upgrading is very difficult. Hence, for the time being, interest in space telescopes is concentrated on overcoming the spectral restrictions imposed by atmospheric transmissivity rather than on improving the spatial resolution.

The expected mechanical energy which is responsible for solar atmosphere charming is generated at the upper layer of photosphere and propagates to solar atmosphere where it is dissipated. The propagating energy probably carries momentum that provides temporal and spatial fluctuations of physical variables; see chapter 2, section 2.2.5 – 2.7.2. The study of 5

minute non-radial solar surface oscillation and 3 minute non-radial solar atmosphere periodic oscillation associated with energy flux change of compressive waves could not provide the sufficient observable energy responsible for coronal heating [36, 37]. However, the energy flux of compressive wave of photosphere may be enough to heat the lower and middle chromosphere layer [38]. In some solar atmosphere studies, the network and spicules indicates that vertical motions and the widespread plasma balance the energy flux.

The plasma up flow observed in spicules is balanced by the return down flow in the network at transition region temperature [39 - 42]. We detect the optical radiation with our eye that is emitted from the solar surface. The optical emission produced by Thomson scattering is less intense in magnitude at the much tenuous plasma density region above the solar surface, chromosphere and corona. The optical radiation produced above the solar surface is observable when the sun is occulted during total solar eclipse and using *Coronagraph*. If we observe the sun in other wavelengths, for instance in *soft X-rays*, *hard X-rays*, extreme ultraviolet (EUV), ultraviolet (UV) or radio wavelengths, the brightest emission comes from the corona corresponding to *X-rays* spectra, while the photosphere becomes invisible, just opposite to optical wavelengths [43, 44]. A breakthrough of coronal observations was started with the space age of rocket flights and spacecraft missions, which enabled soft *X-ray* and *EUV* observations above the absorbing Earth's atmosphere [45]. Friedman in 1963 has obtained the first crude *X-ray* photograph of the Sun with a pinhole camera from rocket flight of NRL on 1960 April 19. These rocket flights last typically about 7 minutes and thus allow only for short glimpses of coronal observations [46]. Finally, the launch of Skylab, which operated from 1973 May 14 to 1974 February 8 initiated a new era of multi-wavelength solar observations from space. Skylab carried a white light coronagraph, two grazing-incidence *X-ray* telescopes, EUV spectroheliometers /spectroheliographs, and an UV spectrograph, recording *approximately* 32,000 photographs during its mission (i.e., see the books of solar physics corona).

The first solar-dedicated space mission that operated a full solar cycle was the SMM, launched on 1980 February 14 and lasting until orbit decay on 1989 December 2 [47]. The SMM instrumental package contained a Gamma Ray Spectrometer (GRS) with an energy range of 10 keV-160 MeV, a Hard X-Ray Burst Spectrometer (HXRBS) in the energy range of 20-300 keV, a Hard X-ray Imaging Spectrometer (HXIS) with moderate spatial resolution (8'' pixels) in the

energy range of 3.5-30 keV, two soft X-ray spectrometers, Bent Crystal Spectrometer (BCS), 1.7-3.2 Å, and a Flat Crystal Spectrometer (FCS), 1.4-22 Å, an Ultraviolet Spectrometer/Polarimeter (UVSP) in the 1150-3600 Å wavelength range, a white-light Coronagraph/Polarimeter (CP) in the 4448-6543Å wavelength range, and an Active Cavity Radiometer Irradiance Monitor (ACRIM) in ultraviolet and infrared wavelengths. The SMM made a number of scientific discoveries in observing some 12,000 solar flares and several hundred CMEs [48, 49].

In April 1991, the Compton Gamma-Ray Observatory (CGRO) was deployed [50], which was designed to detect gamma-ray bursts from astrophysical and cosmological objects, but actually recorded more high-energy γ -ray and hard X-ray photons from solar flares than from the rest of the universe. In particular, the Burst And Transient Source Experiment (BATSE) with its high sensitivity (with a collecting area of 2,000 cm² in each of the 8 detectors) in the energy range of 25-300 keV, Fishman et al. 1989 delivered unprecedented photon statistics, so that energy-dependent electron time-of-flight delays could be determined in solar flares down to accuracies of a few milliseconds, and thus crucially contributed to a precise localization of particle acceleration sources in solar flares. Also the Oriented Scintillation Spectrometer Experiment (OSSE), Kurfess et al. 1998 provided crucial measurements of γ -ray lines in the energy range of 50 keV to 10 MeV in a number of large X-class flares. CGRO recorded a total of some 8000 solar flares during its lifetime. The truck-heavy spacecraft was de-orbited by NASA in May 2000 because of gyroscope malfunctions.

The great breakthrough in soft X-ray imaging of the solar corona and flares came with the Japanese mission YOHKOH, which contained four instruments [51]: the Hard X-ray Telescope (HXT) with four energy channels (14-23keV, 23-33 keV, 33-53 keV, and 53-93 keV) and a spatial resolution of $\approx 8''$, the Soft X-ray Telescope (SXT) with multiple filters sensitive to temperatures of $T > \sim 1.5$ MK, having a spatial resolution of $5''$ in full-disk images and $2.5''$ in partial frames; a Wide-Band Spectrometer (WBS) containing soft X-ray, hard X-ray, and γ -ray spectrometers; and a Bent Crystal Spectrometer (BCS). YOHKOH provided a full decade of soft X-ray images from the solar disk and from flares, revealing for the first time the geometry and topology of large-scale magnetic field reconfigurations and magnetic reconnection processes in flares. The satellite lost its pointing during a solar eclipse in December 2001 and reentered in

September 2005 [52]. The next major solar mission to observe the Sun from inside out to 30 solar radii in the helio-sphere was the ESA/NASA jointly-built spacecraft SOHO, launched on 1995 December 2, and still being fully operational at the time of writing. Twelve instrument teams with over 200 co-investigators participate in this mission. The SOHO spacecraft includes the following 12 instrument packages: 3 instruments for helioseismology (GOLF, VIRGO, SOI/MDI), 5 instruments for observing the solar atmosphere (SUMER, CDS, EIT, UVCS, LASCO), and 4 particle detector instruments that monitor solar wind (CELIAS, COSTEP, ERNE, SWAN) [49].

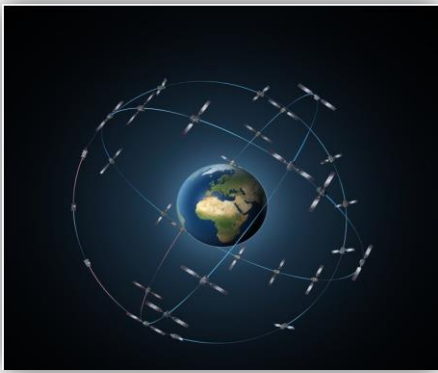


Fig.1.1a Location of satellite above Earth's atmosphere, Credit: NASA

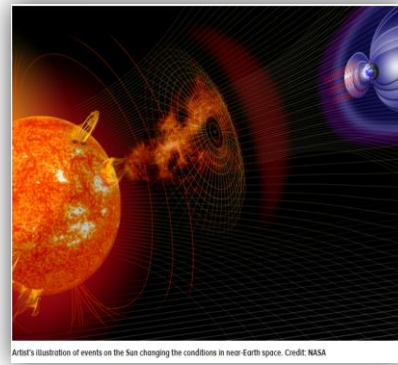


Fig.1.1b Direction of CMEs towards Earth direction, Credit: NASA

The Fig.1.1a shows the location of satellite above Earth surface so as to observe solar explosive events, such as flares and CMEs with all kinds of spectrum. Fig.1.1b shows the emergence of solar magnetic flux tubes and solar eruptive radiations and CMEs ejects to Earth atmosphere. Electromagnetic radiation, particle radiation and CMEs create a storm at Earth's atmosphere.

1.3. Physical Change of Visible Star

Based on observational evidences and theoretical hypothesizes, several researches have been investigated that the solar radius and solar surface luminosities are changing on finite period of time scale. The main mechanism for change of luminosity and radius is the energy transformation or conversion interior of star. The star is a natural nuclear reactor laboratory. During its evolution, Hydrogen gas is burning to Helium at high temperature. However, performing of such nuclear reaction at solar core does not provide observable change on solar surface. The observable change on solar surface luminosity and solar radius is connected to solar

surface oscillation mechanism associated with evolution of magnetic fields. The main mechanism for stellar activities is migration of electrons coupled with self-gravitating dynamic plasma. Instantaneous migration of electron through high conductivity plasma generates instantaneous electric field, shock wave propagation and heat production. At high density plasma, the production of heat is controlled by collision and viscosity effects. However, at rare density plasma, heat production is determined by field-field interaction and field-particle interaction associated with production of shock waves at high conductivity plasma medium.

Interior of star, the highly conductivity plasma convection excites *p-mode* oscillations that produce small effects on the solar irradiance and radius at 5 minute periods. The stellar surface oscillation process is coupled with evolution of magnetic fluxes emerging from interior. The formation and decay of convective cells at the solar surface produces small random change in luminosity. Magnetic activity may influence the solar luminosity and plasma flow on solar surface. The appearance of magnetic fields at the stellar surface causes a small change in luminosity, because sunspots are darker and small scale magnetic fields brighter than the average solar surface [15, 53, 54]. The periodic creation and destruction of magnetic field with in the interior of Star implies temporal sinks and sources in the thermal energy of star.

The emerged magnetic field on solar surface controls the solar explosive events that change the solar luminosity with in very small time. Magnetic field contributes visibly to the solar output by their energetic activities in the atmosphere by dissipating magnetic activities while eruption from below the surface is happened and by channeling energy across the photosphere in mechanical form [55]. The production of magnetic field interior of star causes expansion of stellar radius against the gravitational collapse. The generated magnetic field exerts a pressure on solar surface from interior and is emanated in the form of magnetic flux. Ionized plasma may sink or emanate channeling the magnetic flux. A strong shock wave is produced inside magnetic flux tubes and the flowing plasma is heated and flow along flux tubes, *see* chapter 4, section 4.4.

1.4. Solar Atmosphere

The solar atmosphere is characterized by in-homogeneous distribution of magnetic field through high conductivity plasma associated with nearly static and highly dynamic events, *see*

chapter 1, section 1.5. The solar atmosphere has a unique feature, temperature distribution increases radially outward as density distribution becomes rare. From observational evidences, *X-rays* spectrum is generated most probably at the solar Corona [56]. The broad coronal emission lines suggested that the sun is surrounded by order of $10^6 K$ temperature outermost atmosphere. However, there is no theory that supports generation of *X-rays* spectrum at the rare plasma density of solar atmosphere.

Nowadays, based on space born observational evidences, scientists believed that *X-ray* emission is a common property of rotating stars in connection with force free magnetic field above its thin convective envelopes. Such star is magnetically active, see chapter 3, SWIF-2SAR model, the sun is a representative of active young star. This indicates that the stellar atmosphere is characterized by highly conductive magnetized tenuous dense plasma that emanates all kinds of spectrum. The *X-ray* observability of coronal complex magnetic structures depends both upon the properties of the tenuous plasma and the space telescope, see chapter 1, section 1.2. At solar atmosphere, the dominant physical factors are the plasma density and plasma temperature that reflect heating, trapping and energy loss processes associated with inhomogeneous force free magnetic field or non-potential magnetic field. The configuration of complex magnetic field specifies the appearance of stellar atmosphere *X-ray*, *EUV*, radio, optical and other spectrums inhomogeneity. The occurrence and radiative output of the *X-ray* solar atmosphere directly reflects the cyclical variation of the photosphere magnetic activity [57]. Based on the temperature distribution of stratified solar atmosphere, the atmosphere is classified in to four regions. These are photosphere zone, chromosphere zone, Transition and corona.

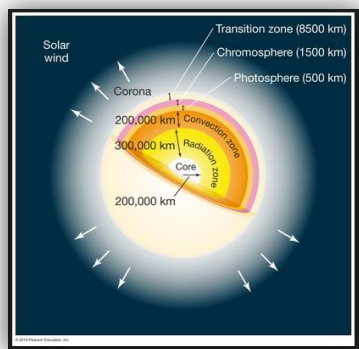


Fig.1.2a Solar wind emanated from corona, Credit: NASA

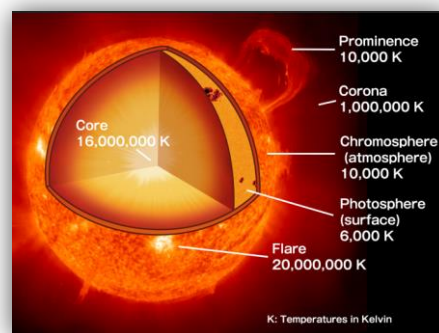


Fig.1.2b Structure of solar atmosphere and prominences, Credit: NASA

The figures of Fig.1.2a and Fig.1.2b shows the solar atmospheric layer classification based on temperature distribution associated with solar flares and prominences.

1.4.1. Photosphere

When we examine the star (Sun) in unfiltered light we are looking at the solar layer called the photosphere. This is the layer from which most of the heat and light that we receive from the sun originates due to Thomson scattering process before its final scape [58, 59]. It is sometimes referred to as the solar surface, although the density of the gaseous hydrogen and helium gases at the photosphere is only about 0.01 of the sea-level atmospheric density on Earth. On looking at the photosphere, we can see up to four different types of static features. These are, in order of ease of observation: sunspots, faculae, granulation and super-granulation, *see chapter 1, section 1.5* are the most observable. Energy transports from solar interior to surface due to convection transport method *see chapter 2, section 2.2 - 2.5*, and chapter 3, *section 3.5, 3.6 and 3.7*.

The plasma that reaches the top of the convection zone is cold by giving of light and heat to surrounding space. This region of the Solar atmosphere is the first part of the sun that is visible to us and we call it the *photosphere*. This is where the light we see from the sun originates. If we could look at the Sun directly (i.e., using special instruments) we would see the photosphere. Its temperature is ranges from 4,200 K to 5,800 K and its thickness also approximated from 200km to 500 km. Photosphere is a luminous, apparently opaque layer of plasma that forms the visible surface of the *sun* or any other *star*. The photosphere lies between the dense interior plasma and the more attenuated plasma of the next layer called chromosphere. The incandescent plasma of the photosphere, estimated to be at maximum temperatures near 5,800 K, are so much brighter than the other layers of the sun that they seem to form a surface. These plasma elements are in a constant state of agitation due to convection currents that reach down to 241,000 km below the photosphere. Differences in the density of the plasma elements result in a grainy appearance of the photosphere, *see Fig.1.5*; the small bright patches, or granules, are several hundred kilometers in diameter and are constantly shifting, *see chapter 1, section 1.5*. Another feature of the photosphere, observed only near the Sun's edge, is the appearance near sunspots of bright, vein like regions known as faculae [60].

1.4.2. Chromosphere

The region above the photosphere is a layer of the atmosphere about 2,000 km thick called the chromosphere. The temperature increases as you move higher to about 20,000 K at the top of the chromosphere. The chromosphere is no longer white light like the photosphere but is mostly red in visible light. It can be seen as red flashes during a total solar eclipse in filters that let through the red light of the hydrogen alpha line at 6562.8 Å. The lower region of chromosphere is more or less *homogeneous*.



Fig.1.3 Solar chromosphere region is indicated by pinkish color at the edge of solar disc. Credit: NASA

The upper region of chromosphere contains comparatively cool columns of ascending hot plasma known as *spicules*, having between them hotter plasma much like that of the corona, into which the upper chromosphere merges gradually. Spicules occur at the edges of the chromosphere's magnetic network, which traces regions of enhanced field strength. Temperatures in the chromosphere range from about 4,500 to 100,000 K, increasing with altitude; the mean temperature is about 6,000 K. Solar prominences are primarily chromosphere's phenomena. The rarefied, transparent plasma in the solar chromosphere; it measures about 9,700 km in thickness and lies between the *photosphere* and the *corona*. Solar scientists have been get information about chromosphere from flash spectrum, see Fig.1.3. They capture the spectrum during eclipse before a solar eclipse reaches totality and is formed from the thin arc of the sun disappearing behind the moon's disk.

By carefully analyzing, the emission lines give information about the heights of the chromosphere and the heights at which various elements exist in it. Using this technique scientists have found that the chromosphere is composed primarily of hydrogen, which causes its visible pinkish tint, and of sodium, magnesium, helium, calcium, and iron in lesser amounts. The chromosphere consists of three distinct layers that, moving outward from the sun's surface, decrease in density and increase abruptly in temperature. The lower chromosphere is about $6 \times 10^3 K$ the middle rises to $5 \times 10^5 K$ and the upper part, merging into the lower corona,

reaches $10^6 K$ [61]. The two main regions of the Sun's atmosphere as seen during an eclipse: corona (top) and chromosphere (bottom).

1.4.3. Transition Zone

To determine the properties of solar transition zone whether the 300s photospheric oscillations penetrate to the transition zone, and to measure the rms velocity disturbance amplitude and its dependence upon solar activity has been studied [61]. The non-thermal velocity in the solar transition zone and corona at temperature range $10^4 K$ to $10^6 K$ has been studied [62]. As we have seen in chapter 1, *section* 1.4.4, the upper layer of transition zone reaches its temperature up to $10^6 K$ lower part of corona. The solar transition zone is visible using EUV sensible telescope above the Earth atmosphere.

1.4.4. Corona

The outer part of the solar atmosphere is called the corona. The corona starts around 10,000 km above the solar photosphere and extends a millions of kilometers to space. Unlike the atmosphere of the Earth, the atmosphere of the Sun continues to get hotter as you move away from the solar surface up to millions of degree kelvin. However, there is no theory that supports increasing in temperature as we recede away from solar surface to outer rare density region. There are two unfulfilled candidate theories for coronal heating mechanism at rare density solar atmosphere. These are wave heating theory and magnetic reconnection theory. The answer of why exactly this happens is one of the biggest questions of solar physics of the 20th and 21st centuries. At 20,000km to 25,000 km away from the solar surface the corona has an average temperature of 1,000,000 to 2,000,000 Kelvin based on plasma density distribution, *see* Fig.1.4a and Fig.1.4b. But density is very low, about 1 billion times less dense than water on the Earth.



Fig.1.4a Nearly uniform shape of lower corona,
Credit: NASA

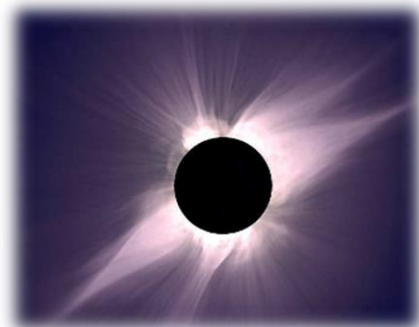


Fig.1.4b Irregular shape of corona, Credit: NASA

The diagram Fig.1.4a and Fig.1.4b show the solar coronal region is observed with EUV and X-ray spectrum region at day time by occulting the sun disk with special instrument, coronagraph.

1.5. Static and Dynamic Events of Solar Atmosphere

1.5.1. Spicules and Plages

At 1,000 km above the photosphere, the chromosphere separates into cool, high-density columns, called spicules and hot low-density plasma. The spicules, each about 800 km in diameter, shoot out at 32 km/s and rise as high as 16,000 km before falling back. Any point on the star (sun) erupt the spicule about once every 24 hours and there may be up to 250,000 of them at any instant. Other types of solar activity are found to occur in the chromosphere. The elements of each layer are sometimes distributed in bright, cloud like patches called plages, or facculi, and in general are located along the same zones as *sunspots* and fluctuate with the same 11-years cycle; the relationship between the two is not yet understood. Faculae are bright areas that are only seen near the limb where the apparent photospheric intensity decreases due to "limb darkening". These features are seen better at the H-alpha wavelength of 656.3 nm, where they are known as "plague" areas. They, like all features on the star, are due to strong magnetic fields emergence, which in this case channel excess heat to the surface in these areas [63].

1.5.2. Quiescent and Eruptive Prominences

Most spectacular of the solar features are the streams of hot plasma, called prominences that shoot out thousands or even hundreds of thousands of miles from the sun's surface at velocities as great as 400 km/s, see Fig.1.2b. Two major classifications are the quiescent and the eruptive prominences. Quiescent prominences bulge out from the surface about 32,000 km and can last days or weeks. Eruptive prominences are thin flames of plasma often reaching heights of 400,000 km; they occur most frequently in the zones containing sunspots. Dark strand-like objects called filaments were discovered on the disk and were originally thought to be a special kind of feature. These are now known to be prominences seen against the bright background of the photosphere. Until the middle of the 19th century, prominences could be viewed extending from the edge of the sun's disk only during a solar eclipse. However, in 1868 a method of observing them with a *spectroscope* at any clear time of day was developed, and in 1930 the invention of the *coronagraph* allowed them to be continuously photographed.

1.5.3. Solar Granulation

If you have a very well designed solar telescope and you are able to convince the Earth's atmosphere to stay quiet and still for long enough, you will see, under high magnification, small cells called granules covering the entire solar photosphere. Observed from the ground, granulation is best observed in green light [64]. This is the convective activity of the sun expressed at the surface. The bright cells or granules are on average about 1100 km across and they are separated from each other by dark lanes which are about 200 km wide. Individual granules are only short lived. Their average lifetime is around 10 minutes, with a range from about 8 to 15 minutes [65 - 67]. Granules are believed to be the tops of convection cells where hot plasma fluid rises up from the interior convection zone. This material spreads out across the surface, cools, and then sinks downward along the dark lanes. The vertical convection velocity is averaged about 2 km/s although it can reach 7 km/s [68 - 70]. These are supersonic speeds in the solar atmosphere, and upwelling currents can create sonic booms. This releasing of acoustic energy generates waves in the photosphere.

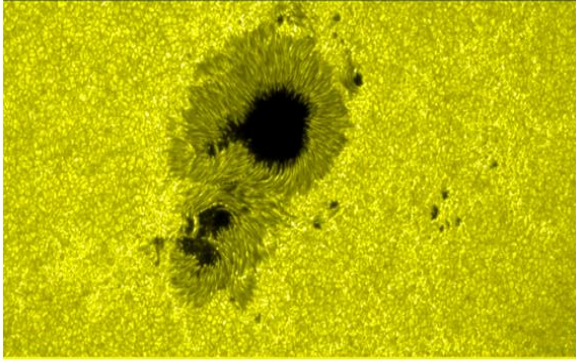


Fig.1.5 Solar granulation associated with sunspot. Credit: NASA

Solar granules cover the entire photospheric surface, except where there are sunspots. In sunspot regions convection is inhibited and there are thus no granules (convection cells) are clearly visible. There are approximately 4 million granules that cover the solar surface at any one time [71, 72]. Solar granulation is the smallest local plasma fluid motion resolved on the surface of the

sun and assumed to be consists of small regions of hot rising plasma surrounded by relatively thin region of cooler falling plasma gas. The granulation is occurred due to the convection operating below the solar surface. The convection process produces columns of rising plasma just below the photosphere that are about 700 km to 1000 km in diameter and has a life time of about 10 minutes same as life time of upper surface layer [73]. Through the column hot plasma rises with velocity of several kilometers.

This can be confirmed by Doppler shift measurement. The top of this rising column is the brighter gray-white cells seen in the granulation image, *see* Fig.1.5. The hot plasma cools at the top of column and sinks down in the darker region surrounding each granule. Thus, granulation is just represents the top of convection currents that are transferring heat from interior to solar surface. Typical vertical and horizontal velocities of the granulation flow are about 1km/s and 2km/s respectively [74].

1.5.4. Solar flares and prominences

Solar flares are intense explosions on the solar surface or atmosphere which releases huge amount of energy in the form of radiation and particle acceleration and heat energy. From observational view points, flares are appeared as a sudden, intense brightening of a local region on the solar surface or atmosphere, typically lasting several minutes [75, 76]. The presence of magnetic field intensifies the flare on solar atmosphere. The propagation of shock waves coupled with magnetic field lines leads to acceleration of charged particles non-thermally before and behind of flares. Intense radiation is released from local region where strong magnetic fields

interact with plasma particles during shock process before flare as well as after flare, see chapters 2, 3 and 4. Thus, Solar flares emit huge bursts of electromagnetic radiation, including X-rays, ultraviolet radiation, visible light, and radio waves *see* Fig.1.6b. The solar flare fall on very broad spectrum emissions, energy of typical 10^{20} joules of energy is considered to be the median for well observed event, while a major event can emit up to 10^{25} Joules as obtained from observations [77]. Although solar flares can be visible in white light, they are often more readily noticed via their bright *X-ray* and ultraviolet emissions. CMEs often accompany solar flares, though scientists are still trying to determine exactly how the two phenomena are related.

Based on our new models, SWIF-1SQR model and SWIF-2SAR model, the small solar flares burst everywhere on the solar surface independent of magnetic field and large solar flares are appeared forth from the intense magnetic fields in the vicinity of active regions, most probably on the solar corona. Large Solar flares are most common during times of peak solar activity, the solar maximum years of the sunspot cycle at region between 10^0 to 60^0 both on northern and southern hemisphere of solar atmosphere. The solar explosive events are not ever existed in the absence of moving shock waves. Even if strong magnetic field is appeared on solar surface, plasma cannot diffuse across magnetic field in absence of inertial force through high conductivity plasma and to store enough magnetic energy at small local region takes about order 10^7 years [78]. However, the presence of shock wave makes the reconnection process is very fast *see* chapter 4, *section* 4.7 and the magnetic field lines form bundles of magnetic flux tubes and charged particles are accelerated. When charged particles move fast along the field lines, the annihilation and creation process of fields (i.e., magnetic field, electromagnetic fields, velocity fields ... etc) is very fast at the region where magnetic pressure is dominant over plasma dynamic pressure, *see* chapter 4.

Evidences from SOHO, LASCO, SDO, YOHKOH, TRACE ... and so on indicates that small and high explosive phenomena are occurred in the corona or chromosphere that provides small and large solar flare; a sudden and intense brightening in a plage that rises to great brilliance in a few minutes, then fades dramatically in a several minutes. This feature is also associated with sunspots and is thought to be triggered by the sudden collapse of low density local region associated with complex magnetic field in the plage, *see* chapters 2, 3 and 4. A flare releases the energy equivalent of a billion hydrogen bombs and is the most energetic of solar

events [79]. The ultraviolet and *X-ray* radiation from larger flares can disrupt magnetic compasses and navigation and radio signals as well as affect the electrical grid on the earth and can damage satellites and space probes, see Fig.1.1a and Fig.1.1b. Cosmic rays and solar wind particles from some flares interact in the Earth Polar Regions magnetized plasma, creating brilliant auroral displays. A powerful solar flare, the bright region towards the right side of this image, erupts from the sun in this ultraviolet image from November 2003.

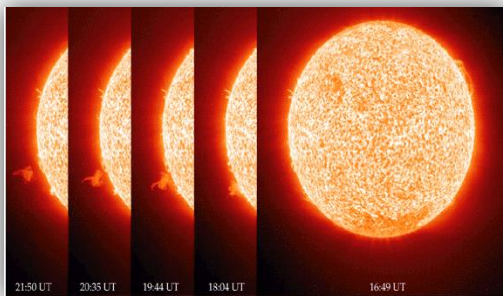


Fig.1.6a Quiescent prominences
Credit: NASA

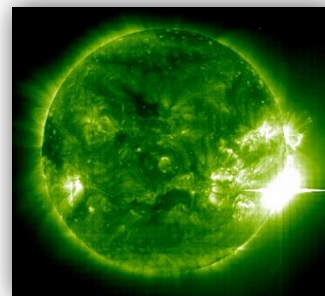


Fig.1.6b Impulse solar flare,
Credit: NASA

1.5.5. Temperature variation of granules

The lower region of solar convection zone where the granulation is driven, the rising granular center must be hotter than the falling plasma gas in the inter-granular space. In the photosphere, this will not necessarily be the case, as the photosphere is stable against convection and such motion must be caused by deeper convection motion overshooting in to the stable photosphere. At the granular center rises, it will cool through expansion and due to the super adiabatic temperature gradient in the photosphere. This cooling can be very fast and there will also be efficient *radiative cooling* [80, 81]. Thus, we can expect that deep in the photosphere, there will be large temperature differences between the up flows and down flows of upper convection region at same position below photosphere. At the top of photosphere this difference in temperature will be smaller comparable to lower region.

1.5.6. Pressure variation of the granulation

Pressure difference within the granulation must be existed because of momentum transform of convective plasma elements. When a local pressure difference is occurred in

isothermal and isotropic plasma, the dynamic pressure difference is arisen due to local plasma density difference. The horizontal flow in granulation is occurred due to pressure difference of local region in granulation and its surrounding cooler plasma. When supper hot plasma rises up vertically and it forms mountain like mass of plasma cloud, due to strong gravitational force the risen up plasma becomes cold and falling down later, *see chapter 2, section 2.2 - 2.7*. The falling down plasma diffuses horizontally because of potential difference with its surrounding region. Horizontal surface electric current is developed due to instantaneous surface charge separation of hot diffusing plasma. The vertical or horizontal surface current is existed due to vertical or horizontal plasma flow, non-radial surface oscillation and local plasma turbulence associated with granulation [82, 83]. Generally, the dynamic pressure deference at solar granulation region creates surface electron current at stellar atmosphere.

1.5.7. Density variation of granulations

The density variation of granulations is arisen because of temperature and pressure variation coupled with complex magnetic field under the control of strong gravitational force. The horizontal density variation of granulation is related to horizontal variations in temperature and pressure. The observable horizontal density variation is occurred at the outer layer of solar photosphere. The emergence of bundles of magnetic flux tubes contributes on formations of horizontal density variation [84, 85]. Local density variation at solar photosphere or atmosphere could be the main sources of solar explosive events associated with force free solar magnetic field activities. The non-radial solar oscillation mode creates horizontal motion of plasma at solar surface. The motion due to solar oscillation is expected as slow plasma motion is responsible for surface plasma density variation associated with granulation.

1.5.8. Horizontal variation of granular flows

The granular flow velocity varies strongly with horizontal position; the up flows move up wards and the down flow moves down wards. The down flows, occupying a smaller fraction of solar surface, have correspondingly higher flow speeds. The speed of the up flows and down flows or at least the difference between them can be approximately measured from red and blue shifts of spectral lines observed with spatial resolution [86]. This only gives an approximated result as the spectral lines do not form at single heights, but rather over a range of heights, so only an average

velocity is detected by contributions to the line from different heights can be found in this manner. The horizontal variation of granular flows may be influenced by the non-radial surface oscillation due to deficiency of local plasma mass and excess agglomerated local plasma mass at solar surfaces. The solar surface rotation also has a significant effect due to Coriolis forces and centrifugal forces against gravitational force of rotating sun possess, see Chapters 2 and 3 that coupled with complex magnetic field [87, 88]. The horizontal granular flow of high conductivity plasma is characterized by its turbulent nature. The horizontal turbulent nature of solar plasma is occurred due to small plasma convection process, non-radial surface oscillation, formation of surface shockwaves and surface gravitational wave. The surface shock wave is developed due to highly non-linear effects of physical quantities.

1.5.9. Supergranulation

This is the hardest of all to see from solar, and is best seen in velocity images (showing Doppler shift) of the photosphere. Supergranulation is a much larger version of granulation. Where large groups of granules are seems moving together. The speed of movement is about 500 m/s and the plasma motion of super-granules carries magnetic field bundles across the photosphere. The structure and evolution of solar supergranulation is studied using horizontal velocity fields, deduced from applying local correlation tracking (LCT) techniques to full-disk, line-of-sight Doppler velocity data observed by the Michelson Doppler Imager on board the *Solar and Heliospheric Observatory* spacecraft [89 - 91].

1.5.10. Sunspots

Sunspots are the easiest feature to detect on the solar photosphere. In fact, some sunspot groups grow so large that they are visible with the naked eye. They are apparent as dark spots, with a central dark umbra and a lighter surrounding penumbra. They occur due to high concentrations of magnetic field which inhibit heat flow to the surface from the lower region of convection zone. Generally, sunspots are dark region appeared on solar surface. Scientists believed, Sunspots are dark because they are cooler than their surroundings partially ionized solar plasma. A large sunspot might have a central temperature of less than the minimum photosphere temperature of 4,200 K, much lower than the 5,800 K temperature of the adjacent photosphere [92, 93]. Sunspots are only dark in contrast to the bright face of the Sun from visible

light detection. If you could cut an average sunspot out of the Sun and place it elsewhere in the night sky, it would be about as bright as a full moon. Sunspots have a lighter outer section called the *penumbra*, and a darker central region named the umbra. Sunspots are caused by disturbances in the Sun's magnetic field welling up to the photosphere, the Sun's visible surface.

The powerful magnetic fields in the vicinity of sunspots produce active regions on the sun, which in turn frequently spawn disturbances such as solar flares and CMEs. Because sunspots are associated with solar activity, space weather forecasters track these features in order to help predict outbursts of solar storms. Sunspots form over periods lasting from days to weeks, and can persist for weeks or even months before dissipating [94, 95]. The average number of spots visible on the face of the Sun is not constant, but varies in a multi-year cycle. Historical records of sunspot counts, which go back hundreds of years, verify that this sunspot cycle has an average period of roughly eleven years. In recent years, astronomers have been able to detect star-spots - "sunspots" on other stars [96, 97].

1.6. Solar Atmospheric Plasma Ionization and Radiation Process

The solar corona is made mostly of hydrogen and helium. The hydrogen and helium in the corona is completely ionized; thus the corona consists of hydrogen nuclei, helium nuclei, and free electrons associated with magnetic field. The high temperature of the corona means that many of the protons, helium nuclei, and electrons are moving faster than the Sun's escape speed. No longer gravitationally bound to the Sun, these fast-moving particles stream away from the Sun into interplanetary space. The charged particle emanated from corona is called the solar wind. Every seconds, millions of tons of plasma flows away from the Sun to interplanetary space. This is less, remember, than the mass loss from nuclear fusion in the Sun's core, which is about 4 million tons a second. During the Sun's lifetime, so great is the mass of the Sun, the mass loss from the solar wind has been negligibly small. It takes about 200 million years to lose the equivalent of the Earth's mass and it takes 330,000 Earths to equal the Sun. The Sun is largely unaffected by losing a million tons of gas a second. However, the solar wind does have a significant effect on other bodies in the solar system. For instance, the interaction of the solar wind with the Earth's magnetic field and the Earth's upper atmosphere produces aurora at poles.

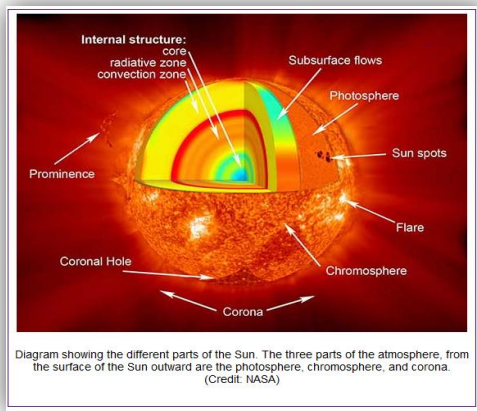


Fig.1.7a Feature of solar phenomena,
Credit: NASA

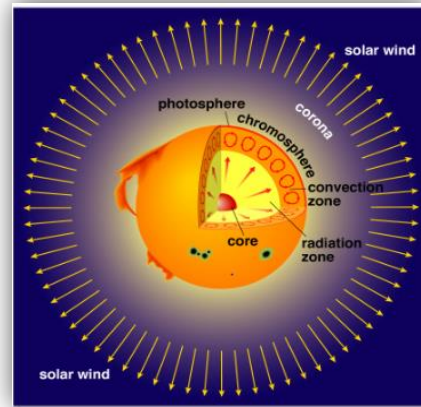


Fig.1.7b Solar wind Credit: NASA

The interaction of the solar wind with a comet produces the comet's long ion tail. The main mechanism of solar wind is the solar atmosphere oscillation, see Fig.1.7a. Below the photosphere, temperature decreases steadily with increasing distance from the Sun's center. However, going outward from the chromosphere to the corona, the temperature leaps upward spectacularly. This is unique behavior of sun. To know this secrete, a deep research is needed.

1.6.1 Fully ionized solar plasma

Since stellar (solar) plasma is created by ionization of neutral atoms most probably hydrogen gas, it consists of positively charged ions and negatively charged electrons along with some neutral hydrogen atoms. In case of hydrogen plasma, the positive charged ions are equal with negative charged electrons. The number density of electrons and ions is determined by the ionization process. By fully ionized plasma we do not necessary mean that there are no neutral atoms in the plasma. However, the number density of neutrals is much less than the number density of ions and number density of electrons. The electrons and ions experience a coulomb force between them. The rate of collisions between electrons, ions and neutrals could be determined by their number densities and range of Coulomb force between them. In completely ionized plasma, electrons-ions collision is dominant at high enough temperature. For instance, 13.6 electron volt of energy is required to separate the electron from hydrogen atom, where 1eV corresponds to 11,600K temperature. Thus, hydrogen plasma would be fully ionized at temperature higher than 11,600K. The solar corona at temperature order of $10^6 K$ and rare

electron-ion collision is fully ionized plasma. However, the rarity of electron-ion collision at high temperature is due to Coulomb force. Collision-less plasma is highly unstable [98, 99].

1.6.2. Partially ionized plasma

The solar photosphere is believed as partially ionized hydrogen plasma. Partially ionized plasma has a degree of ionization that is less than 1, $z = n^+ / (n + n^+) < 1$ where z is degree of ionization, n^+ is number of charged hydrogen ion and n is number of hydrogen neutrals. Presence of enough neutral hydrogen atoms in solar plasma makes it partially ionized plasma. Charged particle-neutral collisions in plasma play a crucial role. In partially ionized plasma, the rate of electron-ion collision is much lesser than rate of electron-neutral collision. This is precisely due to electrons being much lesser neutral hydrogen atoms. Such plasma is existed in solar photosphere. A novel effect called am-bipolar diffusion is arises in a weakly ionized plasma. It is essentially, due to coupling of neutrals and ions; the neutral in the process acquires some of the properties of charged particles, begin to be affected by electric field and magnetic field that are participating in electromagnetic phenomena. The am-bipolar diffusion is actually responsible for diffusion and transport of magnetic flux in weakly ionized plasma [100 - 103].

1.6.3 Plasma formation by photoionization

At solar atmosphere, hydrogen gas can be ionizing by high intensity photon or eliminating it with electromagnetic radiation of the appropriate frequency ν and this process is known as photoionization. A single charged ion results when a single electron is emitted from neutral hydrogen atom at solar atmosphere due to surface radiation pressure.

$$H + h\nu = H^+ + e \quad (1.1)$$

Where, H represents a hydrogen atom and H^+ represents charged hydrogen ion and e is emitted electron charge. Here, $h\nu$ is the energy of a photon of radiation and it must exceed the ionization energy E_I of atom. For instance, the photon energy of $E_I = 13.6 \text{ eV}$ is required to ionize a hydrogen atom. The excess energy of the photon goes to the kinetic energy of the emitted electron. The energy conservation is given by Eq.(1.2) below.

$$h\nu = E_I + \frac{1}{2}m_e v_e^2 \quad (1.2)$$

Where, v_e , is velocity of emitted free electron. The ionization energy E_I defines the threshold of the photon frequency ν required for ionization process. The degree of ionization increases rapidly at the threshold frequency; and then decreases as photon frequency increases [104, 105].

1.6.4. Collisional ionization

Interior of the sun collisional ionization process plays a crucial role. However, at atmosphere collisional ionization could not be frequently. The high energy electrons emitted via photoionization can further produce ionization by their collisions with the atoms and ions. The reverse process of recombination also goes on, which reduces the number of electrons and ions. In addition, electrons may get attached to the atoms to produce negatively charged ions. A steady level of ionization may be obtained under the influence of all this process. Collision of heavy particles such as protons with the gas atoms or molecules can cause ionization in multiple ways. These collisions are governed by *Coulomb* force between the incident particle and electrons bounded to the atom. Collision between atoms of gases of different ionization potentials can also cause ionization [106, 107].

1.6.5. Thermal ionization

The thermal ionization is most probably at deep region of solar interior and a region far away of solar photosphere, coronal region. At high enough temperature, collisions among atoms can often knock off their electrons, resulting in the formation of positively charged ions and negatively charged electrons. The number density of particles corresponding to ionization energy is given by Eq.(1.3).

$$n_l \propto \exp\left(-\frac{E_l}{k_B T}\right) \quad (1.3)$$

The Eq.(1.3) is indicating clearly that the number density of high energy particles diminishing exponentially in a system in thermodynamic equilibrium for negligible force free solar magnetic field. Similarly, the number density of neutral particles n_M with corresponding energy E_M are given by Eq.(1.4).

$$n_M \propto \exp\left(-\frac{E_M}{k_B T}\right) \quad (1.4)$$

If some of the atoms or molecules of solar plasma gas are ionized at temperature T , we have a mixture of neutral atoms as well as electrons and ions. There is one electron for one positive charged ion for completely ionized hydrogen plasma. If there are two positive charges on the ion, there would be two electrons. We can identify the state L with electron-ion pair and define the ion density $n_i = n_L$. The state M can be identified with the neutral atoms. The ratio of ions to neutrals is defined by Eq.(1.5) that measures the strength of ionization process.

$$\mathcal{X} = \frac{n_i}{n_M} \quad (1.5)$$

The ionization energy is described as amount of absorbed energy by atoms that enable to emit electrons. Thus, ionization energy describes fractional ionization and energy difference E_I given by Eq.(1.6).

$$E_I = E_L - E_M \quad (1.6)$$

This represents the ionization energy of atom under consideration. The number density n_i of ion during thermal ionization process can be expressed by Eq.(1.7) in exponential form.

$$n_i \propto \exp\left(-\frac{(E_L - E_M)}{k_B T}\right) \quad (1.7)$$

The proportionality constant is determined from quantum mechanical and statistical considerations and is a function of the electrons mass, the Planck constant h , the Boltzmann constant k_B , the number density $n_e = Z n_i$ of electrons where Ze is the electric charge on the ion with e the magnitude of the charge of an electron. Here, it would suffice to give an approximate expression as

$$n_i \approx 2.4 \times 10^{15} \frac{n_M}{n_e} T^{3/2} \exp\left(-\frac{E_I}{k_B T}\right) \quad cm^{-3} \quad (1.8)$$

The Eq.(1.8) is Saha equation and it is applicable only under condition of thermodynamic equilibrium of local region solar interior and its atmosphere. However, as we have seen in

chapter 1, *section 1.4*, there is no theory that supports solar atmosphere heating as someone goes out to surrounding space vacuum of high plasma beta, β -beta [81, 108].

1.6.6. Pressure ionization

At extremely high mass densities, when the volume per hydrogen atom becomes lesser than normal volume occupied by hydrogen atom, the atoms can no longer be identified as individual units. There is an overlap of outer electronic orbits of the atoms, the outer most electrons become loosely bound to the atom and behave more like a free electron gas. The substance becomes an aggregate of nuclei and electrons, highly compressed plasma. This phenomenon is called pressure ionization. Under such circumstances the electrons behave like a cold degenerate quantum gas provided the temperature is not too high. The energy distribution of the degenerate electrons is very much different from the Boltzmann distribution. The degenerate electrons obey the Fermi-Dirac statistics. This statistics is a consequence of Pauli's exclusion principle. This principle states that no more than one electron can be accumulated in each quantum state specified by the energy of electron. In contrast, in the classical statistics, the temperature determines the occupation of an energy level through Boltzmann factor. The degree of ionization of degenerate gas is mainly a function of pressure or density but not temperature. The pressure ionization property is so effective process at interior of massive stars [109 - 112].

1.7. Radiation from Stellar Atmosphere

The surface of star (sun) emits electromagnetic spectrum including visible light due to Thomson scattering process. Solar radiation is a radiant electromagnetic energy emitted by the solar surface and provides heat, light and energy for Earth. Radiation comes in to two basic types. These are electromagnetic radiation transmitted by photons, and particle radiation consisting of electrons, protons, alpha particles, and so forth. Electromagnetic radiation, transmitted as photons, includes all kinds of spectrums from relatively benign radio waves to dangerous and powerful X-rays and gamma rays. Energy levels across the electromagnetic spectrum vary inversely with wavelength. Particle radiation involves fast-moving sub-atomic particles, such as electrons, protons, and nuclei (ions) of Helium and heavier elements. Exposure to too much radiation of various types can be harmful to humans and other living things on the Earth planet. Radiation can also fry the electronics in spacecraft, disabling them [113 - 116].

1.7.1. Electromagnetic Radiation

The solar atmosphere emits all kinds of electromagnetic waves. In general cases, based on observational evidences, the photosphere emits visible light spectrum, the Chromosphere emits EUV line spectrum and the Corona emits X-ray spectrums. Different size solar explosive events provide all kinds of spectrum including the Gamma-ray spectrum region from small local place of solar atmosphere. Electromagnetic radiation is the result of oscillating electric and magnetic fields. The electromagnetic wave energy is generated by oscillations of electromagnetic fields that move in vacuum at the speed of light. X-rays, radio waves, gamma rays, and infrared and ultraviolet wave are the other main types of electromagnetic radiation. They are all traveling oscillations of electromagnetic waves, each with its own characteristic wavelength. Organized in order of wavelength, they make up the electromagnetic spectrum. Sometimes it is useful to think about electromagnetic radiation as though it came in packets. These packets of EM radiation are called *photons* [117, 118].

1.7.2. Particle radiation

One main type of radiation, particle radiation, is the result of subatomic particles hurtling at tremendous speeds. Protons, cosmic rays, and alpha and beta particles are some of the most common types of particle radiation. Particle radiation can harm living creatures and can short out electronic circuits. So it is dangerous for humans and robots alike. Protons and electrons are two of the most common types of particles encountered. Tear apart an atom of hydrogen, the most abundant element in the universe, and you get a proton and an electron. Hence, an abundance of this type of radiation occurred at solar surface. Strip the two electrons from the second most abundant element, helium, and you are left with a nucleon containing two protons and two neutrons. This helium-nucleus particle is called an "alpha particle". Free electrons, when zipping around as radiation, are known as *beta particles*. A third type, gamma radiation, is not a particle but rather a high-energy form of electromagnetic radiation. Neutrinos are bizarre particles that can pass through almost anything, even miles (kilometers) of solid rock. Because neutrino radiation rates may be able to tell us about the nuclear reactions at the core of the Sun, scientists have gone to great lengths to try to device detectors that sense these elusive particles. Particles are radiated from the solar atmosphere if formed during solar flared and CMEs [119 - 122].

1.8. Shock Wave

A wave that travels faster than the sound speed (i.e., typical information speed) and that changes the state of the medium through which it travels is known as *Shock wave*. A *shock wave* can occur in high conductivity plasma medium where a discontinuity in pressure, magnetic field, and velocity and plasma number density is created. In laboratory, *shock waves* can be generated with high intensity laser plasma interactions [123]. Shock waves occur in nature at time of explosions (i.e., solar flares, CMEs, high explosive weapons ... etc.), at electrical discharges, at supersonic flight in the atmosphere (i.e., supersonic space craft flight), in the space (e.g. explosion of supernova) as evidences are obtained from observations with SOHO, YOHKOH, SDO, LASCO and others. During flaring and CMEs, radiation and material are injected into the solar atmosphere from solar surface, causing interplanetary *shock wave*. The traveling *shock wave* propagates out through solar system. The solar wind has high-speed and low-speed streams, coming from different source regions on the sun atmosphere. Shock waves can be formed at the interface between a slow plasma streams being overtaken by a fast plasma stream of solar winds.

Shock wave is defined as a transition layer which propagates through high conductivity plasma fluid, causing a change of state, which may be stationary or moving on its reference frame. Generally, shock waves can be classified as collisional shock and collision-less shock waves. The thickness of collisional shock is approximated by few mean free paths while the thickness of collision-less shock is smaller than particles mean free path. The physical quantities such as plasma temperature, pressure, flow velocity and magnetic field are changed across the moving or stationary shock fronts. The physical quantities of mass, momentum and energy are conserved before shock and after shock passage in isolated local system. In collision-less high conductivity plasma, the behavior and state of plasma is changed by passage of shock fronts. The shock conversion process is so complex.

Energy and momentum can be transformed from plasma particles to magnetic field and electric field. This process leads to increment in unstable magnetic and electric fields. The charged particles are directly influenced by the instability across the shock fronts as well as near the shock fronts. The influence of moving shock fronts coupled with electromagnetic waves enables us to model and describe the small and intense solar explosive phenomenon *see chapter*

2 and chapter 3 at solar exterior. Studying the nature of plasma before and behind shock fronts tells us about the information of shock process that transits the state. Here, we have been studying fast moving non-relativistic and non-radiative shock waves propagating in high conductivity plasma. The physics of shock wave specifies that like an ordinary wave, a shock wave carries energy, and can propagate through a medium; however it is characterized by an abrupt, nearly discontinuous change in pressure, temperature, density and magnetic field of the high conductivity plasma medium. The energy of collisional shock wave dissipates quickly with distance through high density plasma.

When a shock wave passes through continuum medium, energy is preserved but entropy increases and the process is strongly *irreversible processes*. Shock wave is expected as a thin transitive layer propagating with supersonic speed in which there is a sharp increase or decrease of density, pressure and speeds of plasma fluid. The evolution of a nonlinear compression wave into a shock wave was investigated by Riemann (Riemann 1876) who gave an analytic solution in the case of one-dimensional flow [124, 125]. Generally, shock wave is assumed to be as energy converter and a steady transition layer between the undisturbed (un-shocked) plasma fluid and the plasma through which the shock has been passed. The propagating shock surface may be Langmuir shock surface or turbulent shock surface. Let we assume that shock as a transition region between two uniform states. However, state of the high conductivity plasma behind shock does not persist but changes with time after the shock has passed on. The thickness of non-relativistic collision dominated shock wave is approximated by mean free path at high density solar surface. However, the expected shock surface which is occurred at upper region of chromosphere and corona, the existed shock would be collision-less shock wave. It is difficult to estimate the thickness of collision-less shock waves.

Earlier, the propagation of waves with a velocity higher than that of sound was considered by Stokes, Airy and Earnshaw [126]. Further investigations were made by French engineer, former officer of artillery H.Hugoniot, 1889 and by English scientist Rankine, 1879 [127]. Hugoniot showed that the law of energy conservation is incompatible with the constancy of entropy while considering the flow across a shock wave. Shock waves in air were observed for the first time by famous scientist and philosopher E.Mach, 1878 [128]. He also discovered the so-called irregular (Mach) reflection which has no analogies in acoustics and optics. Various

cases of shock interactions were made possible to investigate after N.E.Kotchine, 1926 had solved the important problem of break-up of an arbitrary discontinuity [129]. The structure of non-relativistic shock waves can be studied, using kinetic equations and Maxwell equations in high conductivity plasma fluid. The Boltzmann equation is used widely in collisional non-relativistic shock waves. The non-relativistic shock wave may be Langmuir shock wave or turbulence shock wave.

However, this term usually signifies only a comparatively narrow region where a transition takes place between an undisturbed medium and disturbed medium. We assumed that the shock surface is at a motion along shock normal vector. The propagation velocity of normal shock surface is given by $(c_1 + V)\hat{n}$ before shock and $(c_2 + V)\hat{n}$ behind of some shock fronts along shock normal. The quantity V_n , c_1 and c_2 are velocity of normal shock, speed of small disturbance before shock and behind shock respectively. Displacement traveled by the normal moving shock surface is given by $\vec{s} = Vt\hat{n}$, where t time traveled by shock surface. The normal vector at a point X_0 on a shock surface $f = f(X, t) = 0$ of negligible thickness $\delta x \rightarrow 0$ is given by Eq.(1.9).

$$\vec{N} = \begin{vmatrix} f_{x1}(X_0) \\ f_{x2}(X_0) \\ -1 \end{vmatrix} \quad (1.9)$$

The functions $f_{x1} = \partial f / \partial x_1$ and $f_{x2} = \partial f / \partial x_2$ in Eq.(1.19) describes the gradient of the function f at position $\vec{X}_0$. The plasma flow before shock and after shock may be in steady or unsteady flow. However, plasma inside the moving shock is considered to be in steady state situation for sake of simplicity. The flowing tangential velocity component of normal moving shock surface before shock remains the same as behind shock surface passage. The unit normal vector of moving normal shock is obtained from Eq.(1.19) that is described by Eq.(1.20) in unmagnetized high conductivity plasma.

$$\hat{n} = \frac{\vec{\nabla} f}{|\vec{\nabla} f|} \quad (1.20)$$

We can extract the shock velocity from the material derivative of shock function $f = f(X, t)$ and can be described in terms of the normal unit vector, $\hat{n}$ in Eq.(1.20).

$$\vec{V}_n = -\frac{1}{|\vec{\nabla}f|} \frac{\partial f}{\partial t} \hat{n} \quad (1.21)$$

The moving shock surface in steady state situation, we assumed that its tangential component of velocity does not appeared $\vec{V}_t \approx 0$ while normal velocity components, $\vec{V}$ is time independent for invariable shock surface. This kind of shock is non-accelerated, non-radiative and non-relativistic shock surface.

1.8.1. Normal Shock Surface

We define that normal shock is a moving shock surface which propagates along its normal unit vector while its tangential velocity component is vanished $\vec{V}_t \approx 0$. Generally, normal shock surface may be time dependent or time independent moving shock surface through high conductivity plasma. Let consider the moving shock surface is in steady state condition for the sake of simplicity. This indicates that normal moving shock surface is situated in steady state situation as long as it passes through physical system of high conductivity continuum medium. In reality, velocity of normal shock surfaces is considered as time dependent due to the slowing and fastening of normal shock along its path.

Even if the normal shock surface is fastening or slowing along its path through the continuum media, it doesn't provide variable effect on the local shocked system. The normal component of mass flux of normal shock surface is associated with the shock velocity that suffices the shock condition, $\vec{V} \cdot \hat{n} \neq 0$ across shock surface. The fast moving normal shock surface is characterized by formation of plasma jet behind it due to implosive or explosive waves. The tangential components of normal shock velocity and flowing plasma velocity do not contribute in complex density profile formation of the continuum shocked medium. When the velocity of fast moving shock wave is time dependent and its magnitude is near to speed of light, it creates electromagnetic wave burst or radiation. This kind of normal shock is known as an *accelerating normal shock surface* or radiative shock wave. When $V \rightarrow c$, where, c speed of sound, the shock is known as normal relativistic shock surface.

1.8.2. Contact and tangential discontinuities

Contact and tangential discontinuities are transition layers across which there is no particle flux transport. Thus, in the frame moving with the discontinuity $\vec{u}_{1n} = \vec{u}_{2n} = 0$ even for $\vec{V} \neq 0$ of fast propagating shock surface. Contact discontinuities are discontinuities for which the thermal pressure, the magnetic field and the velocity are continuous. Only the mass density and temperature change. Tangential discontinuities are discontinuities for which the total pressure (sum of the thermal and magnetic pressures) is conserved. The normal component of the magnetic field is identically zero. The density, thermal pressure and tangential component of the magnetic field vector can be discontinuous across the layer. The tangential discontinuity could not be assumed as a shock in high conductivity plasma medium but it may triggers shock formation as the shock agent is sudden flowing plasma.

1.8.3. Blast wave behind of shock wave

A *blast wave* in high conductivity plasma dynamics, is the pressure and directional flow resulting from deposition of a large amount of energy in a small much localized volume. The directional flow field can be approximated as an agent of *shock wave*, followed by a 'self-similar' supersonic or subsonic flow field. In simpler terms, a blast wave is an area of pressure expanding supersonically outward from an explosive core or imploding surface during collapsing of low density local region. It has a leading shock front of compressed highly conducting plasma. The shock wave is followed by a blast wind of negative pressure, which sucks items back in towards the center of convergence. The sucked items are instantly heated and gain enough kinetic energy and ejected out back forming jets. The blast wave is harmful especially when one is very close to the center or at a location of constructive interference [130]. High explosives, which detonate, generate blast waves. Strong moving shock wave followed by strong blast waves triggers flares, eruptions, surges, jets, filaments and CMEs at solar surface see chapter 2, 3 and 4. Generally, blast wave fronts in high conductivity medium can be formed associated with fast moving shock surface or behind shock surface, see chapter 2.

1.9. Stellar Differential Rotation

Because of the pre-stars accretion phases and the conservation of angular momentum, stellar rotation is induced [11, 131]. Solar physicist believed that differential rotation is caused

by convections in stars (sun) [132]. There is a movement of plasma mass due to steep temperature gradients from the core outwards. This mass carries a portion of the stars angular momentum, thus redistributing the angular velocity, possibly even out far enough for the star to lose velocity in stellar wind. Differential rotation thus, depends on temperature differences in adjacent region. There are many ways to measure and calculate differential rotation in stars to see if different latitudes have different angular velocity. The most obvious being tracking spots on the stellar surface by doing helio-seismological measurements solar *p-modes* it is possible to deduce the differential rotation. A fast and reliable method to measure stellar differential rotation from photometric data is analyzed by Reinhold, T. and Reiners [133].

The sun has very many acoustic modes that oscillate in the interior simultaneously and the inversion of their frequencies can yield the rotation of solar interior. This varies with both depth and latitude. The broadened shapes of absorption lines in the optical spectrum depends on $\Omega \sin \theta$, where θ is the angle between the line of sight and rotation axis, permitting the study of rotational velocity's line-of-sight component $\vec{\Omega}$. This is calculated from Fourier transform of the line shapes [134, 135]. Gradients in angular rotation caused by angular momentum redistribution within the convective layers of the sun are expected to be a minimum driver for generating large scale magnetic fields, through magneto-hydro dynamical mechanisms in the outer envelopes.

The interface between these two regions is where angular rotation gradients are strongest and thus where dynamo process is expected to be most efficient. The inner differential rotation is one part of the mixing process in stars, mixing the materials and the heat or energy of the stars, see chapter 2, section 2.4. Differential rotation affects stellar optical absorption- line spectra through line broadening caused by lines being differently Doppler-shifted across the stellar surface. Solar differential rotation causes shear at the so called tachocline [11, 136, 137]. This is a region where rotation changes from differential in the convection zone to nearly solid body rotation in the interior at 0.71 solar radii from the center [138, 139]. Here, to study solar oscillation associated with strong magnetic field at solar photosphere.

CHAPTER 2

2. SHOCK WAVE INDUCED FLARE ON SOLAR QUITE REGION

2.1. Aim of SWIF-1SQR model development

Here, in this thesis chapter, our aim is to theorize a new flare model, physical model, which explains the stellar explosive events. The SWIF-1SQR is advanced on the basis of plasma dynamic and shock theory. Scientists believed that the main mechanism of stellar (solar) atmospheric (i.e., photosphere, chromosphere, transition region and corona) plasma motion is the dynamical nature of surface plasma associated with non-radial surface oscillation modes, specifically the Sun [140, 141]. The cause of convection motion and non-radial surface oscillation is a small perturbation in pressure interior of the star [142]. The behavior of stellar oscillation in interior part is determined by hydrodynamics theory in connection with kinetic theory at micro scale level of local region. Effect of magnetic field interior of the star is negligible. However, the behavior of stellar atmosphere is specified by magneto-hydrodynamics at macro-scale level and coupled with kinetic theory in micro-scale level.

Here, the stellar explosive events are modeled by hydrodynamic explosion based on shock and kinetic theory at weak magnetic field region of photosphere; chromosphere and corona associated with fast flowing plasma element. The stellar explosive events are triggered due to formation of strong shock front trains at local system. The stellar explosive events at strong magnetic field regions or magnetic flux tubes are modeled with magneto-hydrodynamic explosions theory coupled with particle kinematics *see* SWIF-2SAR model in chapter 3. Magneto-hydrodynamic explosive events associated with plasma kinetic theory will be seen in our next chapter, *see* chapter 3, so as to describe the local explosive events. In this chapter we will develop a shock wave induced stellar (solar) flares model at weak magnetic field region of stellar atmosphere. This model gives a clear and new description for all stellar explosive events and stellar winds mainly focused on solar flares (i.e., impulse flares, Nano-flares and micro-flares) and CMEs. This new model works based on the shock theory and hydrodynamics nature of local plasma system. This gives a new sight for understanding and modeling of stellar explosive events in connection with fast magnetic reconnection (FMR) model and formation of

CMEs from lower region of stellar atmosphere. The further extended new model will be done on chapter 3 that supports strong magnetic field region, solar active region.

To study the dynamical phenomena of stellar (solar) atmosphere such as solar flares, CMEs, solar winds, prominences, filaments, sunspots ... and so on, it is necessary to know the plasma properties interior of star and exterior of star in connection with evolution of stellar magnetic fields in general. The energy required on stellar atmosphere to perform the stellar activity has been transformed from interior of star [143, 144]. Up to now, there is no theory which supports the dynamics of the active star (sun) that gains enough energy from its surrounding objects or surrounding envelop of space-time coordinate. The energy budget of the star which is required for the global solar activity would be expected to obtain from its interior region [145]. In hydrodynamics system (i.e., interior of star) it is assumed that the stellar plasma can be treated as a continuum medium, so that its properties can be determined as functions of position $\vec{r}$ at a given point and time t . Before constructing the shock wave induced solar explosive event model, we give a short and brief explanation of stellar photosphere convection and solar oscillation theory in connection with the stellar differential rotation, in steady state and dynamic situation [146, 147], *see section 2.2 to 2.8*, and in connection with complex force free magnetic field in chapter 3 sections, 3.2 - 3.8.

2.2. Equilibrium Situation of Stellar Surface

At equilibrium situation, the surface of radiating young star is considered in stable condition. Partially ionized surface plasma is stratified under the control of gravitational force of self-gravitating, monotonously oscillating and rotating radiative star.

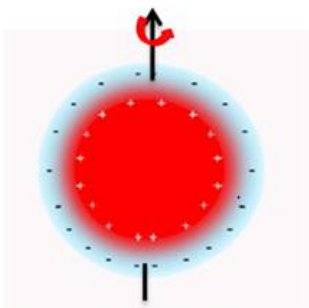


Fig2.1 Charge distribution on stellar surface

When we look the star (sun) from afar, it seems a stable object which emanates all types of electromagnetic spectrum continuously to its surrounding, *see section 1.7* in chapter 1. However, on the atmosphere of the young star high explosive phenomena are observed. The properties of explosive events in the stellar atmosphere, transition zone, are presented by means of detailed statistical analyses. These events are observed as

regions of exceptionally high velocity up to 100 km/s [148, 149]. Consider a finite temperature

of stellar surface plasma consisting of large number of electrons, ions and neutrals. We assumed that ions and electrons densities are initially equal and spatially uniform near stellar surface layer of position $\vec{r}$ measured from center of star at steady state situation. Ions, electrons and neutrals will have a separate temperature of T_i , T_e and T_n respectively. However, at equilibrium situation, the partially ionized plasma is considered as stratified plasma in thermal equilibrium that suffices isothermal condition on stellar surface. For instance, let we put ions, electrons and neutral particles at position, $\vec{r}$ of isothermal stratified stellar surface layer of temperature denoted by T at photosphere region. All kinds of plasma species have gained the same amount of thermal kinetic energy from the background propagating heat energy adiabatically. The plasma particles have random thermal motion; thermally induced perturbations about the equilibrium will cause small, transient spatial variation of electrostatic potential, $\phi(\vec{r})$ of charged particles and the small perturbation of mechanical potential of plasma particles. We consider stellar surface plasma assumptions if magnetic field is neglected to minimize complexity. These assumptions are:

1. The un-magnetized stellar surface plasma is assumed to be nearly collision-less so that collision between particles may be neglected to our first plasma approximation.
2. Each surface plasma species, denoted by subscript j is considered as a fluid having a number density n_j , a temperature T_j , plasma dynamic pressure $p_j = n_j k_B T_j$ where k_B is Boltzmann's constant, $\vec{v}_j$ a velocity of particle, m_j particle mass, q_j is the charge of particle, $\vec{E}$ is induced electric field of the system corresponds to electrostatic potential, ϕ .
3. Inductive electric fields are negligible so that electric field is almost entirely electrostatic (i.e., $\vec{E} \sim -\vec{\nabla}\phi$) on the stratified surface of neutral plasma in steady state.
4. All temperature gradients are smeared out by thermal particle motion so that the temperature of each species is spatially uniform, i.e., $\partial T_j / \partial r \rightarrow 0$ at equilibrium.

This condition suffices the adiabatic process of surface radiating plasma at equilibrium. The stratified charged surface of isothermal photosphere plasma is assumed very thin layer, critical layer (CL) at minimum temperature. Based on the above assumptions, the surface plasma remains in thermal equilibrium throughout the small perturbation. This approximation of un-magnetized surface plasma, describes the thermal equilibrium situation of solar photosphere plasma in steady state or hydrostatic equilibrium condition. Using this simple assumption, considering effects of surface rotation, net surface charge and surface gravitational force the

radial surface charged particle distribution is described by *Boltzmann like* relation given by Eq.(2.1), derived from Newton's second law of motion.

$$n_j = n_0 \exp \left\{ - \left[\frac{q_j \phi}{kT} - \frac{m_j}{2kT} (\Omega^2 r^2 \sin^2 \theta) + \frac{m_j \Phi_g}{kT} \right] + c \right\} \quad (2.1)$$

The quantity r is magnitude of stellar radius, Ω rotational velocity of young star, ϕ surface electrostatic potential due to change in number of charged particles, n_j local number density of charged particle on stellar surface and Φ_g gravitational potential at un-perturbed stellar surface, and n_0 , is a constant initial plasma number density. However, the stratified stellar surface of un-magnetized plasma is under the control of strong gravitational force on isothermal plasma cloud layer coupled with stellar surface rotation in steady state. We use the spherical symmetry condition of stellar surface; the physical quantities are having no horizontal dependence of spatial coordinate at equilibrium situation. The integration constant c in Eq.(2.1) is determined using boundary condition at stellar surface in steady state situation, of course, there is no demarked stellar surface boundary. The radial charge distribution of stellar surface in steady state situation is well understood from graphs of Fig.2.2a - Fig.2.2f. When the polar angle dependent surface net electron distribution given by Eq.(2.1) induces global electron current, non-radial surface magnetic field is generated. The graphs of Fig.2.2a and Fig.2.2b indicate the exponentially of stellar surface radial charge distribution while the graphs of Fig.2.2c - Fig.2.2f show nonlinearity effect of polar angle and position dependent surface radial charge distribution.

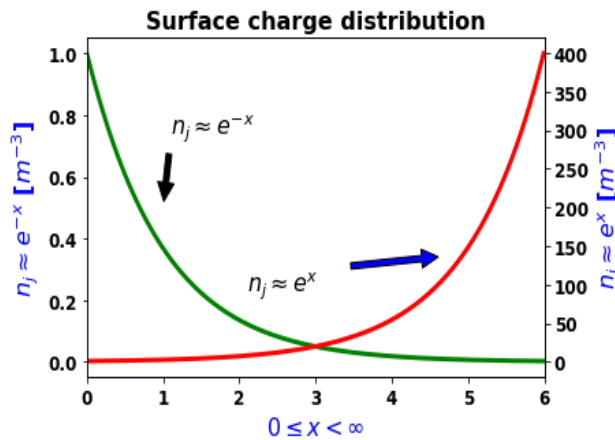


Fig.2.2a Stellar surface net charge distribution

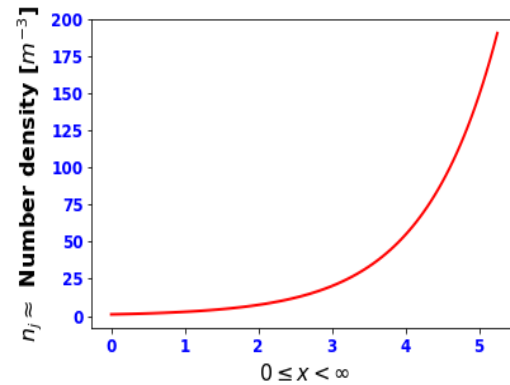


Fig.2.2b Stellar surface net electron charge distribution

Effects of centrifugal force on surface charge distribution

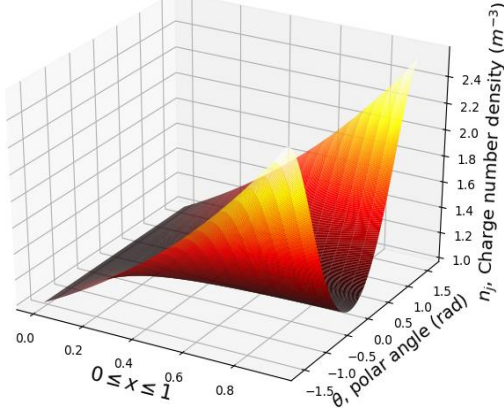


Fig.2.2c Surface positive net charge distribution polar angle (θ) dependent of hot stellar surface

Effects of centrifugal force on surface charge distribution

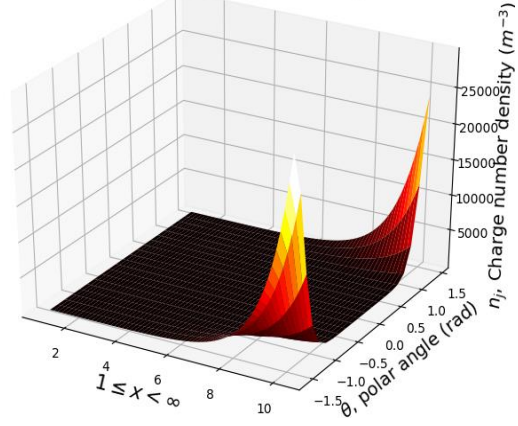


Fig.2.2d Surface positive charge distribution polar angle (θ) dependent of cold stellar surface

Effects of centripetal force on surface charge distribution

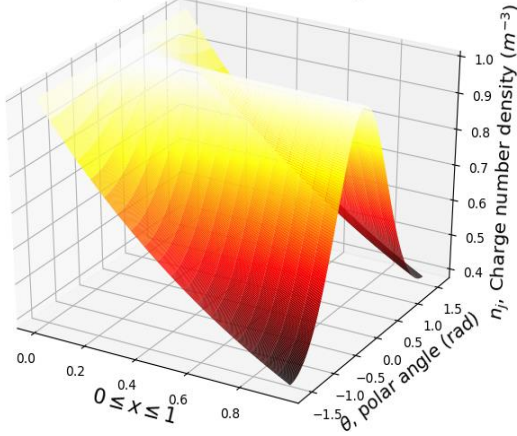


Fig.2.2e Stellar surface net electron charge distribution latitudinal dependent for hot surface

Effects of centripetal force on surface charge distribution

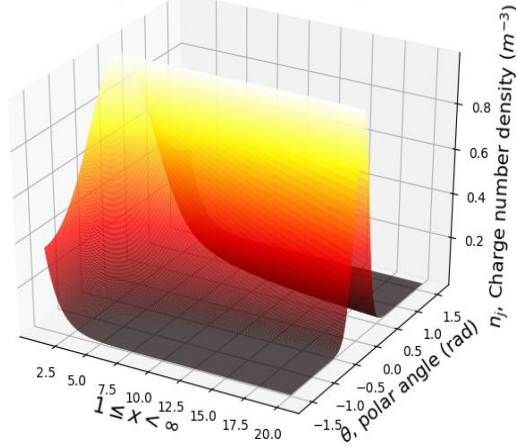


Fig.2.2f Stellar surface met electron charge distribution latitudinal dependent for cold surface

The surface radial charge distribution is determined by the ratio of non-thermal energy to thermal energy, see Eq.(2.1).The variable ' x ' in Fig.2.2a - Fig.2.2f represents the ratio of non-thermal energy to thermal energy. In case of Fig.2.2b, Fig.2.2d and Fig.2.2f the x represents ratio of electrical energy to thermal energy for cold stellar surface. For dominant centrifugal surface force over all forces, x represents the ratio of rotational force over thermal forces. In Fig.2.2a the graph of red colored line represents as the surface radial charge distribution grows exponentially while the blue line represents the surface charge distribution decays exponentially.

2.2.1. Evolution of stellar surface electrostatic potential in steady state

Let us consider fixed position of $\vec{r}$ at isothermal, stratified local plasma layer of stellar (solar) photosphere in steady state situation, for negligible plasma particles collision and viscosity. Let us put ions, electrons and neutral particle at isothermal surface of plasma layer. Electrons have a tendency to move at faster thermal velocity in random direction than ions and neutrals. The hot electrons diffuse from higher temperature of isothermal dense plasma layer to lower temperature nearby isothermal less dense plasma layer. So, using spherical symmetry condition, most electrons move radial outward instantly with constant velocity against the strong gravitational force.

For instance, if we put ions and electrons at the same temperature of isothermal layer, electron move at thermal velocity of 42 times faster than hydrogen ion thermal velocity in absence of external forces. Thus, electrons are more migrating to stellar surface in steady state situation. The heavy neutrals and ions are remained under the control of strong gravitational force and they have a tendency to sluggish slightly behind of the migrating electrons. Those sluggish ions and neutrals need additional thermal kinetic energy to receding away radial outward. Even if they are suffering by continuous collisions, the process is adiabatic and plasma particles do not get significant heat fluctuation in steady state. The isothermal condition remains consistent for long period of time. The adiabatically heated ions and neutrals move back and so forth. Those ions and neutrals are oscillating at isothermal layer in smaller distance than electrons due to compressing gravitational force and adiabatically generated thermal kinetic energy. Because of this kind of process interior of the star, the stellar surface is near adiabatically and in non-radial oscillation *p-mode* as it gains small perturbation about equilibrium [150, 151].

The hot electrons are simply migrating to upper layer of stellar surface. However, at the maximum stellar radius which is demarked by lower stellar (solar) temperature, migrating electrons lost their thermal kinetic energy, they are trapped by gravitational force and can emit radiation due to Thomson scattering process. We expect that at the upper layer of stellar photosphere the plasma temperature is expected at minimum temperature region, at which layer the gravitational energy is dominant; most radial moving out electrons could not pass out any more the low temperature boundary layer. Only, accelerated electrons and ions can escape away the cooler stratified layer against gravitational force, centripetal forces of rotating stellar surface.

Instantaneous electrostatic potential is created at low temperature stellar surface layer, let we call it critical surface (CS) or critical layer (CL). The electron number density is expected as much greater than ion number density at CL in steady state situation. The CL is considered as an ideal demarcation layer that separates the stellar interior region from its exterior region.

Generally, the surface of steady star is surrounded by electron cloud that generates static electric field. The thickness of electron density layer depends on the ages of star. The quasi neutrality condition is violated at the minimum temperature layer of steady stellar surface; see Fig.2.1 in isothermal condition due to strong charge separation process. Below CL, small change in electron kinetic energy creates small perturbation over the gravitational energy a small bit. At this lower isothermal stratified plasma layer, most electrons are out of trapping of gravitational energy relative to ions and neutrals. The gravitationally un-trapped oscillating hot electrons migrate to the outer lower density interior of star. After suffering several collision processes, electrons reach the cooler region of CL layer (spherical shell). Electrons and ions are in monotonously slow oscillation mode at solar surface, CL, associated with strong instant electrostatic field. The upper cooler layer is expected as an oscillating electron plasma cloud surface in *thermal equilibrium*. The thickness of the surface electron plasma cloud is approximated by the order of *Debye length* λ_D away from the lower nearby isothermal boundary of neutral layer, see Eq.(2.7), in chapter 2, section 2.2. Generally, the upper boundary of stellar surface at equilibrium situation is negatively charged. More electrons are populated at upper surface boundary of stable and stratified photosphere, see Fig.2.1.

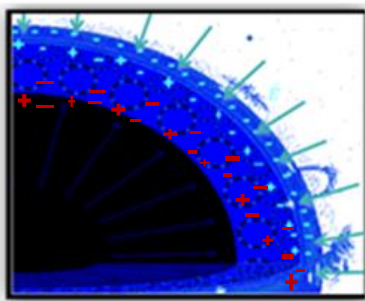


Fig.2.3 Stellar surface static electric field

The oscillating charged stellar surface generates instant electrostatic potential $\phi(r)$ which plays a crucial role on non-thermal acceleration of charged particles and generation of radiation on solar surface due to Thomson scattering process in steady state situation [152, 153]. The main mechanism for formation of instantaneous surface charge separation is a steep density gradient, pressure gradient and gravitational potential gradient interior of the star. The Boltzmann like surface radial particle distribution assumption is very important to emphasize that the small perturbation

is very slow to suffice thermal equilibrium. However, for fast perturbing system, the temperature gradient, inertial effects and inductive electric fields cause the surface plasma fluid to have a complete different character. In this situation, we do not use the Boltzmann like relation of Eq.(2.1) to specify dynamical nature of stellar surface or atmosphere.

Now, let us consider the stratified steadily oscillating surface electrons are at thermal equilibrium on stellar critical surface. Let us insert, slowly or suddenly, a single positive charge of hydrogen ion with its charge of q_t in to initially unperturbed and spatially uniform thin stratified electron plasma layer at minimum temperature region. The injected hot hydrogen ion, with magnitude of its velocity is much greater than ion acoustic sound speed but less than speed of light. Before inserting the positive hydrogen ion, the electrostatic potential $\phi(r) \neq 0$ and may be constant of position, everywhere inside the thin electron cloud isothermal layer for uniform net charge distribution.

A small perturbation is occurred due to attraction and repulsion of electrostatic force. The injected hydrogen ion is suddenly surrounded by the electron cloud. The surface electrostatic potential starts perturbing around the injected hydrogen ion. The deviation in electrostatic potential creates a strong electrons discharge towards the hydrogen ion. The injected ion and the incident discharging electrons have got rest instantly at the thermal situation. Since velocity of injected ion and attracted electrons is greater than the acoustic sound speed, a shock wave is generated around the hydrogen ion. The agent of shock wave is the fast moving electron beam in side high conductivity plasma, as soon as quasi-neutrality condition is violated. The shock surface accelerates the ion and nearby plasma particles, i.e., electrons, neutrals and the ion itself.

Generally, the positively charged particles strike the oscillating surface electron layer and shock wave is generated on stellar surface. The generated shock wave propagates to interior of star as well as exterior. The shock wave is followed by strong blast waves which can discharges plasma particles against the gravitational attraction force in the form of radiation and stellar winds to surrounding space. The effect of electrostatic potential on the stellar surface of lower density region can be described using Poisson's equation.

$$\bar{\nabla}^2 \phi - \phi/\lambda_D^2 = -\frac{1}{\epsilon_0} \rho_s \delta(\vec{r}) \quad (2.2)$$

The quantities $1/\lambda_D^2 = \sum_j (1/\lambda_j^2)$, $\lambda_j^2 = \epsilon_0 k T_j / n_j q_j^2$ Debye length is denoted by λ_D and $\delta(\vec{r})$ is the Kronecker delta function. The symbol ρ_s represents surface net charge density of the star. When the surface net charge (i.e., electron layer) is created slowly, the surrounding plasma response will be Boltzmann-like and we use radial charged particle distribution of surrounding plasma $n_j(\vec{r})$, using Eq.(2.1). The solution of Eq.(2.2) is given by Eq. (2.3) for net electron number density, n_e , that responsible for surface electric field formation.

$$\phi(\vec{r} - \vec{r}_0) = -\frac{en_e}{4\pi\epsilon_0|\vec{r}-\vec{r}_0|} e^{-|\vec{r}-\vec{r}_0|/\lambda_D} \quad (2.3)$$

where, $\delta r = |\vec{r} - \vec{r}_0| \leq \lambda_D$ represents the thicknesses of net surface charge. The electrostatic potential that is approximated by Eq.(2.3) is formed due to surface charge separation process. When $\delta r \gg \lambda_D$ the net charge is completely screened by the surrounding neutral higher density plasma fluid from below and also surrounded by rare dense plasma from outside, see Fig.2.3. Thus, ions are injected in to electron cloud stellar layer of minimum temperature region and they are decelerated non-thermally. Some hot electrons which are emitted from the surface electron cloud layer that formed radiation and accelerated particle are replaced quickly by the other injected hot electrons from surrounding due to spontaneous electron diffusion.

Far away from electron cloud layer, the quasi-neutral condition is sufficed at rare density region of steady stellar surface. However, the non-neutrality condition is occurred due to depletion of more electrons at maximum radial distance of $r_0 + h$, critical layer. Let $\vec{h}$ be the maximum charge separation vertical displacement where moving net charges are depleted near the immobile surface ions. Since heat is transported adiabatically from interior of star to solar surface, a random thermal fluctuation causes all the electrons to move and pass the ions to reach the upper cooler surface layer of star faster than thermal ions. The sluggish ions are populated beneath the separated electron cloud layer. The electron cloud charges on the cold region of solar surface is given by $Q = -\frac{4\pi}{3}en_e[r_h^3 - r_0^3]$ which is vacated by surrounding plasma. The position $\vec{r}_h$ is the upper boundary of thin electron cloud, CL, while $\vec{r}_0$ is the lower boundary of electron cloud layer that is measured from stellar center. The surface induced electric field is given by $E_r = Q/4\pi\epsilon_0 r^2$ evaluated at position on stellar surface. The plasma density of separated cooler electron cloud, CL, is intermediated between plasma density stellar interior and stellar atmosphere while its temperature is at minimum value of both interior and exterior. We can

evaluate the stellar surface electric field at region of $\vec{r} > \vec{r}_h$ rare dense surrounding plasma. The surface induced electric field is approximated by Eq.(2.4a) that defines stellar surface nature.

$$\vec{E} = \frac{\rho_s}{3\epsilon_0 r^2} [r_h^3 - r_0^3] \hat{r} \quad (2.4a)$$

The Fig.2.4a shows the surface electric field of steadily rotating active star such as our sun in steady state. The stellar surface induced electric field depends on the separated charged particles in steady state situation. Fig.2.4b and Fig.2.4c tell us that the surface induced electric field has non-linear behavior due to variations of surface electron number density and surface ions number density associated with corresponding position.

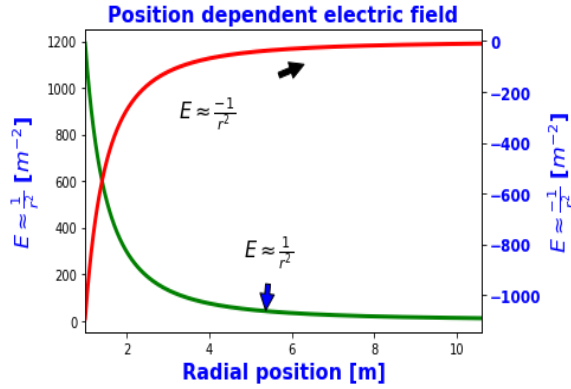


Fig.2.4a Stellar surface electric field

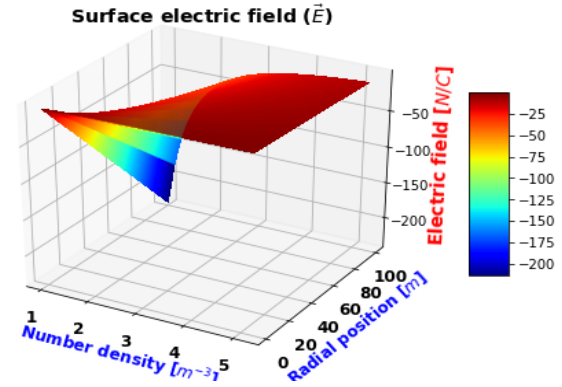


Fig.2.4b, Non-linear behavior of surface electric field

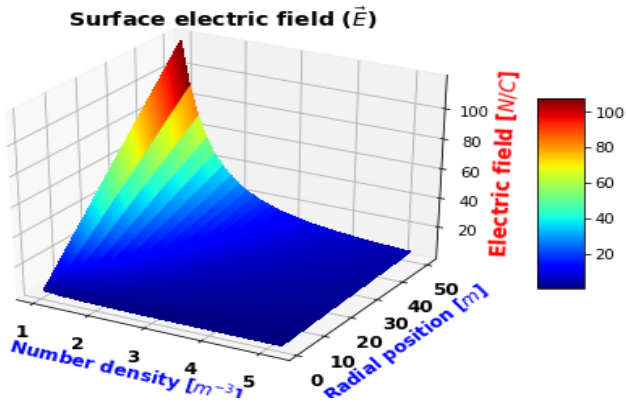


Fig.2.4c Non-linear behavior of surface ions induced instant electric field

The electrostatic potential at the region of thickness $\vec{h}$ is approximated by Eq.(2.4b), and it is manipulated from Eq.(2.4a).

$$\phi \approx \frac{1}{\epsilon_0} q_j n_j h^2 \quad (2.4b)$$

Eq.(2.4b) tells us that the surface induced electrostatic potential has maximum magnitude at upper boundary of CL in isothermal and steady state condition. The electrostatic energy density at position $\vec{r}$ of stellar surface given by, $\epsilon_0 E_r^2/2$, above CL, *see* Fig.2.3. Here, we have used the spherical symmetry of non-radial component of space coordinate at equilibrium or steady state situation. If $\vec{E}_r \gg \vec{E}_D$ the charged particles are accelerated on the stellar surface due to electron *runaway* and ion *runaway* condition near stellar surface, where $\vec{E}_D$, Dirac electric field. We can evaluate the energy stored in the form of electrostatic field resulting from violation of quasi-neutrality at steady state or equilibrium condition that is obtained when maximum electron depletion layer is occurred, CL shell for $|\vec{h}| \ll |\vec{r}_0|$ and $r \rightarrow \infty$ to bring charged particles from infinity to stellar surface. We get the characteristic work done by depletion layer,

$$W \approx \frac{1}{\epsilon_0} 2\pi r_0^3 e^2 n_e^2 h^2 \quad (2.5)$$

where, W , is work done by surface electrostatic field on a charged particle at position $\vec{r}$ inside the layer where quasi-neutrality is violated. If we assume that the low density plasma of stellar atmosphere is neutral at a position $\vec{r} > \vec{r}_h$ the work done on charged particle at solar atmosphere by surface electrostatic potential is given by the Eq.(2.5) in steady state situation.

2.2.2. Evaluation of net charge layer on steady stellar surface

During stellar surface charge separation process, the instantaneous surface electric field behind the receding inertial electron is assumed to be produced by the remnant sluggish surface ions beneath CL. The electrostatic potential energy which is responsible to bring charged particle or ions from the lower neutral layer behind of electron layer creates a cumulative surface plasma oscillation. The characteristic charge separation distance between upper boundary of electron cloud surface and immobile ions of neutral plasma against the gravitational force is approximated by thickness of net charge, CL, in terms of net electron number density. The thickness of oscillating electron cloud layer is approximated by maximum charge separation distance.

Using Newton's equation of motion and Eq.(2.4b), we have obtained Eq.(2.6a) in steady state situation that specifies instantaneous charge separation distance of isothermal layer for negligible effects of stellar surface rotation coupled with constant dynamic pressure.

$$d = 1.78 \times 10^{-2} [\Phi_g/n_e]^{1/2} \text{ Hz}^{-2} \quad (2.6a)$$

The variable d represents characteristic charge (i.e., electrons) separation distance between nearby charged particle. In Eq.(2.6a) the function $\partial\Phi_g/\partial r = g_\odot \approx \Phi_g/d$ denotes a local gravitational acceleration at stellar surface. When the star becomes aged, the thickness of electron cloud became thicker and thicker as surface gradient gravitational potential is so steepening and surface electron density also increasing slowly.

However, it is difficult to know the true value of net electron number density on stellar (solar) atmosphere even at static equilibrium or in steady state of surface oscillation. Generally, we suggest that electron charge separation distance at stratified steady solar surface is approximated by $h \approx 0.3n_e^{-1/2} m$, rising electrons are return back due to gravitational force at the top of CL. From Eq.(2.6a) we can understand that the stellar surface is negatively charged since the net electron number density is significant. The Eq.(2.6a) tells us that the surface net charge layer oscillates radially in monotonous pattern under the strong controlling action of stellar surface gravitational potential. However, if the plasma fluid behind of electron cloud remains neutral, the work done by the surface electric field to pick up heavy ions in case of negligible gravitational force is obtained from Eq.(2.4a) that yields Eq.(2.6b) in case of $\vec{r}_0 < \vec{r} < \vec{r}_h$ on stellar surface.

$$w = -\frac{4\pi}{2\epsilon_0} e^2 n_e^2 h^2 r_0^4 \left[\frac{1}{r_0} - \frac{1}{r_h} \right] \quad (2.6b)$$

In a steep region of $\vec{r}_0 \leq \vec{r} \leq \vec{r}_h$, the characteristic maximum charge separation distance denoted by $\vec{h} = \delta\vec{r}$ inside thin layer of stellar surface in static equilibrium or steady state condition is approximated by Eq. (2.6a). Evaluating Eq.(2.6b), for $\vec{r}_0 \ll \vec{r}_h$ results Eq.(2.5) that defines electrostatic potential is varied through net charge cloud layer. The characteristic thickness of net charge layer can be defined in terms of Debye length. The Coulomb force has been vanished at a moment due to immobile ion that is balanced by replaced electron spontaneously below the CL. Here, we use the idea of energy conservation at the upper and lower boundary layer of

stellar surface electron cloud layer for young star such as sun which has a rare surface electron density with thickness that is approximated by Eq.(2.7). Equating the thermal electron energy responsible for charge separation process is balanced by the developed electrostatic potential for negligible effects of gravitational potential and centrifugal potential leads to find Eq.(2.7).

$$h = 3.88\lambda_e \quad (2.7)$$

To approximate Eq.(2.7), we choose the surface electric field is vanished at dense lower boundary layer due to effects of remnant ions beneath CL. The radially diffusing electrons from lower boundary outward are assumed as spontaneously diffusing electrons, suffering several collisions [154]. However, the initial electron number density and ion number density are the same at interface boundary of CL before charge separation process is happened. Spontaneous diffusion of electron is arisen due to transportation of heat energy from stellar interior to surface in adiabatic condition. Oscillating electron below stellar surface layer gets additional heat energy and radiation pressure energy. The oscillating electrons gain thermal kinetic energy and non-thermal instant potential energy from radiation pressure force faster than ions.

Consequently, those electrons have a tendency of spontaneously diffusing to lower density region of stellar surface. When we assumed that the electrostatic field at lower boundary of surface electron cloud, CL, is vanished but the work done by thermal energy of plasma gas has significant effects, the thickness of stellar electron cloud layer can be approximated in terms of stellar radius for negligible effects of gravitational force in comparison to electric forces. For old cold surface star, the surface net charge thickness is approximated by Eq.(2.8) that is described in terms of stellar radius and electron Debye length before supernova explosion.

$$h \approx 3^{1/4}(\lambda_e r_0)^{1/2} \quad (2.8)$$

The Eq.(2.8) indicates that the transformed energy from stellar interior to surface is a mechanism for formation of oscillating surface electrons. The work done by induced electric field to passes electron or ion through the thin electron cloud is obtained from Eq.(2.4a) by integrating along the thickness of electron cloud layer yields Eq.(2.9) given by polynomial function form.

$$w = 2.0 \times 10^{-27} n_e^2 \left[\frac{1}{5} r^5 - r_0^3 r^2 + \frac{4}{5} r_0^5 \right] Nm^2 \quad (2.9)$$

From Eq.(2.9), we can understand that work done by charged particles at lower and upper boundary layer of stellar surface electron cloud is vanished. Equating the work done on charged particles passing through surface electron cloud that is described by Eq.(2.9) with the thermal kinetic energy at lower boundary layer of CL, and using the idea of unspecified boundary condition of stellar surface net charge, we get the following polynomial function.

$$r^5 - 15\lambda_e^2 r^3 - 5r_0^3 r^2 + 4r_0^5 + 15\lambda_e^2 r_0^3 = 0 \quad (2.10)$$

The Eq.(2.10) describes oscillation of surface net charge due to generation of instantaneous electrostatic field introduces non-linear effect. We assumed that the surface electric field is self-consistent that is produced at isothermal electron layer, CL. The specified Eqs.(2.7), (2.8) and (2.10) describe thickness of thin surface electron layer for negligible gravitational force in strong charge separation process that violates the quasi-neutrality condition of surface plasma.

However, the lower, beneath boundary layer of position at $\vec{r}_0$ the net charge is most probably vanished. In this special case, if we integrate along radial distance above surface of neutral plasma from 0 to h we get the Eq.(2.10) itself expecting with spontaneous generation of surface electric field and spontaneous electron plasma diffusing radial out. The terms containing λ_e in Eq.(2.10) is vanished since $\lambda_e \ll r_0$ for negatively charged stellar surface of young star (sun). Thus, Eq.(2.10) is reduced to the polynomial terms given by $r^5 - 5r_0^3 r^2 + 4r_0^5 = 0$ for work done by charged particles passing through surface electron cloud is zero. This shows that the stellar surface is wrapped by neutral plasma and the surface charge separation is instantaneous for young star (sun) that is G2 group mean sequence stars. If the instantaneous charge separation process is continuous on young stars, sudden stellar explosion (supernova explosion) is inevitable, due to instantaneous volume charge separation process.

2.2.3. Convection motion of photosphere plasma

As we see in *section 2.3* and *2.4*, the surface of the star (sun) is not smooth enough. In reality, it is characterized by inhomogeneous plasma dynamics properties, such as plasma turbulence, plasma convection, dynamic prominences, oscillating magnetic flux and granulations, *see chapter 1, section 1.5* and *1.6*. From ground based and space born telescopes, we observe that solar surface bright granules are separated by darker inter-granular lanes. The structures appear to have dimensions of the order of about 5×10^5 km in diameter and therefore

can only be recognized under conditions of very good seeing [71, 83, 155]. There may be even smaller structures which we cannot resolve because of the atmospheric seeing and because the solar observation satellites so far do not have mirrors large enough to resolve such small-scale structures. The bright regions motions, measured by the *Doppler shift*, are mainly directed outwards; while in the dark inter-granules the motions are mainly downwards. These motions in the solar convection zone are believed to be the source of the mechanical energy flux which heats the solar chromosphere and corona.

The surface plasma convection makes the surface net charge density enters to non-homogeneity situation. Before we develop the stellar explosive model, SWIF model, on stellar (solar) atmosphere, we will discuss briefly in sections 2.6 - 2.8, the nature of stellar surface and the reason for photosphere convection, the velocities expected to be generated by convection, and how the mechanical energy flux is generated by these motions as expected to vary for different local regions.

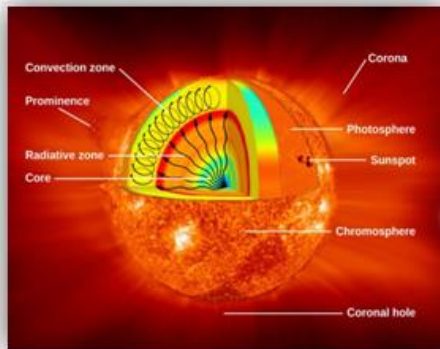


Fig.2.5 structure model

At the convection region heat is transported by hot plasma parcels from interior to surface. As plasma at lower region of convection region gets hotter, eventually the plasma starts to churn and turbulent may occurred. The hot plasma from the lower region of convection zone rise upward, while the cold plasma at the top falls toward the lower region of solar convection zone. The plasma convection process below the solar photosphere is assumed in adiabatic process. No heat is gain or loss

from plasma elements during plasma convection process interior of star.

2.2.4. Adiabatic temperature gradient of uniformly rotating surface

The stellar photosphere is the visible layer of uniformly rotating layer where photons last interact with neutral particles, ions and electrons before escaping from the star (sun), see chapter 1, section 1.7. The temperature profile of stellar photosphere depends on plasma density stratification and plasma dynamics of local system coupled with strong surface charge separation process, see chapter 2, section 2.3. The average temperature of upper layer of solar photosphere

is approximated to $4200K$ and the lower layer of photosphere has $5800K$ in general based on stellar thermal particle distribution [107, 156]. At the stellar convection zone, we assumed that the plasma behaves adiabatically on short time scale. A parcel of plasma along stellar radius moves to a different radius adiabatically. We assumed that the parcels of plasma are also at the same pressure as their neighbors, because any difference in pressure will lead to compression or expansion until the pressure balance.

Assumed that the ideal plasma is in convective process below upper boundary of photosphere, CL, it obeys the dynamic pressure is given by $p = \mathcal{R}\rho T/\eta$ at local position $\vec{r}$. The quantities p, ρ, T and $\mathcal{R}$ represents plasma dynamic pressure, plasma mass density, temperature and plasma gas universal constant respectively. If we move the parcels of plasma upward a small radial distance $\delta r \approx dr$, the change in pressure fulfills the adiabatic condition and no effective temperature fluctuation during plasma convection beneath photosphere. We assumed that the compression is uniform, η is constant, molecular weight of ion or gas. The effects of particle collision frequency and plasma viscosity coupled with centrifugal surface force and Coriolis force may play a crucial role on radially moving out convective plasma. We assumed that the convective stellar surface is rotating about its axis at constant angular velocity, $\vec{\Omega}$, independent of radial and azimuthal position and time, the same as rotation of solid body.

However, if we consider the convective solar layer is thick enough, the rotational velocity becomes position and time dependent $\vec{\Omega}(\vec{X}, t)$ interior of the gaseous star. This differential rotation is beyond our scope here, since we have focused on thin plasma surface layer that interacts with stellar atmosphere. Using the above aforementioned assumption of adiabatic process, beneath the surface of rotating star, surface plasma convection in the absence of magnetic field suffices the adiabatic condition given by Eq.(2.11a) that describes the plasma kinematic properties at steady state situation. The Eq.(2.11a) is verified from Newton's 2nd law motion of convective surface of uniformly rotating star in steady state situation.

$$\left(\frac{dT}{dr}\right)_{ad} = (\gamma - 1)T \frac{d}{dr}(\ln \rho_j) - \frac{T\gamma}{c_{sj}^2} \left[\frac{\partial}{\partial r} \left[\frac{1}{2} v_j^2 + \frac{q_j \phi}{m_j} + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta \right] - (\nu - 2\Omega) v_j + \frac{2\mu}{r^2} v_j \right], \quad (2.11a)$$

where ν , μ , ν_j and c_j represents particles collision frequency, kinetic coefficient of plasma fluid, convective velocity and acoustic velocity. The subscript j denotes the plasma species of electron, ion and neutral. All physical quantities are radial position dependent except the surface rotational velocity that may be described as polar position dependent. The global effects of collision and viscous terms in Eq.(2.11a) do not violate the adiabatic condition below stellar surface but leads to adiabatic heating in steady state. Considering the stellar surface plasma as super fluid, the Eq.(2.11a) of adiabatic condition can be expressed by Eq.(2.11b) so as to fulfill the adiabatic condition of convective photosphere in the absence of viscosity.

$$\left(\frac{dT}{dr}\right)_{ad} = (\gamma - 1)T \frac{d}{dr}(\ln \rho_j) - \frac{T\gamma}{c_{sj}^2} \left[\frac{\partial}{\partial r} \left[\frac{1}{2} v_j^2 + \frac{q_j \phi}{m_j} + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta \right] - (\nu - 2\Omega) v_j \right] \quad (2.11b)$$

For surface incompressible and collision-less neutral plasma of rotating young star, the adiabatic condition of stellar surface is described by Eq.(2.11c) for steadily uniform rotating surface.

$$\left(\frac{dT}{dr}\right)_{ad} = (\gamma - 1)T \frac{d}{dr}(\ln \rho_j) - \frac{T\gamma}{c_{sj}^2} \left[\frac{\partial}{\partial r} \left[\frac{GM}{r} - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta \right] + 2\Omega v_j \right] \quad (2.11c)$$

Using adiabatic equation of state, the term $(dT/dr)_{ad}$ is adiabatic temperature gradient while dT/dr is the temperature gradient. We use the equation of equilibrium balance dp/dr , because we assumed that the pressure of rising high conductivity plasma fluid is the same as the pressure of its neighbor which are in steady state or hydrostatic balance during the plasma convection process. The term $g = Gm/r^2$, represents a local gravitational acceleration of the static star. When the stellar convection zone has a temperature gradient equal to adiabatic temperature gradient, then as the parcel of plasma fluid rises or falls, its temperature changes exactly as the same way as the background temperature. Since the rising parcel of plasma has the same temperature and pressure as its new surroundings, and it has the same density and thus nothing is really changed by the motion.

Moreover, the adiabatic process is violated on stellar surface [157]. The solar surface is specified by wave-particle interaction principle and emanating of light waves due to Thomson scattering process [158]. Instability of local stellar surface plasma leads to formation of solar explosive events, CMEs and oscillations of magnetic flux tubes.

2.2.5. The Brunt-Vaisala like Frequency of rotating surface

Now consider what happens to the rising parcel of plasma of uniformly rotating star if the temperature gradient of the convection surface plasma is not equal to adiabatic temperature gradient, $(dT/dr)_{ad}$ beneath the upper stellar surface. We start with a parcel of plasma that is at the same pressure, density, and temperature as its surroundings and small perturbation is occurring upward by a distance $dr \sim \delta r$ of weak magnetic field region. It stays at the same pressure as its new surroundings, but it is at a different temperature, and therefore a different density. If the parcel of plasma is initially at a density $\rho_{in}(\vec{r}_0) = \rho_{ex}(\vec{r}_0)$ after it rises a distance δr its new density is $\rho_{in}(\vec{r})$ and $\rho_{ex}(\vec{r})$ for density of plasma inside the plasma element fluid and its exterior respectively. Since the parcel of plasma is in adiabatic process during plasma convection, the *Bruit-Visalia* like stellar surface plasma frequency N of uniformly rotating star is given by Eq.(2.12) for $\rho_j = \rho$, see below.

$$N^2 = \frac{H}{\rho} \left(\frac{d\rho}{dr} - \frac{1}{c_s^2} \frac{dp}{dr} \right) \quad (2.12)$$

where H is effective surface gravitational acceleration of uniformly rotating stellar surface and its value is also real. The effective surface gravity of uniformly rotating star is given by Eq.(2.13) in cases of negligible collisional and viscosity terms for compressible surface plasma.

$$H = -\frac{\partial}{\partial r} \left[\frac{1}{2} v_j^2 + \frac{q_j \phi}{m_j} + \Phi_g + \frac{1}{2} \Omega^2 r^2 \sin^2 \theta \right] - 2\Omega v_j \quad (2.13)$$

At equilibrium situation the upper layer of uniformly rotating stellar surface is negatively charged due to strong charge separation mechanism in steady state situation, see Chapter 2, section 2.2, and 2.3. The Eq.(2.11c) is more probably applicable for incompressible high conductivity convective surface plasma fluid in connection with small perturbation that specifies the adiabatic plasma convection process below stellar surface, CL. The upward displacing parcel of plasma fluid is expected in adiabatic condition while the surrounding plasma is not necessarily adiabatic. Now, that we have computed the difference in density between the parcel of plasma and its surrounding plasma, consider what this implies about the forces on that moving parcel of plasma. The parcel of surface plasma fluid feels the *gravity*, and *buoyancy* force in connection with centrifugal force, Coriolis force and surface electrical force on the convective surface of

rotating star. The *buoyance* force is the difference in pressure between the photosphere and its lower region of convection plasma.

As we have investigated before, when considering homogeneous perturbation, the behavior of the solution depends on whether the term inside square root is positive or negative, corresponding to a real or imaginary value for N given by Eq.(2.12). If N is real, the solutions are oscillatory, and the system is stable. When N is imaginary, the solution is corresponding to an exponentially decaying or exponentially growing mode, and the system is unstable. When N is real then the differential equation for dr looks like a harmonic oscillator, in the sense that the force $-H \left(\frac{d\rho}{dr} - \frac{1}{c_s^2} \frac{dp}{dr} \right) dr$ is opposite to the displacement. It therefore constitutes a restoring force, which pushes the system back to stability. The value of $\left(\frac{d\rho}{dr} - \frac{1}{c_s^2} \frac{dp}{dr} \right)$ in turn is determined by the balance between gravity and buoyancy in connection with centrifugal force and Coriolis force, with $\left| \frac{d\rho}{dr} - \frac{1}{c_s^2} \frac{dp}{dr} \right| < 0$ corresponding to the case where gravity is stronger. As a result, we get a real value for N , and any displaced fluid element just oscillates, moving up and down. If the condition $\left| \frac{d\rho}{dr} - \frac{1}{c_s^2} \frac{dp}{dr} \right| > 0$ fulfills that the net force is at same direction as the displacement vector field.

Physically, what is going on is that a parcel of fluid plasma rises and expands because it is at higher pressure than its surroundings. Although gravity wants to pull it back down, its high pressure makes it expand so much that it experiences a large buoyancy force that is stronger than gravity. The net force is therefore upward, and the parcel of plasma accelerates further up. This is an unstable situation, hence N is imaginary. This physical interpretation makes sense if we examine the terms inside the square root, and recall that $d\rho/dr$ and dp/dr are both negative. If $d\rho/dr$ is very big, then the system is *unstable*. This is because the value of $d\rho/dr$ determines how much the rising plasma element expands, and thus how large the buoyancy force. If $d\rho/dr$ is very large, the system is *stable*. That is because $d\rho/dr$ measures how much denser the rising plasma element is than its new surroundings, and thus how strongly gravity wants to pull it down. Thus, we have derived the condition for stability against convection. To determine the nature of Brunt-Väisälä like frequency, N , we use two kinds of assumption which determine the stability and un-stability of system during adiabatic convection process of high conductivity

plasma fluid of uniformly rotating stellar surface, the interpretation corresponding Eq.(2.12) is described as follow.

1. $\left| \frac{d\rho}{dr} \right| > \left| \frac{1}{c_s^2} \frac{dp}{dr} \right|$, the value of $N^2 > 0$ for positive value of effective surface gravity H , the value of N is real and the motion is oscillatory due to the responding force of effective gravity, it is neither amplified nor damped. The fluid element experiences a negligible displacement from the equilibrium level r_0 of stellar radius. The medium is stable with respect to convection.
2. $\left| \frac{d\rho}{dr} \right| < \left| \frac{1}{c_s^2} \frac{dp}{dr} \right|$, the value of $N^2 < 0$ for positive value of effective gravity H and the value of N is imaginary. The medium is unstable with respect to convection, and plasma elements are rising continuously or sinking to the deeper region of stellar interior.

2.3. Surface Convective Stability and Adiabatic Temperature Gradient

Now, we have determined a condition for stability in terms of the gradients of pressure p , and gradients density ρ , but it is helpful to instead phrase things in terms of temperature, because this allows us to see how convective stability relates to the adiabatic temperature gradient, we derived a moment before, see Eqs.(2.11a), (2.11b) and (2.11c). For stellar surface plasma of uniform composition, in the sense on non-adiabatic surrounding high conductivity plasma, the stability condition of local system against surface convection of neutral plasma is specified as

$$\frac{dT}{dr} > (\gamma - 1)T \frac{d}{dr} (\ln \rho_j) - \frac{T\gamma}{c_{sj}^2} \left[\frac{\partial}{\partial r} \left[\frac{1}{2} v_j^2 + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta \right] - (\nu - 2\Omega) v_j + \frac{2\mu}{r^2} v_j \right] \quad (2.14)$$

In Eq.(2.14) terms containing collision and viscosity may leads to violation of adiabatic condition at local region if surface shock wave is developed. The right-hand side Eq.(2.14), however, is just the adiabatic temperature gradient for uniform effects of collision and viscosity in sense of kinetic theory at local system. Thus, the criterion for no convection is that $(dT/dr) > (dT/dr)_{ad}$ is given by Eq.(2.14). Thus, this equation means that a system is stable to surface convection as long as the true temperature gradient is less negative than the adiabatic temperature. To avoid confusion, it is common to take the absolute value of both sides, which, since both sides are negative, gives

$$\left| \frac{dT}{dr} \right| < \left| \frac{dT}{dr} \right|_{ad} \quad (2.15)$$

Thus, the system is stable against convection as long as the actual temperature gradient is shallower than the adiabatic temperature gradient. Equivalently, the condition for surface convective stability can be written as $\frac{d \ln p}{d \ln T} > \frac{\gamma}{\gamma-1}$ beneath the stellar surface for non-rotating static star. The star within which the temperature gradient is steeper than the adiabatic temperature gradient is said to be *super-adiabatic*. What we have shown is that super-adiabatic temperature gradients are convectively unstable. Finally, it is important to point out that this analysis is for regions of a star dominated by plasma pressure. It can be extended to include radiation pressure in a fairly straightforward manner, and this extension can be important in the centers of massive or evolved star where radiation pressure is important. The general result is that, if radiation pressure is important, surface convection is more likely.

2.4. Effects of Convection Motion on Rotating Surface Plasma

As a first step toward this, let us consider where convection is likely to occur under the rotating stellar surface. To do this, it is helpful to write down the temperature gradient that is produced by radiation alone at solar photosphere upper boundary, and compare it to the adiabatic value. If there is no convection beyond stellar surface, then the temperature gradient is given by Eq.(2.16), we have already derived from hydrostatic surface condition of non-rotating star.

$$\frac{dT}{dr} = - \frac{3}{4ac} \frac{k_c \rho}{T^3} \frac{F_{rad}}{4\pi r^2} \quad , \quad (2.16)$$

where F_{rad} is the flux carried by radiation, which need not match the total flux if convection is occurring. The propagating heat flux is independent of stellar surface rotation as far as collisional effect is balanced by viscosity effects. Note, here we define F as the *heat flow*, which is the *heat flux* time $4\pi r^2$ if we neglect other fluxes. The convective stability condition that $dT/dr > (dT/dr)_{ad}$ defined by Eq.(2.14) corresponds to Eq.(2.15) therefore implies that

$$\left| \frac{3}{4ac} \frac{\rho c_s^2}{(\gamma-1) T^4} \frac{k_c F_{rad}}{4\pi r^2} \right| < \left| (\gamma-1) T \frac{d}{dr} (\ln \rho) - \frac{\gamma T}{c_s^2} \left[\frac{d}{dr} \left[\frac{1}{2} v_j^2 + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta \right] - \left(\nu - 2\Omega + \frac{2\mu}{r^2} \right) v_j \right] \right| \quad (2.17)$$

Above the stellar surface, since plasma collision and viscosity are negligible, the viscosity and collision terms are vanished in Eq.(2.17) but the Coriolis terms may not be vanished. The surface convection begins if this inequality of Eq.(2.17) is violated. In practice, it is violated in many situations. First, if the surface stellar opacity (k_c) is so large, the inequality is violated, see Eq.(2.16). Physically, this occurs because a large opacity means that temperature gradient must become steep to carry the same heat flow at deep stellar photosphere or convection zone. The star responds, by developing a steeper temperature gradient until it becomes so steep that it exceeds the adiabatic gradient, at which point convection starts. Since the stellar opacity (k_c) generally increases with decreasing temperature, this situation occurs most commonly in the cooler outer parts of stellar photosphere than in its interior.

We expect the hydrogen ionization region in the star to be highly convective, see chapter 1 at section 1.6. Again, this occurs fairly near the stellar surface, since the deep interior is fully ionized. If the energy generation rate in the star is very sharp function of temperature, then the flux, F , rises rapidly as $\vec{r}$ approaches to smaller inside a star near to radiation zone. This large heat flow at a small radius leads to violation of the inequality. This may happens only in the center of the star, and only if the nuclear reactions are very sensitive to temperature, e.g. the CNO cycle or the triple- α process. In the star, since the $p - p$ chain dominates, the other type of convective instability doesn't occur. The center of star is convectively stable while the outer surface of star is convectively unstable.

2.5. Convective Energy Transport beneath Stellar Dynamic Surface

In region interior of star where convection does not occur, it can transport energy in addition to radiating diffusion. This will modify the stellar structure equations, since the equation for dT/dr is derived based on the assumption that transport is entirely by radiation at solar core and solar atmosphere for negligible stellar magnetic field energy. We therefore need to understand how much energy is carried by convection beneath the solar surface. To determine that, we can return to our picture of surface convection as a parcels of material rising through the star, being driven by buoyancy force that dominates over gravity. The parcel of plasma rises adiabatically until it spreads out and mixes with the surrounding material, delivering its heat. This process of hot plasma element rising and then mixing with their surroundings is what carries the heat flux in a surface convective region, and it is that flux we want to calculate.

In this picture, the sun has some temperature gradient, dT/dr , which is more negative than the adiabatic gradient $(dT/dr)_{ad}$ defined by Eq.(2.17) may be for negligible collisional and viscosity terms. Thus when the plasma element rises a distance, δr , the plasma surrounding it has decreased in temperature by an amount $dT^{(s)} = \frac{dT}{dr} dr$ for non-adiabatic surrounding. The parcels of plasma, on the other hand, are adiabatic until the point where it stalls and mixes with its environment. Therefore after plasma element rises a distance, δr , its temperature changes by an amount $dT^{(p)} = (dT/dr)_{ad} dr$ for incompressible ionized plasma below stellar surface. The difference in temperature between the parcels of plasma and its surroundings is therefore given by $\delta T = \delta((dT/dr)_{ad} - dT/dr) dr$ interior of the star. The instantaneous temperature of convection plasma of rotating stellar surface is approximated by Eq.(2.18) in steady state situation.

$$T(r) = T_0 \exp \left\{ \frac{(\gamma-1)}{2} \ln \rho_j - \frac{\gamma}{2c_s^2} \left[\frac{1}{2} v_j^2 + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta \right] - (\nu - 2\Omega) v_j l + \frac{2}{l} \mu v_j \right\} + c \quad (2.18)$$

The integration constant c is determined using boundary condition at steady state situation and radial characteristic convective distance given by l at convective surface. The quantity $\delta((dT/dr)_{ad} - dT/dr)$ that we have defined is a measure of how super-adiabatic the plasma. At $\delta(dT/dr) = 0$ the temperature gradient is adiabatic and convection shuts off. Now suppose that a hot, rising parcels of plasma travel a distance $dr \approx l$ before it fully mixes with the surrounding plasma and gives up its thermal energy. As the parcels of plasma mixes at upper boundary surface of photosphere, the amount of energy per unit parcel or plasma element volume that it transfers to its surroundings which is approximated by $\delta q = \rho c_p \delta(dT/dr) l$ as.

$$\delta q \approx -c_p \rho T \ln \left(\frac{T}{T_0} \right) + c_p \rho T \left[\frac{(\gamma-1)}{\gamma} \ln \left(\frac{p}{p_0} \right) - \frac{\gamma}{2c_s^2} \left[\frac{1}{2} v_j^2 + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta - (\nu - 2\Omega) v_j + \frac{2}{r} \mu v_j \right] + c \right] \quad (2.19a)$$

where, c_p , is the specific heat capacity of the plasma at constant pressure. For an ideal monatomic plasma, $c_p = (5/2)(\mathcal{R}/\eta)$, but we leave the expression as c_p because in surface convective zones where ionization is important one must use a value of c_p that accounts for

ionization energy. This is the heat per unit volume carried by one parcel of plasma. If we want to know the heat flow associated with the collective motion of all the rising parcel of plasma in the star, we must multiply by the average speed with which the plasma elements move and the area through which they move has fluxes described by Eq.(2.19a) as follow in steady state.

$$F_c = 4\pi r^2 \rho c_p \left[(\gamma - 1)T \frac{d}{dr} (\ln \rho) - \frac{\gamma T}{c_s^2} \left[\frac{d}{dr} \left[\frac{1}{2} v_j^2 + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta \right] - \left(\nu - 2\Omega - \frac{2\mu}{r^2} \right) v_j \right] - \frac{dT}{dr} \right] l \bar{v}_c \quad (2.19b)$$

If we approximate the characteristic small vertical convective distance is l and the corresponding characteristic surface convection surrounding temperature is given by $\bar{T}$ in Eq.(2.19b). This expression gives the convective heat flow on the rotating surface of star, which must be added to the radiative flow to find the total surface flux. The remaining steps are to evaluate l and $\bar{v}_c$, the characteristic distance that plasma parcels get before dissolving, and the characteristic velocity with which they rise.

Unfortunately at this point we lack a “spherically symmetric” theory of surface convection that would tell us with certainty. Instead, we are forced to use an empirical approximation called *Mixing Length theory* [11, 159]. This is right at the order of magnitude level, and mostly tells us what we need to know; but it is definitely not complete. Getting a better understanding of how convection really works is a major challenge in 3D time-dependent fluid stellar dynamics. The first approximation of *Mixing Length theory* is to guess that the typical distance that a surface convective plasma travels before breaking up is set by the condition that the pressure change significantly, so that the parcels of plasma must expand significantly to stay in pressure balance. As long as the parcel expands by a small amount, it should survive, but once it has to roughly double its volume, it should break up. To make this definite, we use the equation of hydrodynamic balance in steady state of stellar photosphere coupled with constant surface rotation that is described by Eq.(2.20) in steady state situation.

$$\frac{dp}{dr} = -\rho g_{eff} - \rho \left(\nu - 2\Omega - \frac{2\mu}{r^2} \right) v_j \quad (2.20)$$

As we go away from stellar interior to surface with constant plasma viscosity, the viscosity term on the right hand side in Eq.(2.20) is vanished. This leads us to neglect the effects of plasma viscosity at stellar surface. The acceleration of surface convective plasma at

photosphere given by Eq.(2.21) is the consequence of interior stellar dynamics. The quantity $g_{eff} = \frac{d}{dr} \left[\frac{1}{2} v^2 + \frac{q\phi}{m} + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta \right]$ is radial component of local effective surface gravitational acceleration that we have defined for convenience and q is net charge.

We are interested in the distance dr that one must travel before the change in pressure dp is of order p , we can approximate the scale height of stellar dynamic convective plasma $|p|/|-\rho[(v - 2\Omega)v_j + g_{eff}]| \approx h_p$ where h_p is local scale height of convective plasma from below stellar surface. The instantaneous electrostatic potential is vanished beneath electron cloud layer, CL, due to quasi-neutral nature of hot conducting plasma. Thus, we expect a change in the dynamic pressure of order unity when $dr \sim p/(\rho g_{eff})$ in the absence of viscosity and collision and we define this quantity as the pressure scale height, considering the first basic assumption of *Mixing Length theory* is that $l \approx h_p$ below CL. To make it formal, we write $l = \alpha h_p = \alpha p/|-\rho g_{eff} + 2\rho\Omega v_r|$ where, α is a dimensionless parameter of order unity that represents our ignorance. The second thing we need to approximate is the velocity of the convective parcels of plasma $\bar{v}_c$ of photosphere.

To estimate this, recall our equation of motion for the parcels of plasma, which we have used in deriving the *Brunt-Vaisala* like frequency to specify the raising or lowering plasma acceleration in non-steady state condition suffices the azimuthal and polar symmetry in spherical coordinate. The convective acceleration of rising plasma element is approximated as

$$\vec{a} = -\frac{2}{\rho} \frac{p}{\alpha h} \hat{r} - \frac{2}{\alpha h} \left[\frac{1}{2} v^2 + \frac{q\phi}{m} + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta \right] \hat{r} - \left(v - 2\Omega - \frac{2\mu}{r^2} \right) v \hat{r} \quad (2.21)$$

The vector field $\vec{a}$ is inertial acceleration of moving up plasma elements from below. The quantity on the left-hand side is the inertial acceleration of the moving parcels of plasma. Since the acceleration decreases along increasing distance of l , we make a simple assumption that the characteristic acceleration is given by its value at the point halfway between the final and initial points. However, acceleration due to Coriolis force remains constant or it may depend on radial velocity field. The horizontal plasma motion under the stellar photosphere has negligible acceleration compared to radial plasma motion under CL. The velocity of parcel of plasma at the terminal point (i.e., at the solar surface or upper part of convection zone) is given by simple formula of Eq.(2.22) so as to specify the average raising dynamic convective velocity.

$$\vec{v}_c = 2 \left[\frac{1}{2} \Omega^2 r^2 \sin^2 \theta - \frac{1}{\gamma} c_s^2 - \frac{1}{2} v_j^2 - \frac{q\phi}{m} - \Phi_g - \frac{1}{2} (v - 2\Omega) v_j \alpha h \right]^{1/2} \hat{r} \quad (2.22)$$

This is a good calculation in simple way to understand how plasma convection process is working in stellar convective surface. The convection surface has a significant effect on the stellar explosive events such as solar flares, solar winds and CMEs, prominences and other active phenomena [160]. Small perturbation of stellar surface plasma is the source of stellar activity energy. Convection instability condition is violated at the solar surface during small perturbation of surface plasma. Plasma flows horizontally as well as vertically on observable solar surface region [161, 162].

The motion of plasma at the photosphere is specified by two conditions. The first condition is motion of partially ionized plasma at weak magnetic field region, properties of a local region is controlled by hydrodynamic system as a view point of macro-system associated with particle kinematics and particle wave interaction (i.e., non-linear waves). The second condition is that a local surface of star is highly dominated by magnetic field; this local region is described by magneto-hydrodynamics and charged particle kinematics in connection with particle-wave interaction. From Eq.(2.19), we can understand that the heat flux may penetrate the local part of solar surface as a large heat flux flow from the lower region of solar convection zone through a thin column of hot plasma region to solar photosphere. When the quantity of change in temperature gradients $\delta(dT/dr)$ is extremely steeping at the local solar surface, the surrounding plasma particles absorb heat energy and this local plasma is extremely heated and hot plasma can flow from photosphere to chromosphere is observed from SOHO, LASCO and SDO... etc [63, 163 - 165].

When the change in temperature gradient is vanished $\delta(dT/dr) \approx 0$ at the solar surface, the photosphere has a minimum constant temperature of about $4200K$ and the local region is characterized by its convection amplitude associated with surface oscillation. In this condition, convective heat flux is negligible and the adiabatic condition does not violated near the solar surface. However, in reality the adiabatic process is violated at stellar surface due to dynamical nature of stellar surface plasma perturbation and non-radial surface oscillation coupled with wave propagation (i.e., non-linear wave interaction).

2.6. Stellar Surface Induced Magnetic Field

The stellar mechanical equilibrium is a necessary condition for stable stellar luminosity and surface temperature over long periods of time approximated to 5×10^9 years [166]. This is a fundamental property of the star, implying the exact balance between the gravity force which attracts the matter (i.e., plasma) toward the center and the force due to the thermal pressure, which resists gravity leads to thermal equilibrium of self-gravitating ball of plasma in space. Any tendency from this equilibrium situation will immediately lead to a strong reaction for restoring the habitual equilibrium state of local system. If there were no fast radial and non-radial motion of plasma interior of star, we would have a situation of hydrostatic equilibrium or magneto-static equilibrium. The internal pressure gradient is balancing the gravity everywhere interior of star. Initially we assumed that at equilibrium, the solar photosphere is stratified partially ionized plasma at nearly isothermal condition with scale height of $h = kT/g_{eff}m$ at constant gravitational force below the CL. The thermal plasma dynamic pressure on the stellar surface is discontinuous. There could not be significant interaction with its surrounding vacuum. On other hands, the gravitational potential is completely dominant over the thermal plasma potential at stellar surface. In hydrostatic equilibrium or magneto-hydrostatic equilibrium stellar plasma particles (i.e., electrons, ions and neutrals) are well stratified.

We assumed that plasma pressure, temperature and density profile depends only on stellar radius due to symmetry condition at equilibrium situation. As we go radially outward plasma pressure, temperature and density are decreasing up to solar surface boundary [69, 167]. Let we assume the solar surface is a thin plasma layer of isothermal surface in steady state situation. The stellar photosphere plasma is assumed to be partially ionized plasma. The heavy plasma particles (i.e., ions and neutrals) are more attracted than the lightest plasma particles; electrons by solar gravitational force on its surface, *see section 2.2 and 2.3*. As the heavy plasma particles are attracted by gravitational force, the fastest hot electrons are ascending towards surface against gravitational force instantly and finally may be radiated. More electrons are populated on solar surface instantly; *see section 2.2, 2.3 and 2.4, chapter 2*. Generally, hot electrons are migrating to solar surface by passing away relatively immobile ions and neutrals.

The intense instantaneous surface electric field creates instantaneous steady electric current. Electron number density is much higher than ion number density and neutral number

density on the upper thin layer of stratified solar surface in steady state while ions and neutrals are settled beneath the thin net charge layer at equilibrium condition. The upper cold stellar surface is assumed as isothermal plasma boundary surface, CL, with its minimum temperature distribution. It is expected that electrons, ions and neutrals are in thermal equilibrium at stellar surface with discontinuous plasma pressure beyond it. The surface condition in thermal equilibrium is given by $|\rho(g_{eff} + (\nu - 2\Omega - 2\mu/r^2)v_j)| \gg |\vec{\nabla}p|$ for isothermal surface plasma. However, the static stellar surface is negatively charged surface due to migration of hot electrons and strong instantaneous surface charge separation process. Instantly separated hot electrons on stellar surface are replaced by another migrating electrons because of electrons plasma diffusion spontaneously from interior to surface.

The radiating active star uniformly rotates with polar dependent angular surface velocity, $\vec{\Omega}$ about its rotational axis. Surface differential rotation is observed on the star with angular velocity varies with latitude [168, 169]. The solar angular velocity decreases with increasing latitude. The expected mechanism for differential rotation is a turbulent convection inside the star. The difference in angular velocity between solar pole and equator is given by $\Delta\vec{\Omega} = \vec{\Omega}_p - \vec{\Omega}_{eq}$, where $\vec{\Omega}_p$ and $\vec{\Omega}_{eq}$ are the polar and equatorial surface angular velocity. In real situation the stellar differential rotation is coupled with the solar surface oscillation, surface convection is influenced by steep gradients of magnetic field, *see chapter 3, section 3.3 to 3.6*. However, we may assume that the stratified solar surface is in differential rotation where $\vec{\Omega}(\theta)$, the surface angular velocity is functions of polar coordinate only. The surface rotation reduced the plasma pressure on the isothermal surface.

An instantaneous surface current is created due to radial electrons migration from interior to surface and solar surface rotation. The equation of motion for rotating stellar surface in steady state equilibrium situation becomes non-linear term due to presence of plasma viscosity at stratified stellar surface. The viscosity terms introduce the second order differential equation of high conductivity plasma which makes the process is complex. Reducing the nonlinear momentum equation in to its linearized form enables us to predict the effective radial surface current $\vec{j}_{eff}$ of the uniformly rotating stellar surface. The effective steady surface current is arisen due to the migrating charged particles from stellar interior to surface followed by strong

charge separation process at CL, centrifugal force, steep electron density gradient and steep electron velocity gradient of surface plasma. The radial steady surface current is verified from $\vec{J} = q_j n_j (\vec{v}_i - \vec{v}_e)$ over the relatively immobile ions and neutrals of surface plasma. Here, we use radially migrating electrons governed by diffusing process against collisions, viscosity, coriolis and gravitational force in steady state.

$$\vec{J}_{eff} = -q_j n_j \left[\frac{q_j}{m_j(v-2\Omega)} \frac{\partial \phi}{\partial r} + \frac{k_B}{m_j n_j (v-2\Omega)} \left[T_j \frac{\partial n_j}{\partial r} + n_j \frac{\partial T_j}{\partial r} + \frac{4\sigma\varepsilon}{ck_B} T_j^3 \frac{\partial T_j}{\partial r} \right] - \frac{1}{(v-2\Omega)} \left[\frac{GM}{r^2} + \Omega^2 r \sin^2 \theta \right] \right] \hat{r} \quad (2.23)$$

At the stellar surface, when instantaneous electric field is effective for viscous-less surface plasma fluid, the radial velocity component of electrons and ions is determined using the boundary condition at lower and upper electrons cloud layer boundary in steady state [170, 171]. The radial effective current generates non-radial micro-magnetic field on the stellar surface. This induced surface micro-magnetic field may be much weaker than the stellar force free magnetic field which is emerged from stellar interior.

Using Ampere's law, the induced micro-magnetic field is obtained from Eq.(2.23) that described by Eq.(2.24) of non-radial surface induced magnetic field. When we use the condition that B_φ is independent of θ and φ and B_θ is also independent of θ from Eq.(2.23) the surface micro-magnetic field is obtained as purely non-radial surface induced micro-magnetic field for B_φ is constant.

$$\vec{B} = 4\mu_0 \left[\frac{q_j^2 n_j r}{m_j(v-2\Omega)} \frac{\partial \phi}{\partial r} + \frac{k_B q_j r}{m_j(v-2\Omega)} \left[T_j \frac{\partial n_j}{\partial r} + n_j \frac{\partial T_j}{\partial r} + \frac{4\sigma\varepsilon}{ck_B} T_j^3 \frac{\partial T_j}{\partial r} \right] + \frac{q_j n_j}{(v-2\Omega)} \left[\frac{GM}{r} + \frac{2}{3} \Omega^2 r^2 \right] \right] \hat{\theta} + B_\varphi \hat{\varphi} \quad (2.24)$$

The surface induced non-radial magnetic field inhibits the radial motion of stellar charged particles. It prevents electrons and ion from dispersing to its environment against gravity. If the star were fast rotating, small radius and aged enough, the surface induced magnetic field becomes so strong and its magnitude could be comparable with its force free surface emerged magnetic field. When plasma collision frequency is the same with stellar surface rotation frequency, there could not be induced micro-magnetic field on the stellar surface. When electron

collisional frequency is approximated by stellar angular frequency, our idea fits with the current model of solar magnetic field [172 - 174].

However, our investigation of non-radial purely surface magnetic field is the minimum requirement for stellar surface plasma to persist for long time rather dispersing its material to surrounding high vacuum potential against local gravity of star. This idea is clearly shown from Eqs.(2.24), (2.25a) and (2.25b). If we consider the liner term which contains viscosity and velocity gradient is not vanished, by solving the first order differential equation for radial velocity and using Ampere's law, the surface induced micro-magnetic field is investigated by Eq.(2.25a), that is more complex at steady state.

$$\vec{B} = 4\mu_0 \left[q_j n_j r \exp \int \left\{ \frac{1}{2\mu} (\nu - 2\Omega) m_j n_j r dr \right\} \left[\int \exp \int \left\{ \frac{1}{2\mu} (\nu - 2\Omega) m_j n_j r dr \right\} \left[\frac{q_j n_j r}{2\mu} \frac{\partial \phi}{\partial r} + \frac{k_B r}{2\mu} \left(T_j \frac{\partial n_j}{\partial r} + n_j \frac{\partial T_j}{\partial r} + \frac{4\sigma \varepsilon}{ck_B} T_j^3 \frac{\partial T_j}{\partial r} \right) - \frac{m_j n_j}{2\mu} \left(\frac{GM}{r} + \frac{2}{3} \Omega^2 r^2 \right) \right] dr \right] + c \right] \hat{\theta} + B_\phi \hat{\phi} \quad (2.25a)$$

The integration constant c in Eq.(2.25a) is determined using boundary condition in steady state. We use the assumption of that if $\frac{2}{r} \frac{\partial v_j}{\partial r} \gg \frac{2v_j}{r^2}$ for steep velocity gradient $\frac{2v_j}{r^2} \rightarrow 0$ we have gotten Eq.(2.25a). From Eq.(2.25a) we can understand that even if plasma collision frequency is the same as surface rotational frequency, the surface induced magnetic field is inversely proportional to coefficient of kinetic viscosity as we see in Eq.(2.25b).

$$\vec{B} = 4\mu_0 \left[q_j n_j r \left[\int \left[\frac{q_j n_j r}{2\mu} \frac{\partial \phi}{\partial r} + \frac{rk_B}{2\mu} \left(T_j \frac{\partial n_j}{\partial r} + n_j \frac{\partial T_j}{\partial r} + \frac{4\sigma \varepsilon}{ck_B} T_j^3 \frac{\partial T_j}{\partial r} \right) - \frac{m_j n_j}{2\mu} \left(\frac{GM}{r} + \frac{2}{3} \Omega^2 r^2 \right) \right] dr \right] + c \right] \hat{\theta} + B_\phi \hat{\phi} \quad (2.25b)$$

We assumed that stellar surface radiation may be thermal radiation and non-thermal radiation. The source of non-thermal radiation could be the presence of intense magnetic field and production of shock waves because of particle-field interaction. The Eqs.(2.25a) and (2.25b) have non-vanished magnetic field due to steep electron velocity gradient when $\nu = 2\Omega$ condition is sufficed. For constant electron mass density flux is balanced by ion mass density flux of plasma elements on stellar surface, $n_i \approx 5.44 \times 10^{-4} n_e$ (i.e., equal electrons mass flux and hydrogen ion mass flux) at steady state situation.

Considering that ions and neutrals are relatively at rest, the dynamic pressure is dominated by surface electron pressure. If the surface electron mass flux is the same with ions mass flux, the quasi-neutrality condition is strongly violated. In steady state situation, the stellar surface can produce static non-radial magnetic field *see* Eqs.(2.25a) and (2.25b) on the stellar surface. This provides the evolution of surface magnetic field on the stellar surface. From Maxwell's equations $\mu_0 \vec{j} = \vec{\nabla} \times \vec{B}$ and $\vec{\nabla} \cdot \vec{B} = 0$ in connection with MHD and kinetic theory, the effective radial current induces micro-magnetic field. The induced surface magnetic field may create a discrete bundle of magnetic flux tubes. The radially migrating surface electron current generates instantaneously micro-magnetic field exterior of star, *see* Eqs.(2.24),(2.25a) and (2.25b) at steady state. The strength of static non-radial micro-magnetic field is determined by the evolution of surface electron number density gradient, temperature gradients, surface gravitational potential, surface electrostatic potential, centrifugal and surface Coriolis force.

2.7. Oscillation Mechanism of Rotating Surface of Young Star

Surface of young stars like our Sun is characterized by rare dense electron cloud in monotonous steady state situation. Thus, the thickness of electron number density stratification manifest the age of the star, *see section 2.2 in chapter 2*. Initially, we considered that electrons on stellar photosphere are separated and precipitated at outer cooler layer and creates instantaneous radial electrostatic field. The diffusing electrons take several seconds to reach the cooler stellar surface layer. At nearly isothermal radial height scale, hot electrons slightly move radially outward against gravitational collapse and supported by centrifugal forces while ions are also slightly moving to center of star due to gravitational attraction force and effects of centripetal forces, *see section 2.3 and 2.4 in chapter 2*.

High dynamic pressure gradient is created at small local region due to strong instantaneous charge separation process associated with plasma collisions. Due to inhomogeneous surface plasma motion, a local low density cavity is created. A temperature fluctuation is also created in small local cavity. If this kind of cavity is formed at deep interior of the star, a nuclear reaction may be performed due to production of high temperature fluctuation at extremely high density plasma. The effect of local heat fluctuation interior of the star provides global stellar p-mode oscillation in young star (sun).

2.7.1. Stellar surface oscillation

The stellar (solar) surface oscillates in non-radial harmonic oscillation mode monotonously throughout its life. Several observations and researches have been carried out on the young star (sun). The expected main mechanism for surface oscillation is a small perturbation in dynamic pressure interior of the star associated with generation of magnetic fields. Currently, several thousand individual stellar (solar) harmonic oscillation modes have been identified [167, 175].

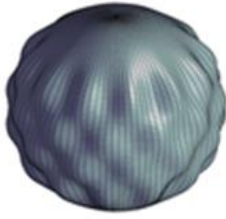


Fig.2.6 Non-radial stellar surface oscillation, Credit: NASA

It is expected that with more careful observation, frequencies for as many as 10^6 modes can be determined precisely. Even given likely advances in observations of other pulsating stars, this would mean that more than half the total number of known oscillation frequencies for all stars would belong to the Sun. The observed solar oscillations mostly have periods in the vicinity of five minutes, and considerably shorter than the fundamental radial period for the Sun, which is approximately 1 hour [176]. Both the solar 5 minute oscillations and the fundamental radial oscillation are acoustic modes, or *p-modes*, driven predominantly by dynamic pressure fluctuations; whereas the fundamental radial mode has no nodes, the five-minute modes are of high radial order, with 20 - 30 nodes in the radial direction.

Since we have believed that the Sun to be a normal star, similarly rich spectra of oscillations would be expected in other similar stars. Most of the observed solar modes have relatively short horizontal wavelength on the solar surface, and hence would not be detected in stellar observations. Another problem in trying to detect the expected solar like oscillations in other stars is their very small amplitudes. On the Sun the maximum velocity amplitude in a single mode is about, 15 ms^{-1} , whereas the luminosity amplitudes are of the order of 1 micro-magnitude or less [177 - 179]. Clearly extreme case is required in observing such oscillations in other stars, where the total light-level is low. Nevertheless, to obtain information, although less detailed than available for the Sun, for other stars would be extremely valuable; hence a great deal of effort is being spent on developing new instrumentation with the required sensitivity. A non-radial mode is characterized by three wavenumbers: the degree l is polar, azimuthal order m which determine the behavior of the mode over the surface of the star and the radial order n

which reflects the properties in the radial direction. In general the frequencies ω_{nlm} of stellar oscillations depend on all three wave numbers. It is convenient, however, to separate the frequency into the multiplet frequency ω_{nl} , obtained as a suitable average over azimuthal order m and corresponding to the spherically symmetric structure of the sun, and the frequency splitting $\omega_{nlm} - \omega_{nl}$ is obtained [180]. The small-amplitude oscillations of the sun can be described in terms of spherical harmonics function $Y_{lm}(\theta, \varphi)$ of polar angle θ and longitude angle φ of non-radial coordinate.

$$Y_l^m(\theta, \varphi) = (-1)^m c_{lm} p_l^m(\cos \theta) \exp(im\varphi) \quad (2.26)$$

The non-radial function $Y_l^m(\theta, \varphi)$, is defined as spherical harmonic function and p_l^m is a Legendre function. The normalization constant c_{lm} is determined by Eq.(2.27).

$$c_{lm} = \left[\frac{(2l+1)(l-m)!}{4\pi(l+m)!} \right]^{1/2} \quad (2.27)$$

The degree l measures the total horizontal wave number on the surface by $k_h = L/R_\odot$, where, $L = \sqrt{l(l+1)}$ and $R_\odot$ is the critical radius of the Sun at minimum constant temperature layer or CL. Equivalently the wavelength is $\lambda = 2\pi/k_h$ obtained from non-radial components of wave numbers and L represents the number of wavelengths along the solar circumference. The azimuthal order m measures the number of nodes (i.e., zeros) along the equator. Observations show that the solar oscillations consist of a superposition of a large number of modes, with degrees ranging from 0 to more than 1500 nodes [76, 181, 182]. The simplest form of mode isolation is obtained in whole-disk (or integrated-light) observations, where the intensity variations or velocity in light from the entire solar disk are observed.

To describe the global stellar surface oscillation mode, we consider small perturbations of stellar surface about the equilibrium state, which is space-time dependent perturbation. The pressure, density, velocity field, surface electric field and gravitation field of rotating star are perturbed about the equilibrium point. The physical quantities with subscript 1 represent the perturbed quantities while the quantities with subscript zero represent unperturbed physical quantities. Let we decompose any arbitrary vector physical quantities, $\vec{A}$ on stellar surface in to two components are known as radial component, $\vec{A}_r$ and horizontal component, $\vec{A}_h$ of the vector

field which contains polar and azimuthal components in spherical coordinate. The uniformly rotating active stellar surface partially ionized plasma is considered as incompressible plasma fluid in this special case. The solar dynamical phenomena are observed as solar winds, flares, filaments, prominence, sun spots, and CMEs. The non-radial oscillation of star is described by the small perturbation of the system about its monotonous equilibrium situation. Evolution of magnetic fields, formation of intense instantaneous electric current associated with the fast flowing of local plasma on solar atmosphere control the solar activities.

The perturbing physical quantities of star can be expressed by first order linearized equation of continuity, momentum and energy in spherical coordinate. The surface charge density at radial scale height which is comparable to Debye length on upper layer of photosphere is considerable for dynamics solar surface activities. The first order linearized form of continuity and momentum equations of uniformly rotating stellar surface is described by Eqs.(2.28) and (2.29) respectively for negligible case of viscosity effects.

$$\frac{d\rho_1}{dt} + \vec{\nabla}(\rho_0 \vec{v}) = 0 \quad (2.28)$$

$$\rho_0 \frac{d\vec{v}_1}{dt} = -\vec{\nabla}p_1 + \rho_0 \vec{g}_1 + \rho_1 \vec{g}_0 - qn_0 \vec{\nabla}\phi_1 - qn_1 \vec{\nabla}\phi_0 - \rho_0 v \vec{v}_1 + \frac{1}{2} \rho_1 \Omega^2 \vec{\nabla}(r^2 \sin^2 \theta) - 2\rho_0 \vec{\Omega} \times \vec{v}_1 \quad (2.29)$$

Where, $\vec{v}_1 = (\vec{v}_e \pm \vec{v}_i)$ relative velocity of electron with respects to ion for completely ionized solar surface plasma. Since the lighter electrons of hot surface plasma move much faster than ions and neutrals, we approximate that ions and neutrals are relatively at rest, $\vec{v}_{rel} = (\vec{v}_e \pm \vec{v}_i) \approx \vec{v}_1$ on perturbing stellar surface. Adding viscosity terms to Eq.(2.29) introduces the non-linear effects of perturbing physical quantities. To minimize complexity we neglect the effects of plasma viscosity terms in this section. Since the perturbation has non-linear behavior, the system becomes highly complex and the process is non-adiabatically. From Eq.(2.29) the radial and horizontal components of momentum equation of perturbing parcels of stellar surface plasma are given by Eqs.(2.30) and (2.31) respectively, in linearized form uniformly rotating stellar surface.

$$\rho_0 \frac{\partial^2 \xi_r}{\partial t^2} = -\frac{\partial p_1}{\partial r} - \rho_1 g_0 - \rho_0 \frac{\partial \phi_{g1}}{\partial r} - qn_0 \frac{\partial \phi_1}{\partial r} - qn_1 \frac{\partial \phi_0}{\partial r} - \rho_0 v v_r + \frac{1}{2} \rho_1 \Omega^2 \frac{\partial \xi}{\partial r} + 2\rho_0 \Omega v_r \quad (2.30)$$

$$\rho_0 \frac{\partial^2 \vec{\xi}_h}{\partial t^2} = -\vec{\nabla}_h p_1 - \rho_0 \vec{\nabla}_h \Phi_{g1} - q n_0 \vec{\nabla}_h \phi_1 - q n_1 \vec{\nabla}_h \phi_0 - \rho_0 v \vec{v}_h + \frac{1}{2} \rho_1 \Omega^2 \vec{\nabla}_h \zeta + 2 \rho_0 \Omega \vec{v}_h, \quad (2.31)$$

Where, $\vec{\nabla}_r \zeta = 2r \sin^2 \theta \hat{r}$, $\vec{\nabla}_h \zeta = 2r^2 \sin \theta \cos \theta \hat{\theta}$, and $\vec{v}_r$ and $\vec{v}_h$ are radial relative velocity field and horizontal velocity field respectively and $\vec{\Omega} = \Omega \hat{\Omega}$ where $\hat{\Omega}$ obtains radial and polar direction. The perturbed Poisson's equation of harmonically oscillating upper boundary layer of stellar surface plasma can be described by Eq.(2.32) at static stellar surface. Here we neglect the effects of rotation, viscosity and plasma particle collision.

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial}{\partial r} [\Phi_{g1} + \phi_1] \right) + \vec{\nabla}_h^2 [\Phi_{g1} + \phi_1] = 4\pi G \rho_1 - \frac{q n_1}{\epsilon_0} \quad (2.32)$$

The quantity $n_{i1} + n_{e1} \approx n_1$ represents the perturbing surface net electron number density. Generally, we can evaluate the surface oscillating plasma by assuming that the perturbed quantities are in exponential form, and the surface oscillating displacement of plasma element is specified by Eqs.(2.33a) and (2.33b) for its radial and horizontal components.

$$\xi_r(r, t) \cong \tilde{\xi}_r e^{i(\vec{k} \cdot \vec{r} - \omega t)} \quad (2.33a)$$

$$\xi_h(X, t) \cong \tilde{\xi}_h e^{i(\vec{k} \cdot \vec{X} - \omega t)} \quad (2.33b)$$

Where, $\tilde{\xi}_r$ and $\tilde{\xi}_h$ are amplitudes of the stellar surface oscillating displacement. The wave vector $\vec{k}$ can be decomposed in to radial and horizontal components $\vec{k} = k_r \hat{r} + \vec{k}_h$ on the oscillating stellar surface plasma. The Eqs.(2.30) and (2.31) using Eqs.(2.28), (2.33a) and (2.33b) yields the radial and horizontal components of sinusoidal perturbing stellar surface displacement that is specified in terms of wave vector field as shown in Eqs.(2.34) and (2.35) including stellar rotational effects of collision.

$$\vec{\xi}_r = \frac{i \vec{k}_r}{\omega^2} \left[\frac{p_1}{\rho_0} + \Phi_{g1} + \frac{\rho_1 \Phi_{g0}}{\rho_0} \right] + \frac{i \vec{k}_r q}{\omega^2} \left[\frac{n_0}{\rho_0} \phi_1 + \frac{n_1}{\rho_0} \phi_0 \right] + \frac{1}{\omega^2} [\nu - 2\Omega] \vec{v}_r - \frac{\rho_1 i \vec{k}_r}{2 \rho_0 \omega^2} \Omega^2 r^2 \sin^2 \theta \quad (2.34)$$

$$\vec{\xi}_h = \frac{i \vec{k}_h}{\omega^2} \left[\frac{p_1}{\rho_0} + \Phi_{g1} \right] + \frac{i \vec{k}_h q}{\omega^2} \left[\frac{n_0}{\rho_0} \phi_1 + n_1 \frac{\phi_0}{\rho_0} \right] + \frac{1}{\omega^2} [\nu + 2\Omega] \vec{v}_h - \frac{\rho_1 i \vec{k}_h}{2 \rho_0 \omega^2} \Omega^2 r^2 \sin^2 \theta \quad (2.35)$$

Where, $\vec{v}_r = (\vec{v}_{er} \pm \vec{v}_{ir})$, and $\vec{v}_h = (\vec{v}_{eh} \pm \vec{v}_{ih})$, for collision dominated terms of radial and horizontal components of relative velocity of plasma element. Using Eq.(2.28) and Eq.(2.31), the

perturbing dynamic pressure of stellar surface plasma, photosphere is approximated by Eq.(2.36) and neglecting plasma viscosity term in steady state situation.

$$p_1 = \frac{\omega^2}{k_h^2}(\rho_1 + ik_r\rho_0\xi_r) + i\rho_0\frac{v_h}{k_h}[\nu + 2\Omega] - \rho_0\Phi_{g1} + e(n_0\phi_1 + n_1\phi_0) + \frac{1}{2}\rho_1\Omega^2r^2\sin^2\theta \quad (2.36)$$

The perturbed surface dynamic pressure consist of hydrogen plasma gas pressure and surface radiation pressure after scattering of electron due to Thomson scattering process [152, 183]. Thus, $p_1 = p_{gas} + p_{rad}$, on the dynamic boundary of solar photosphere at CL boundary. However, beyond the stratified boundary of stellar surface the plasma pressure is negligible, and only $p_1 \approx p_{rad}$ is remained rather accelerated particles in the form of solar wind and other solar activities. Above the stratified stellar surface only perturbed plasma particles are there, most of them are expected as light electrons. The plasma hydrogen gas pressure is vanished beyond the stellar surface compare to stellar interior. The surface radiation pressure can be approximated by thermal radiation and vanishing of static plasma density at steady state condition or hydrostatic equilibrium $\rho_0 \approx 0$ beyond boundary of stellar surface relative to central pressure of star. Only perturbed plasma particles coupled with non-potential magnetic field are take part on solar atmosphere activities see chapter 3.

The acoustic radiation pressure on rotating stellar surface in the absence of magnetic field is obtained by Eq.(2.36) implies that $p_1 \approx p_{rad}$ beyond stellar surface boundary layer. Below the stellar surface (i.e., convection zone) the plasma gas dynamic pressure is dominant over radiation pressure and the surface electrostatic potential has no significant effect interior of the star. The perturbing plasma dynamics pressure below stellar boundary layer is given by Eq.(2.36) with vanishing terms that contains surface electrostatic potential. Since the surface boundary electrostatic potential has no significant effects on the interior part of oscillating stellar surface, the oscillation condition interior of the star is determined using the assumption of *Bruit-Vaisala* like frequency. Substituting Eq.(2.36) in to Eq.(2.34) for plasma below the surface boundary layer of star; using the expression $ik_r\rho_1\Phi_{g0} = \rho_1g$ we have gotten Eq.(2.37) that describes the net surface resultant radial force applied on oscillating stellar surface.

$$\rho_0\omega^2\left(1 + \frac{k_r^2}{k_h^2}\right)\xi_r = \rho_1\left[g + \frac{\omega^2}{k_h^2}ik_r\right] - \rho_0v_h\frac{k_r}{k_h}[\nu + 2\Omega] + \rho_0v_r[\nu - 2\Omega] \quad (2.37)$$

The last two terms on right hand side of Eq.(2.37) arises due to effects of Coriolis force coupled with collision and viscosity effect. In the absence of viscosity and collision, the gravitational force is balanced by centrifugal force and dynamic pressure gradient force on stellar surface. The global solar *p-mode* oscillation is independent of surface electrostatic potential interior of the star. However, the effect of instantaneous surface charge separation process plays a crucial role on evolution of strong surface magnetic field. From Eq.(2.37) we can understand that the constant surface rotational velocity has no significant effects on the solar surface multi-mode oscillation for vanishing Coriolis force on stellar surface.

However, the stellar rotation velocity affects its atmospheric *multi-mode* oscillation. Stellar atmosphere plasma particles are not strictly attached with the rotating surface. The stellar atmosphere particles may not rotate with the same velocity as the stellar surface, far away from surface. The plasma rotational velocity beyond the stellar surface becomes position and time dependent. It is a nice idea that the perturbing physical quantities on solar surface specified by normalized quantities. The normalized vector fields and scalar fields can be expressed in the form of spherical harmonic function.

$$\xi_r = \sqrt{4\pi}\tilde{\xi}_r(r)Y_{lm}(\theta, \varphi)e^{-i\omega t} \quad (2.38a)$$

$$p_1 = \sqrt{4\pi}\tilde{p}_1(r)Y_{lm}(\theta, \varphi)e^{-i\omega t} \quad (2.38b)$$

$$\Phi_{g1} = \sqrt{4\pi}\tilde{\Phi}_{g1}(r)Y_{lm}(\theta, \varphi)e^{-i\omega t} \quad (2.38c)$$

$$\phi_1 = \sqrt{4\pi}\tilde{\phi}_1(r)Y_{lm}(\theta, \varphi)e^{-i\omega t} \quad (2.38d)$$

At small perturbation about equilibrium situation, we have used spherical symmetry of gravitational potential that is varied radially. The perturbing surface displacement field due to oscillation of stellar surface is manipulated from Eqs.(2.28), (2.34) and (2.35) using the expression of Eq.(2.38a) to (2.38d) on the stellar boundary layer, we have obtained Eq.(2.39) that describes the perturbing displacement amplitude of surface plasma element.

$$\tilde{\xi} = \sqrt{4\pi} \left[\left(\tilde{\xi}_r(r)\hat{r} + \tilde{\xi}_{h1}(r)\hat{\xi}_h \right) Y_{lm} + \tilde{\xi}_h(r) \left[\frac{\partial Y_{lm}}{\partial \theta} \hat{\theta} + \frac{1}{r \sin \theta} \frac{\partial Y_{lm}}{\partial \varphi} \hat{\varphi} \right] \right] e^{-i\omega t} \quad (2.39)$$

The perturbing surface displacement field is specified by spherical harmonic oscillation function. During stellar surface non-radial oscillation, the normalizing radial displacement field, $\tilde{\xi}_r$ and normalized horizontal displacement field's $\tilde{\xi}_h$ expressed by Eq.(2.40a) as follow.

$$\tilde{\xi}_r(r) = \frac{1}{\rho_0 \omega^2} \left[\frac{\partial \tilde{p}_1}{\partial r} + \rho_0 \frac{\partial \tilde{\Phi}_{g1}}{\partial r} + \rho_1 g - \rho_1 \Omega^2 r \sin^2 \theta - e n_0 \frac{\partial \phi_1}{\partial r} - e \tilde{n}_1 \frac{\partial \phi_0}{\partial r} + \rho_0 v_r [\nu - 2\Omega] \right] \quad (2.40a)$$

$$\tilde{\xi}_h(r) = \frac{1}{\omega^2 r} \left[\frac{\tilde{p}_1(r)}{\rho_0} + \tilde{\Phi}_{01}(r) - \frac{e n_0}{\rho_0} \tilde{\phi}_1(r) \right] \quad (2.40b)$$

$$\tilde{\xi}_{h1}(r) = \frac{\Omega}{\omega^2} \left(\frac{1}{2} \frac{i \Omega k_h}{\omega^2} \frac{\tilde{p}_1}{\rho_0} r^2 \sin^2 \theta + 2 v_h \right) \quad (2.40c)$$

We have $\hat{\xi}_h$ is horizontal unit vector lies on surface plane. For non-rotating star, ignoring the surface electrostatic potential and collision of plasma particles the term $\tilde{\xi}_{h1}(r)$ is vanished. The perturbing oscillating displacement vector of stellar surface coupled with interior of star is approximated by Eq.(2.41) according to Gray, D.F. and Hatzes [184].

$$\vec{\xi} = \sqrt{4\pi} \left[\tilde{\xi}_r(r) Y_{lm} \hat{r} + \tilde{\xi}_h(r) \left(\frac{\partial Y_{lm}}{\partial \theta} \hat{\theta} + \frac{1}{\sin \theta} \frac{\partial Y_{lm}}{\partial \phi} \hat{\phi} \right) \right] e^{-i\omega t} \quad (2.41)$$

The stellar surface oscillation frequency ω is in general complex due to presence of plasma collision, viscosity, surface electron induced micro-magnetic field and force free stellar magnetic field in connection with plasma dynamics. The displacement field that is given by Eq.(2.39) provides instantaneous velocity field of stellar surface during oscillation. It is possible to calculate the kinetic energy of surface oscillating plasma fluid of non-radial oscillating stellar surface from Eqs.(2.39) and (2.41) on surface boundary and interior respectively. When the stellar surface oscillates in monotonously non-radial spherical harmonic mode, plasma elements simply gain enough kinetic energy and depart from stratified stellar surface opposing the gravitational attraction force. The kinetic energy of the pulsation is given by integrating over the whole volume of convection surface. The perturbing oscillating velocity field of stellar surface is obtained from Eq.(2.39) or (2.41).

$$\vec{v} = -i\omega \vec{\xi} \quad (2.42)$$

When the oscillation frequency is complex the system may not be stable. Interior of the star, during stellar oscillation the effects of magnetic fields, viscosity, and plasma turbulence are

ignored to minimize complexity of the system. The instantaneous velocity field of displaced plasma element on stellar surface is given by Eq.(2.42) that describes the oscillating velocity field. The kinetic energy of oscillating stellar surface of perturbing plasma elements can be approximated by Eq. (2.43).

$$E_{kin} \approx 2\pi\rho_1\omega^2\tilde{\xi}^2 \quad (2.43)$$

The quantity E_{kin} represents the kinetic energy of perturbing surface plasma elements. The local acceleration of oscillating surface plasma coupled with stellar interior proportional to square of surface plasma oscillation frequency and is described by Eq.(2.44).

$$\vec{a}_{\tilde{\xi}} = -\omega^2\vec{\tilde{\xi}} \quad (2.44)$$

The quantity $\vec{a}_{\tilde{\xi}}$ is local acceleration field of oscillating surface. Due to this kinds of plasma acceleration field, the oscillation of solar surface plasma can be detected in manner of Doppler shift mechanism [141, 185, 186].

2.7.2. Stellar atmosphere oscillation

Since there is no remarkable demarcation between stellar atmosphere and its interior, the oscillation interior of the star is coupled with solar atmospheric oscillations. By assuming isothermal stellar atmosphere lower boundary layer, the oscillation of solar atmosphere is detected as 3 minutes solar oscillations while the solar surface oscillation period is 5 minutes [36, 187, 188]. These evidences are obtained from the ground based observations (i.e., using light and radio spectrum) and space born satellite observations such as SOHO, LASCO, SDO and YOHKOH ... etc, (i.e., all kinds of spectrum such as light, radio, EUV, soft X-ray and hard X-ray are detected). To detect the stellar atmospheric oscillation is very difficult due to limited optical observational equipment.

Moreover, some extreme amplitude of non-radial stellar (solar) surface oscillations is expected at local region of solar surface which triggers the bottom region of solar atmosphere oscillations and local plasma motions. This extreme non-radial solar oscillation is occurred due to extreme local pressure perturbation which blows stream of plasma elements associated with intense heat flux to lower layer of stellar atmosphere. The blown stream of plasma elements

create a cloud of relatively cold plasma a few kilometers above the solar surface and falls down in a velocity slower than that of surface oscillation. The presence of bundles of magnetic flux tube distribution and flowing of plasma jets of stellar atmosphere make the system more sophisticated. We will see effects of magnetic field on local region of oscillating stellar surface in our next chapter, see chapter 3.

Based on several observational evidences and on the dynamical theory of solar surface, high plasma density gradient occurred at atmosphere [189]. The high density gradient associated with plasma dynamics creates inhomogeneity in temperature profile of stellar atmosphere. In case of extreme finite amplitude, the stellar surface plasma rises up a higher displacement beyond its normal oscillating amplitude. The extreme amplitude displacement is much higher than the normal amplitude. For instance imagine how high amplitude ocean wave is occurred on Earth planet. This extreme amplitude also may be downward amplitude when the rising part of stellar surface returns back. This extreme case is created due to high energy production at small local region interior of the star which creates extreme radial pressure difference between surface and interior of star.

In connection with atmospheric oscillation above stellar surface, a dense plasma cloud is created somewhere. This plasma cloud falls down due to gravitational attraction force when it cools. A low density local region is created above the minimum temperature stellar surface due to extreme cases of surface oscillation and extreme cases of plasma convection process. The multi-mode harmonic oscillation of stellar atmosphere is more complex than oscillation of stellar interior. The oscillation complexity of stellar atmosphere arises from inhomogeneity in its dynamic nature of associated with non-linear wave propagation .

2.8. Formation of Partial Vacuum Region on Stellar Surface

The nature of high conductivity plasma fluid at local stellar (solar) photosphere is treated in hydrodynamics theory associated with particle kinematics at weak magnetic field region. Hot plasma cloud lifts up from surface due to plasma convection motion and overloading nodes of extreme amplitude displacement of non-radial oscillation modes. During stellar surface extreme amplitude oscillations, perturbing plasma element is blown out to atmosphere [179]. This process is triggered due to *acoustic radiation pressure* of photosphere perturbing plasma and due to local

nuclear reaction interior of star. The acoustic radiation pressure arises from plasma potential fluid coupled with convection and surface oscillation. Several observational evidences have shown that plasma element lifts up from solar surfaces in fountain like manner about 100km to 200km due to surface plasma convection case [190]. The rising plasma creates a cloud layer above the surface in the form of plague till the plasma cold, and falls down because of gravitational attraction force. The falling down cold dense plasma strikes with the relatively stratified stellar surface plasma.

We assumed that the local layer of plasma cloud with thickness s and plasma layer density of $\sigma(s)$ at radial displacement of $\delta\vec{r}$ much higher than oscillation amplitude displacement of the stellar surface. This local plasma cloud layer may lifts up due to two conditions at weak magnetic field region as plasma flows on stellar surface. The first condition is that when local surface of star becomes hotter due to transport of extreme intense heat flux from interior of the star, it gets higher in temperature than its surrounding surface temperature. This hottest plasma heats the surrounding local region and hot plasma cloud lifts up above the local oscillating surface. The oscillating local solar surface provides additional kinetic energy for the rising hot plasma particles. When the extreme oscillating local surface returns down, a layer of hot dense plasma cloud remains behind of the surface until it cools down. Density of the floating plasma cloud above the stellar surface is higher than beneath. Thus, a low density region is crated between the floating plasma cloud and normal surface plasma. This plasma cloud is observed a few kilometers above the solar surface as plagues [191].

When this plasma cloud moves down later, at the *low density* region instantaneous electrostatic potential is created due to instantaneous strong charge separation process of hot local plasma region associated with surface gravitational force. The instantaneous electrostatic potential also creates a negative mechanical pressure at convergence point, line or plane inside the low density region. Let we call this low density local region is *partial vacuum region* (PVR). The PVR is situated between stellar surface stratified plasma and falling down cold plasma cloud before striking. The second condition is that at local region of photosphere plasma flows horizontally due to plasma convection, non-radial surface harmonic oscillation mode and local plasma turbulence. As streams of horizontal flowing plasma cloud meets head on or head-tail. An excess mass plasma cloud lifts upward from stellar photosphere against gravitational force

during colliding of head on or head-tail. The colliding streaming plasma elements may be in different temperature local region. The front surface of ejecting or streaming hot plasma element creates intense instantaneous surface electric field $\vec{E}$. Induced surface electric field is created due to fast moving hot electron enter to instantaneous charge separation process.

When the electron surface current is collapsing at lower background density, instantaneous negative mechanical pressure is developed. This leads to the formation of local PVR before collapsing. The local electrostatic surface potential at the front surface of flowing plasma is accompanied by generation of fast moving shock surfaces. Anomalous plasma resistivity is created due to sudden formation of shock wave fronts. However, the lifting up plasma layer is trapped by the stellar gravitational force and created strong electric current at atmosphere [192]. As long as the dense plasma layer moved a displacement $\delta\vec{r}$ away from photosphere is much higher than the normal amplitude of surface oscillation displacement, the plasma layer falls down due to internal source of gravitational potential field. When low density cavity is formed at deep stellar atmosphere, intense surface eruption is created, CMEs. This surface eruption is observed as flares and CMEs see chapter 2, chapter 3 and chapter 4 in this thesis work.

The main mechanism for local stellar surface plasma motion is the dynamical nature of surface plasma such as plasma convection, surface non-radial oscillation and plasma turbulences. The surface plasma flowing may be Langmuir flow or turbulent flow. Due to these kinds of irregular plasma motion, the stellar surface, CL, is not a smooth surface. Plasma mass deficiency and plasma mass excess is occurred on stellar local surface. Excess plasma mass is accumulated above stellar surface in a manner of mountain like on the Earth for short period of time due to high plasma turbulence of local region.

When the surface extremely moves down, a mass deficiency also occurred near to mass excess region. When the excess mass falls down, the surrounding plasma creates a strong disturbance on surface. As plasma cloud moves horizontally to fulfill the mass deficiency from all direction, partial vacuum region (PVR) or small cavity is developed on surface coupled with instantaneous charge separation of hot flowing local plasma. This cavity is a good sight for stellar (solar) explosive events and CMEs on weak magnetic field region, mainly for Nano-flares and micro flares. The gravitational potential field of oscillating star above its surface is obtained

by solving Poisson's gravitational differential equation, considering the outer mass distributions and ignoring the surface electrostatic potential from Eq.(2.32) during perturbation of stellar surface results Eq.(2.45),

$$\Phi_g = \frac{-GM}{R_s} \sum_{l=0}^{\infty} \sum_{m=0}^{\infty} \left(\frac{R_s}{r}\right)^{l+1} [A_l^m \cos(m\varphi) + B_l^m \sin(m\varphi)] p_l^m(\cos \theta) \exp(-i\omega t) \quad (2.45)$$

where $R_s = R_{\odot}$, critical solar radius demarked at CL ideal layer and the coefficients A_l^m and B_l^m are determined by boundary conditions. By keeping symmetry condition of spherical harmonic condition in terms of space coordinate dependent spherical harmonic potential, $\Phi(h)$, we get Eq.(2.46) outside the uniform surface of mass distribution.

$$\Phi_g = \left(\frac{R_{\odot}}{r}\right)^{l+1} \Phi(h, t) \quad (2.46)$$

The falling down layer of cold plasma cloud with thickness of order of degree l has an approximated surface density of $\sigma(l)$ independent of time. The characteristic oscillation length of $h \sim l$ gets the local gravitational acceleration approximated by Eq.(2.47). This is true if the thickness of plasma cloud above photosphere is approximated by small perturbed distance of $\alpha \xi \approx l$ for extreme local perturbation and α is real number.

$$\vec{g} = R_s^{l+1} (l+1) \frac{1}{r^{l+2}} \Phi_g(l, t) \hat{r} \quad (2.47)$$

Where, $\hat{r}$, radial unit vector. When the layer of plasma cloud lifts a radial displacement field given by Eq.(2.39), the falling down plasma cloud of the excess plasma mass accelerates downward to stellar surface with local gravitational acceleration $\vec{g}$ is given by

$$\vec{g} = R_s^{l+1} (l+1) \frac{1}{(R_s + \alpha \xi_r)^{l+2}} \Phi_g(\xi_r, t) \hat{r} \quad (2.48)$$

The current layer develops surface electric field which accelerates charged particles non-thermally at stellar atmosphere during small perturbation. A shock is developed at the surface of moving plasma cloud due to development of instantaneous electrostatic potential. Electrons simply gain kinetic energy from moving shock fronts. They move much faster than ions even if gravitational force much affects motions of ions. The Eq.(2.48) determines the gravitational local acceleration of spherical oscillating surface suffice spherical symmetry over azimuthal and polar

components of space coordinate. During surface oscillation, a part of the stellar surface moves up and down monotonously. When the excess mass part of surface plasma moves down, a layer of hot plasma cloud remain behind of the sinking surface. A PVR is created between the falling down plasma element and normal oscillating surface. This is necessarily true when the extremely oscillating surface is hotter than surrounding plasma due to migration of super-hot plasma elements from interior. As soon as intense heat waves penetrates this moving down normal surface, plasma particles between surface and falling down plasma cloud are heated by the wave.

As the source of heat flux in PVR ceased suddenly electrons, neutrals and ions are not accelerated furthermore or not ejected from the PVR by heat energy. High density gradient of local plasma element creates a difference in dynamic pressure between convergence region and ambient plasma. The ambient thermal pressure responds to balance the broken down pressure inside PVR. Huge amounts of ambient plasma implode to the center of PVR in order to fill up the cavity. The surrounding plasma particles change their velocity suddenly and flow to center of cavity from all direction due to strong local vacuum potential (VP) at center of convergence. The flowing local plasma moves with a velocity higher than the background sound speed of plasma or ion acoustic speed because of additional inertial force. The shock wave fronts travel from the dynamic boundary of PVR towards the center of convergence as well as outward direction while the ambient plasma moves towards the center of convergence point.

Let we assumed that the model of PVR is a spherical symmetric cavity for the sake of simplicity. As plasma implodes from all direction in to center of convergence, electrons move faster than ions and neutrals when they are at the same background temperature. A layer of electron beam is created at inner side of imploding dynamic boundary surface of PVR, during collapsing or growing. Electrons inside the PVR are oscillated several times and accelerated due to induced intense electric field and fast moving shock surfaces. The oscillating electrons are accelerated non-thermally near the convergence region as well as near the dynamic oscillating boundary of electron layer. A steep potential gradient is created between the center of convergence and its dynamic boundary layer. Here, we assumed that velocity of imploding plasma is aligned radially inwards to minimize complexity, during collapsing (growing). No plasma rotation at the dynamic boundary surface of PVR is considered here. Electrons do not have a waiting time at the center of convergence point or line or plane inside PVR. Due to

sudden formation of intense instantaneous electric field and fast moving shock surfaces, non-thermal radiation process is occurred. They are accelerated instantaneously in non-thermal manner and they leave the PVR quickly in the form of radiation before completing the collapsing process. Ions are decelerated near the dynamic boundary of collapsing PVR.

However, those decelerated ions absorb energy from the imploding strong shock surfaces and finally they have recovered their acceleration instantly. Only neutral particles remain free of electric field inside PVR until they are bombarded or ionized due to development of shock waves followed by blast wave fronts responsible for ionization process. At final stage, the neutral particles inside PVR become completely ionized since they have gained enough energy from shock waves and self-consistent electromagnetic field. The PVR is surrounded by cold partially ionized high conducting ambient plasma of stellar atmosphere. Let consider again the imploding plasma fluid is collision-less, and has no viscosity and the process is adiabatically before collapse or before passage of shock waves. No external pre-existed magnetic field is considered here for a time being till *chapter 3* in this work to minimize complexity. Plasma implodes to the PVR with instantaneous inertial velocity, $\vec{v}$, higher than the background plasma acoustic velocity. The background plasma velocity is changed suddenly at the dynamic boundary of PVR when ambient plasma starts imploding to center of convergence point. The imploding plasma velocity gets its new instantaneous inertial velocity, $\vec{v}$, which is faster than acoustic velocity.

2.8.1. Primary imploding and exploding shock wave fronts

Shock waves are continuously generated at dynamic boundary of PVR during collapsing or growing. The first existed shock waves are known as primary *imploding* shock wave and primary *exploding* shock waves. The strong imploding shock fronts propagate towards the convergence point of PVR with relative velocity of propagation $\vec{V} \pm c_1 \hat{r}$ followed by imploding blast wave. The exploding primary shock wave fronts that are followed by exploding blast wave engulf the ambient plasma. The exploding shock wave behind of imploding shock wave propagates with velocity $\vec{V} \pm c_2 \hat{r}$ behind of former moving shock surface for constant shock velocity. Where V , c_1 and c_2 are shock speed, sound speed before and after some shock wave fronts respectively.

Imploding electron beam from surrounding ambient plasma joins to shock regime faster than ion due to their higher velocity and lighter mass. The front side or inner surface of the imploding plasma cloud layer or electron beam is followed by heavy imploding ions behind of them associated with moving trains of shock surface. Those imploding ambient electrons do not return back due to attraction of ions and they quickly reach the dynamic boundary of PVR. However, the imploding electron beam is oscillating radially at dynamic boundary of PVR. The negative velocity shock potential sucks the surrounding plasma.

This means that electrons are simply sucked by local VP of the convergence point. The size of PVR diminishes at the rate of radially imploding velocity of plasma during collapsing. This intense electric field depends on the surface electron density in front of imploding plasma followed by continuously shocked ambient plasma. As the radial inflowing is continual; PVR is remained with field energy and some neutral particles before collapse if and only if the cavity is characterized by strong radiation process. The electrons, ions and neutrals get excess energy from continuous trains of successive shock fronts in addition to their inertial kinetic energy. Electron *runaway* and ion *runaway* condition is developed due to instantaneous electron induced electric fields in collision-less process. Electrons and ions are radiated from the PVR due to mainly the shock fronts and runaway condition is fulfilled. The radiating out electrons and ions may collide with imploding ambient plasma when the local system is high dense enough at photosphere.

Generally, the PVR is developed at local region of stellar atmosphere where local temperature difference is higher and the extreme high temperature is finished up suddenly at center of convergence point inside PVR. The main mechanism for formation of PVR is transport of local energy from interior of star to its atmosphere associated with surface oscillation, local plasma convection and high plasma disturbance and dynamics of magnetic flux tubes. Thus, the irregular surface plasma motion or surface plasma ejection to atmosphere provides PVR at local space.

2.8.2. Electrons runaway and ions runaway inside PVR

Inside PVR, the slowly moving electrons and ions experience a frictional force that is proportional to their velocity. However, for fast moving electrons and ions the dependence is

reversed and as flowing velocity increases, the frictional force or collisional force decreases. The faster charged particle moves, the more free of frictional force. Thus, electrons and ions enter to *electron runaway* (ER) and *ion runaway* (IR) condition inside PVR. Inside PVR, surface electric field will tend to accelerate the most energetic electrons and ions present in plasma almost indefinitely. The steep gradient of surface electrostatic potential inside PVR creates a preferable condition for electrons runaway and ions runaway condition. The runaway condition is more effective at the region of collisionless flow inside PVR before collapse. Charged particles are accelerated in the form of particle radiation and electromagnetic radiation observed as lightning.

2.8.3. Charge separation process of dynamic PVR on stellar atmosphere

When electron runaway condition is developed at local region inside hot neutral plasma medium, there could be a probability of cavity formation due to development of negative mechanical local pressure. A local electrostatic field is formed in small region due to instantaneous *strong charge separation* condition. When parcel of plasma fluid is ejected through low density background of high conductivity medium, electrons and ions of background plasma are accelerated suddenly due to instantaneous self-consistent electric field of ejecting plasma element. The electrostatic potential of ejecting plasma is effective at front side and tail of streaming plasma. The strong electric field is the consequence of instantaneous charge separation process. Generally, fast flowing plasma stream induces dipole electric field, see Fig.2.7, the streaming plasma is polarized.

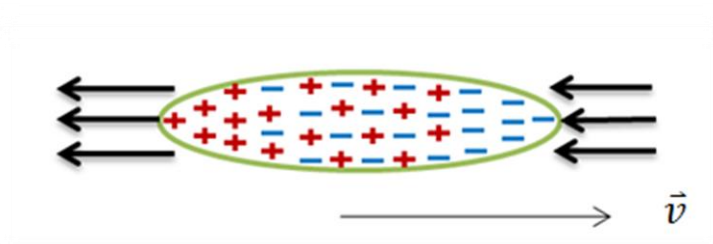


Fig.2.7 Charge separation of streaming plasma (strong polarization)

At stellar atmosphere, PVR is created because of dynamic behaviour of high conductivity flowing plasma. A negative pressure is developed at center of PVR because of coulomb force formation. Due to overloading of phase waves, a compressive shock wave is developed during collapsing or

growing of PVR. During collapsing, secondary shock waves may be created behind imploding shock waves. Finally, the compacted local region is exploded after primary shock wave change the behaviour of plasma. The *velocity shock potential* (VSP) is responsible for discharging of electrons, ions and neutrals. The velocity of propagating shock fronts is equal or greater than background ion's acoustic or electron acoustic velocity, see the diagram Fig.2.7.

2.9. Plasma Motion on Stellar Atmosphere

Several observations have been carried out on solar atmosphere from ground based and space born telescopes. Dynamic plasma motion is clearly observed on solar photosphere and chromosphere associated with structure of solar magnetic field [161, 193]. Horizontal and vertical plasma motion through nearly stratified background plasma creates a disturbance at local region of solar atmosphere. Plasma clouds are observed above solar surface in the form of prominences, filaments at relatively stable manner [161, 194]. The mechanism for plasma motion at stellar atmosphere is due to steep number density gradient of local region associated with plasma convection motion, extreme amplitude oscillation of local surface, explosive events and inhomogeneity distribution bundles of active magnetic fluxes. From observational and theoretical evidences, a local low density cavity is created at stellar atmosphere, see chapter 2, section 2.8.

The formation and distraction of low density cavity is due to extreme unstable local plasma motion associated with emanating energy from interior of star. When energy is transported from interior of star to its surface, it creates a significant effect on the surface such as normal and extreme local plasma convection, local surface oscillation, vertical and horizontal plasma motion, foot point heating of magnetic flux tubes, emergence of magnetic flux tubes and formation of sunspots [69, 84, 195 -199]. The stellar surface (i.e., photosphere) is characterized by non-uniformity plasma and magnetic field distribution, see chapter 3. Parcels of plasma are ejected and form plasma jets above the surface due to explosive events and emanating of super-hot plasma from interior to surface of local region [200]. An intensive local plasma flow is expected as to be a mechanism for stellar explosive events. The main primary mechanism for formation stellar explosive events is formation of velocity shock potential, VSP, during evolution of space-time coordinate, $\psi \propto V^2 t$ at instantaneous time, see chapter 2, section 2.11 – 2.16, in case of non-relativistic sence.

2.9.1. Evolution of dynamic PVR on stellar atmosphere

When PVR is developed at local region of stellar surface, formation of fast moving shock surfaces are inevitable. Trains of strong shock surfaces are imploding to center of convergence from its dynamic boundary surface while slow shock surfaces are exploding to ambient surrounding plasma from the dynamic boundary of PVR during collapsing or growing. Initially, a shock wave surface is created at dynamic boundary of developing PVR because of supersonic plasma flow arisen due VP. The source of supersonic plasma flow is formed due to steep density gradient of high conductivity plasma of continuum medium. Suppose the PVR is spherical low density cavity with initial position radius $\vec{r}_0$ measured from its convergence point. When plasma elements start imploding radially in to center of convergence, electrons always implode in front of ions. Those fast imploding electrons create a beam layer at the inner dynamic boundary of PVR. The electron beam layer with thickness of l_e which can be approximated by order of Debye length λ_{De} is created at inner boundary surface.

We assumed that charged particles have high inertial kinetic energy and they are beyond the effect of nearby charges until strong charge separation condition provides enough effect on electrons and ions. When the induced instantaneous electric field is higher than Dirac electric field like, $\vec{E}_D$, electrons and ions are starting acceleration inside PVR. In reality, the geometrical shape of PVR may be spherical, cylindrical or plane like (i.e., a sheet of partial vacuum layer) at stellar atmosphere. The average electrostatic field intensity may be vanished inside the PVR only for uniform distribution of surrounding electrons which results constant surface electrostatic potential. The radial components of continuity, momentum and energy equations respectively inside PVR can be described in Euler form given by Eqs.(2.49), (2.50) and (2.51).

$$\frac{\partial n_j}{\partial t} + \frac{\partial}{\partial r} [n_j v_j] + \frac{2}{r} n_j v_j = 0 \quad (2.49)$$

$$\frac{\partial v_j}{\partial t} = -v_j \frac{\partial v_j}{\partial r} + \frac{1}{\rho_j} \frac{\partial p_j}{\partial r} + n_j q_j \frac{1}{\rho_j} \frac{\partial \phi_s}{\partial r} \quad (2.50)$$

$$\frac{\partial}{\partial t} \left(\frac{1}{2} \rho_j v_j^2 - \frac{\gamma p_j}{\gamma-1} + \frac{1}{2} \rho_c \phi \right) = -\frac{\partial}{\partial r} \left[\frac{1}{2} \rho_j v_j^2 - \frac{\gamma p_j}{\gamma-1} + \frac{1}{2} \rho_c \phi_s \right] v_j \quad (2.51)$$

The variable n_j represents a number density of plasma particles inside PVR and the subscript of j represents the plasma species of electron, ion and neutral. We assumed that the negative dynamic pressure and surface induced electric field is given by $-p_j$ and $-\vec{E}_r$ respectively inside

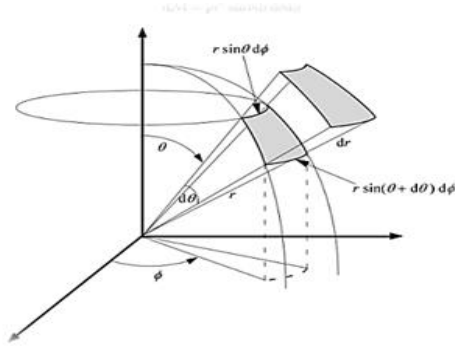


Fig. 2.8 Spherical coordinate

the PVR to distinguish them from surrounding dynamic pressure and electric field.

However, we have taken that the imploding or compressing velocity is positive here. The function ϕ_s represents the instantaneous surface electrostatic potential of PVR. The local charge density inside PVR is given by $\rho_c = e(n_e - zn_i)$ were initially at thermal equilibrium situation in the absence of inertial forces. Since we have taken only the negative dynamic pressure, we assumed that collision is absent

in the aligned motion of collapsing cavity till the electron beam is collapsed at convergence point and reflection would be started. In this situation, the electrons and ions enter to electron runaway (ER) and ion runaway (IR) condition respectively.

However, evaluating Eqs.(2.49), (2.50) and (2.51) at a region where position vector is given by $\vec{r}(t) \ll \vec{r}_0(t)$ as the cavity is diminished in size, the negative local dynamic pressure becomes strong enough due to strong VP. For the sake of simplicity, we assumed that the imploding or exploding radial velocity field of plasma species is given by $v_{rj} = v_j(r, \theta, \phi, t) = \pm v_j$, and inside PVR the total number density also given by $n_j = zn_i + n_e + n_n$ with corresponding mass density of $\rho_j = \rho_i + \rho_e + \rho_n$ for ion, electron and neutral particles respectively. The instantaneous electric field inside PVR propagates much faster than fast moving shock wave fronts in non-relativistic case. The VP sucks the surrounding ambient plasma and the PVR is destroyed suddenly. The imploding shock surfaces compacts the imploding plasma fluid at convergence point. The quantity, q , represents $-e$, charge of electron and $-ze$ charge of ion of hydrogen plasma, m_e is electron mass, and $n_e = n_e(r, t)$ is electron number density inside spherical shell layer. The quasi-neutrality condition is violated due to development of VP and shock waves. We neglect the effect of gravitational potential of small local system on the surface of uniformly rotating star.

We consider the imploding local electron beam of spherical layer field depends only on radial component of space-time coordinate. The local system is independent of angular space components to satisfy spherical symmetry. The quantity, v_{0e} , is initial electron speed. In the absence of initial inertial velocity of plasma species inside PVR, the initial speed v_0 is equivalent to the background plasma species of (i.e., electron, ion and neutral) thermal speed. Utilizing Eq.(2.50), it is possible to evaluate how electron plasma fluid behaves inside the PVR. The collapsing electron velocity near the convergence point is obtained from Eq.(2.50) neglecting the second order term at steady state situation. The collapsing electron velocity for position independent imploding near the convergence point before stagnation process would start, given by Eqs.(2.52a) and (2.52b) when the viscosity and collisional have significant effects near convergence point.

$$\vec{v}_e = \left(v + \mu \frac{2}{r^2} \right)^{-1} \left[\frac{en_e}{\rho_e} \frac{\partial \phi_s}{\partial r} - \frac{k_B n_e}{\rho_e} \frac{\partial T_e}{\partial r} - \frac{k_B T_e}{\rho_e} \frac{\partial n_e}{\partial r} \right] \hat{r} \quad (2.52a)$$

For $|2\mu/r^2| < 1$ the above expression of Eq.(2.52b) becomes

$$\vec{v}_e = \left[v - \frac{2\mu}{r^2} \right] \left[\frac{en_e}{\rho_e} \frac{\partial \phi_s}{\partial r} - \frac{k_B n_e}{\rho_e} \frac{\partial T_e}{\partial r} - \frac{k_B T_e}{\rho_e} \frac{\partial n_e}{\partial r} \right] \hat{r} \quad (2.52b)$$

The position vector $\vec{r}_0$ represents the initial radius position of PVR before collapsing is started in steady state. The shocked region behind of the collapsing dynamic boundary becomes high dense than its surrounding. The local collapsed high conductivity plasma would explode at a region of $\vec{r} \ll \vec{r}_0$ suddenly due to strong shock wave generation. The generation of strong shock wave develops anomalous plasma resistivity. The formation of strong shock wave is followed by imploding blast wave and explosive blast wave. The blast waves can be implosive blast waves which are converged at a point like region or exploding blast wave that converges at infinity.

2.9.2. Dynamic boundary surface of PVR

Let we consider the PVR is collapsed suddenly to convergence point, in steady state situation. Only accelerated electron and ion have been passing through the electron beam dynamic boundary. In steady state condition, the collapsing plasma flux is conserved before reflection at convergence region for no mass penetrates the dynamic boundary. The collapsing electron beam layer followed by imploding ambient plasma is given by Eq.(2.53), in the region

of $r_0 \geq r > 0$ before reflection at convergence point. However, we assumed that no sink or source at convergence point before generation of secondary shock waves at a point so as to fulfill the particle flux and energy conservation law at the isolated local system, for $|r_0| \geq |r|$, we get,

$$\Gamma = \Gamma_0 \left(\frac{r_0}{r} \right)^2 \quad (2.53)$$

The function $\Gamma = zn_i v_i + n_e v_e + n_n v_n$ denotes the imploding plasma flux in to convergence region. The Eq.(2.53) shows that the imploding plasma flux is conserved at the local isolated system for negligible radiation effects in non-relativistic sense in steady state situation. We assumed that Γ_0 is time independent imploding flux at initial boundary layer of radius position $\vec{r}_0$ of PVR as soon as collapsing is started. The collapsing velocity of imploding electron beam in steady state situation is followed by imploding ambient plasma flux of isolated local system. Separately, considering the electron beam flux in collision-less motion, the collapsing radial electron current of local system is given by Eq.(2.54a), describes steady radial electron current.

$$\vec{J} = -e\Gamma_0 \left(\frac{r_0}{r} \right)^2 \hat{r} \quad (2.54a)$$

The electron current is available during the evolution and collapsing of PVR and will be vanished at convergence point even in the absence of collision at that point. Once the PVR is destroyed, an intense explosion is created due to creation of explosive shock (secondary shock waves) and reflection of imploding shock (primary shock waves) in connection with particles-wave interaction process in non-relativistic sense. Using Ampere's law and divergence theorem, by assuming B_θ is independent of θ and φ , B_φ is independent of φ , the non-radial induced magnetic field is obtained as

$$\vec{B} = -\frac{e\mu_0\Gamma_0 r_0^2}{\pi r} [\cot \theta \hat{\theta} + \pi \tan \theta \hat{\varphi}] \quad (2.54b)$$

In steady collapsing of PVR, let we consider two special cases. These are:

Case 1: If $n_e = n_0$ number density of electron beam of collapsing PVR is constant in steady state, the collapsing velocity field of electron beam followed by ambient plasma is obtained from Eq.(2.53) in the absence of initial inertial force for isothermal condition.

$$\vec{v}_e = c_s \left(\frac{r_0}{r} \right)^2 \hat{r} \quad (2.55a)$$

The variable c_s represents acoustic speed. The graphs Fig.2.9a and Fig.2.9b show that the imploding electron velocity increases when the small disturbance inside PVR remains constant. However, this increasing velocity is ceased suddenly at convergence point, see at Fig.2.9a and Fig.2.9b when $\vec{r} \rightarrow 0$ during implosion and $\vec{r} \rightarrow \infty$ during explosion.

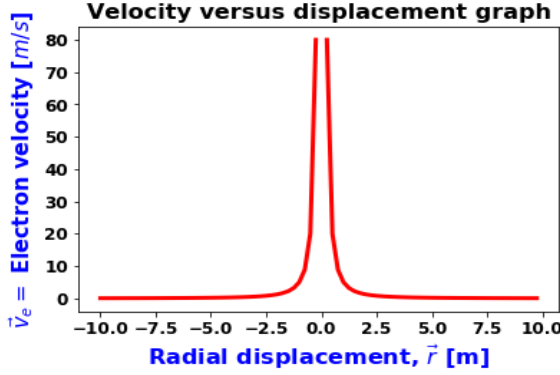


Fig.2.9a Singularity of imploding velocity at convergence region as $\vec{r} \rightarrow 0$

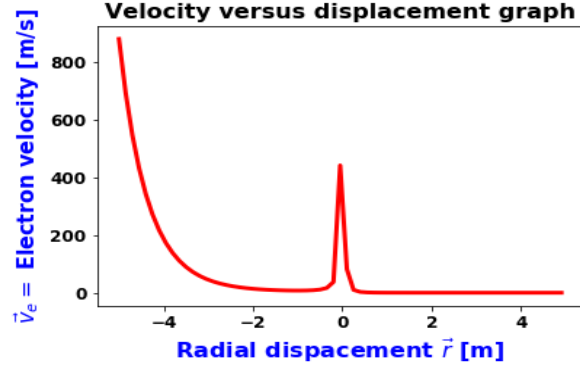


Fig.2.9b Imploding velocity of collapsing electron decreases rapidly than exploding velocity.

From Fig.2.9 we understand that the collapsing velocity is ceased at convergence point. The imploding electron current coupled with the dynamic boundary layer is verified from Eq.(2.55b) as follow for purpose of predicting its numerical analysis during collapsing. The collapsing process is instantaneous and the steady electron current is described in terms of dimensionless parameter β and α so as to compute its predicted value in computational purpose. The collapsing distance is in comparison with the thickness of collapsing oscillating electron beam.

$$\vec{J}_e = -en_e c_s \left(\frac{\beta}{\beta - \alpha} \right)^2 \hat{r} \quad (2.55b)$$

Where, $r_0 = \beta l_e$, and $r = \alpha l_e$ for $\beta \geq \alpha$ implies, β and α are dimensionless parameters. When the PVR is collapsing with constant electron number density of dynamic boundary, the collapsing inertial velocity increases and reaches its maximum limit followed by abrupt drop. The displacement $\vec{r}$ is traveled by electron beam layer followed by surrounding ambient plasma from initial boundary of PVR to convergence region associated with imploding shock waves.

Generally, the collapsing electron current is inversely proportional to radius of collapsing dynamic PVR at steady state situation. Here, we understand that in this condition, the collapsing or growing electron current is inversely proportional to square of radius of PVR, $\vec{J}_e \propto 1/r^2$ in high conductivity plasma fluid, see Eqs.(2.54a) and (2.55a) and (2.55b).

Case 2: If $\vec{v}_e = \vec{v}_0$ electron inertial velocity of collapsing PVR is constant, heat has not been generating along the collapsing path. This shows that adiabatic compression of electron plasma fluid inside the collapsing local region. The compression of electron beam depends on the ratio of initial radius of PVR to final position radius of PVR during collapsing process that suffices $|\vec{r}| \leq |\vec{r}_0|$ condition, the electron beam density is described by Eq.(2.56a).

$$n_e = n_0 \left(\frac{|\vec{r}_0|}{|\vec{r}|} \right)^2 \quad (2.56a)$$

Only the moving shock changes the behavior of neutral plasma particles inside PVR. When continuous trains of shock fronts are passing through neutral high conductivity plasma, the neutral plasma becomes ionized. If $\vec{v}_e$ is constant of time, in steady state situation for $\vec{v}_e \gg \vec{v}_i$ in isothermal condition before they are accelerated inside PVR electrons enter to electron runaway condition. The collapsing electron current is verified from Eq.(2.56a) and yields Eq.(2.56b).

$$\vec{J}_e = -en_0 \left(\frac{\beta}{\beta - \alpha} \right)^2 \vec{v}_e \quad (2.56b)$$

Cur of collapsing velocity field coupled with radial imploding moving shock can be specified as,

$$\vec{\nabla} \times \vec{v} = \frac{1}{r} \frac{1}{\sin \theta} \frac{\partial v_r}{\partial \theta} \hat{\theta} - \frac{1}{r} \frac{\partial v_r}{\partial \theta} \hat{\phi} \quad (2.57)$$

the collapsing radial velocity field is functions of space and time, $\vec{v} \approx \vec{v}_r(r, \theta, \phi, t)$ at the local isolated region specified with negative dynamic pressure. This Eq.(2.57) is corresponds to irrotational plasma fluid of single particle since we have, $\vec{\nabla} \times \vec{v} = 0$, the radial velocity field only radial space and time dependent. Until the fast imploding plasma fluid reaches the *stagnation region*, it has incompressible behavior. It is a good assumption that electron beam velocity field is converged ($\vec{\nabla} \cdot \vec{v} \neq 0$), at the stagnation region during collapsing time before reflection. Density profile of the fast moving separated electron plasma associated with normal imploding primary shock surface remains constant instantly. We have $m_i \gg m_e$ and $m_n \geq m_i$ and for fast

moving electron $v_e \gg v_i$ and $v_e \gg v_n$ if we put electrons, ions and neutrals at the same temperature in vacuum, electrons are diffusing faster, due to their lighter mass supported by space-time gradient of functions. For steady state situation that suffice isothermal condition, the collapsing electron velocity field associated with ions and neutrals can be obtained from Eq.(2.50) far away from convergence point for collision-less flow.

$$\vec{v}_j = c_{sj} \left[2 + 2 \ln \left(\frac{n_j}{n_0} \right) + \frac{2q_j \phi_s}{kT_j} \right]^{1/2} \hat{r} \quad (2.58a)$$

The radially imploding velocity electron beam followed by ambient plasma is controlled by the strength of VP at center of convergence point in the absence of magnetic field.

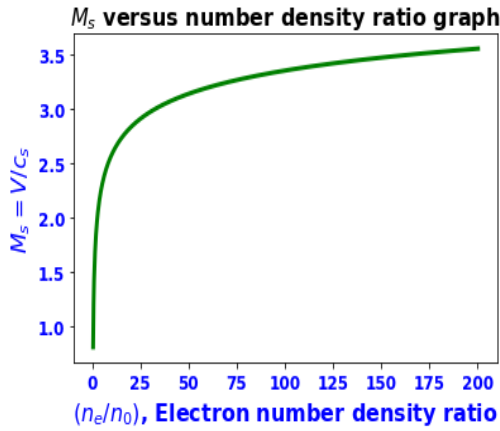


Fig.2.10a Mach number versus electron number density

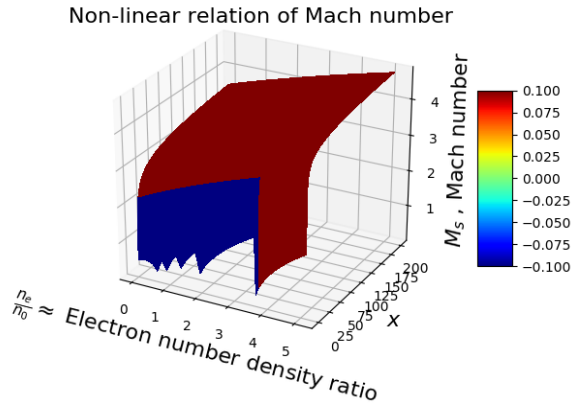


Fig.2.10b Mach number versus electron number density and energy density ratio

The graph of Fig.2.10a and Fig.2.10b show that the relationship between shock Mach number and electron density ratio and energy density ratio across shock surface. The variable 'x' in Fig.2.10b represents the ratio of electrical energy to thermal energy. Plasma particles are suddenly diffusing from high density region to low density region. For spontaneous electron diffusion, $n_e \gg n_i$ of in isothermal situation, velocity of electron is obtained below.

$$\vec{v}_e = c_{se} \left[2 + 2 \ln \left(\frac{n_e}{n_0} \right) + 2 \frac{m_e}{m_i} \ln \left(\frac{n_i}{n_0} \right) - \frac{2e\phi_s}{kT} \right]^{1/2} \hat{r} \quad (2.58b)$$

For simple hydrogen ion with no further nuclear reaction and no radiation process, the spontaneous corresponding collapsing electron current is given by Eq.(2.58c).

$$\vec{J}_e = -en_e c_{se} \left[2 + 2 \ln \left(\frac{n_e}{n_0} \right) + 2 \frac{m_e}{m_i} \ln \left(\frac{n_i}{n_0} \right) - \frac{2e\phi_s}{kT} \right]^{1/2} \hat{r} \quad (2.58c)$$

Initially, the average inertial velocity inside local region is assumed to be vanished because plasma particles move in random direction. However, due to a sudden formation of negative dynamic pressure, the motion of plasma element is aligned towards the convergence region. For completely ionized plasma, the collapsing process is in steady state situation instantly. Neglecting neutrals inside PVR, if electrons and ions are at the same temperature, $T_e = T_i = T(r)$, for non-isothermal condition but heat is not dissipated, initial thermal velocity is much lower than final thermal velocity, the low density plasma is in adiabatic heating. If $(T - T_0) \gg 1$ and $m_i \gg m_e$ in the absence of external force, initial velocity of inflowing plasma element is given by the initial thermal velocity. The condition $(T - T_0) \gg 1$ shows that the temperature gradient is so high at the dynamic boundary of PVR. The adiabatic propagating heat is generated at the dynamic boundary of electron shell due to presence of continuous shock wave fronts in steady state situation. We suggest that once heat is generated due to continuous passage of shock wave fronts, the generated heat does not lose. Thus, the momentary shock front is a mechanism for violation of adiabatic heating mechanism in an instant of time at the isolated local system.

Generally, we have investigated that the collapsing of PVR generates heat non-adiabatically at its dynamic boundary when the imploding plasma is at constant velocity. The process is very fast during the evolution of PVR in steady state and its distraction in connection with condition of neglecting collisions, viscosity and thermal conduction. The corresponding agent that triggers non-adiabatic heat production is collision-less shock waves. The thickness of collision-less shock is expected as much less than the collision mean free path. The collision mean free path of collapsing plasma particles are approximated by the characteristic length of the local isolated system (i.e., initial radius of PVR). If plasma is completely ionized at the collapsing boundary of PVR, radiation pressure may influence the local isolated system.

The local isolated system remains in isothermal condition for ideal ionized hydrogen gas to conduct adiabatic heating behind the imploding moving shock fronts. If plasma particles are accelerating across the moving shock fronts non-thermally, the moving shock does not generate heat. Particles crossing the moving shock fronts gain enough kinetic energy from shock wave directly without dissipation of heat energy. The electron number density and ion number density

at the initial boundary of PVR are the same; $n_{e0} = n_{i0} = n_0$ coupled with the surrounding plasma that suffices the quasi-neutrality condition. The inertial velocity of $\vec{v} = \vec{v}_r$ is radial inertial velocity of imploding plasma fluid. When the size of PVR diminishes, its back ground density also decreases and the field energy is becoming dominant before collapsing. The developing surface electrostatic potential is due to instantaneous strong charge separation process at the dynamic boundary. If we assume that only the surface induced electrostatic potential influences the PVR, the electron beam sheet, which is surrounded by high density ambient plasma from outside, gives the Lagrangian form of Eq.(2.50) for electrons and ions separately. The collapsing acceleration of plasma elements in non-steady state of collision-less and non-viscous plasma element also given by Eq.(2.59) that suffices the electron runaway region.

$$\vec{a}_j = \left[\frac{qn_j}{\rho_j} \frac{\partial \phi}{\partial r} + \frac{kn_j}{\rho_j} \frac{\partial T_j}{\partial r} + \frac{c_{sj}^2}{\gamma n_j} \frac{\partial n_j}{\partial r} \right] \hat{r} \quad (2.59)$$

The electron temperature is assumed to be constant of position at characteristic distance of charge separation of electron beam is denoted by l_e behind the first shock front. When inner dynamic boundary surface of the cavity is completely dominated by electron beam before collapsing, hot electrons are completely separated from ions at a distance l_e .

However, density gradient is steep $\partial n_e / \partial r \approx \partial n_e / \partial l_e \neq 0$, for $\delta r = l_e$ at the isothermal scale height of electron beam. The instantaneous surface electrostatic field of the local system is quickly dominated by energy gained from shock surfaces and the PVR continuously sucks surrounding plasma and finally collapsed suddenly. The electron temperature gradient and density gradient are so steep, anomalous plasma resistivity is developed due to non-linear nature of independent variables that provide overloading of phase waves. At the stagnation region near the center of convergence point, collision and viscosity play a crucial role.

2.9.3. Collapsing dynamic PVR coupled with plasma collision and viscosity

When electron-ion collision plays a crucial role during collapsing of PVR at convergence point, some amounts of mass elements penetrate the dynamic boundary. The equation of motion becomes non-linear in the presence of plasma *viscosity* and *collision* in connection with steep velocity gradient and temperature gradient. When the imploding plasma fluid has inertial

velocity field higher than thermal plasma velocity in aligned motion, it is considered as incompressible plasma.

We consider only radial viscosity force and radial velocity field are effective because of the assumption of spherical symmetry at convergence region for the sake of simplicity. Thus, the local acceleration of collapsing PVR is obtained by neglecting the second order term of momentum equation; we get Eq.(2.60) that describes inertial acceleration.

$$\vec{a}_j = \left(\frac{\partial}{\partial r} \left(\frac{v_j^2}{2} \right) + \frac{qn_j}{\rho_j} \frac{\partial \phi}{\partial r} + \frac{kn_j}{\rho_j} \frac{\partial T_j}{\partial r} + \frac{kT_j}{\rho_j} \frac{\partial n_j}{\partial r} - v v_j + \mu \frac{2}{r^2} \left[v_j + r \frac{\partial v_j}{\partial r} + \frac{1}{2} \cot \theta \frac{\partial v_j}{\partial \theta} \right] \right) \hat{r} \quad (2.60)$$

The viscosity term introduce the *non-linear effects* of flowing high conductivity plasma during collapsing process of PVR leads to producing shock phenomena. The linearized form of collapsing acceleration of non-rotating PVR is obtained by assuming the first derivative of velocity field with respects space coordinate is constant. We consider only electron-ion collision and neglect neutrals to minimize complexity here. The fast imploding electron collides with slowly moving ion and neutral which move at lower velocity in front of electrons in the same direction. Collapsing the electron current layer is expected as collision-less incompressible and non-viscous hot electron beam for the sake of simplicity.

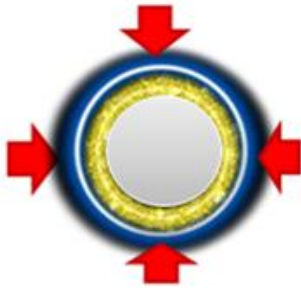


Fig 2.11 Collapsing cavity of PVR

When the characteristic length travelled by electron beam layer radially inward $|\delta \vec{r}| = \delta r = \alpha l_e$, where, α , positive real number and τ also characteristic collapsing time of electron beam. The quantity which is written as $\vec{r} = \vec{r}_0 - \delta \vec{r}$ in Eq.(2.60) leads to negative velocity. If we take velocity is negative quantity, from Eq.(2.50), the electron velocity $\vec{v}_e$ could be replaced by $-\vec{u}_e$ so as to indicate direction of flow, in equation of motion. Let $\delta r = \alpha l_e(t)$ and $r_0 = \beta l_e(t)$ during collapsing dynamic boundary, a radial distance of $\delta \vec{r} = -\vec{r}_0$ for complete collapsing of cavity. When the dynamic boundary travels a distance r_0 it would reach at convergence point. If we consider the boundary were fixed initially and it moved with radial velocity field, we assumed that $r_0(t) = \beta l_e(t)$ using $v_r = v_e \pm v_i = -u_j$, Eq.(2.60) can be expressed as follow.

$$\frac{du_j}{dt} = -\frac{1}{(\beta-\alpha)} \left[\frac{qn_j}{\rho_j} \frac{\partial \phi}{\partial l_e} + \frac{kn_j}{\rho_j} \frac{\partial T_j}{\partial l_e} + \frac{kT_j}{\rho_j} \frac{\partial n_j}{\partial l_e} \right] - \nu u_j + \frac{2\mu}{l_e(\beta-\alpha)^2} \left[\frac{\partial u_j}{\partial l_e} + \frac{\cot \theta}{2(\beta-\alpha)l_e} \frac{\partial u_j}{\partial \theta} - \frac{u_j}{(\beta-\alpha)l_e} \right] \quad (2.61)$$

The dimensionless parameter, β , is the upper limit of value of α during collapse process of PVR at convergence point and the lower limit value α is determined at initial position boundary of PVR before collapsing is started. The value of α is vanished at initial dynamic boundary surface. If we assumed that the boundary of PVR is nearly static, the value of $\alpha \ll \beta$ shows slow collapsing and Eq.(2.61) becomes as follow.

$$\frac{du_j}{dt} = -\frac{1}{\beta} \left[\frac{qn_j}{\rho_j} \frac{\partial \phi}{\partial l_e} + \frac{kn_j}{\rho_j} \frac{\partial T_j}{\partial l_e} + \frac{kT_j}{\rho_j} \frac{\partial n_j}{\partial l_e} \right] - \nu u_j + \frac{2\mu}{\beta^2 l_e} \left[\frac{\partial u_j}{\partial l_e} - \frac{\cot \theta}{2l_e} \frac{\partial u_j}{\partial \theta} - \frac{u_j}{l_e} \right] \quad (2.62a)$$

Imploding ions and neutrals are accelerated at dynamic boundary of PVR while imploding electrons are decelerated at dynamic boundary of PVR, so, there could be a sink or singularity at convergence point of PVR and the parameter β is always remains constant. The accelerated charged particles have no time to settle at boundary of PVR, suddenly and they are accelerated. However, if no radiation of charged particle is considered at dynamic boundary, velocity of imploding becomes time independent. Thus, Eq.(2.62a) is treated in steady state situation

$$\left[\frac{qn_j}{\rho_j} \frac{\partial \phi}{\partial l_e} + \frac{kn_j}{\rho_j} \frac{\partial T_j}{\partial l_e} + \frac{kT_j}{\rho_j} \frac{\partial n_j}{\partial l_e} \right] = -\nu \beta u_j + \frac{2\mu}{\beta l_e} \left[\frac{\partial u_j}{\partial l_e} - \frac{\cot \theta}{2l_e} \frac{\partial u_j}{\partial \theta} - \frac{u_j}{l_e} \right] \quad (2.62b)$$

At initial condition when $\alpha = 0$ and the PVR were static and collapsing process could not be started $du_j/dt = 0$ and imploding velocity is constant of time. The constant coefficients ν and μ are electron-ion collision frequency and kinetic viscosity coefficient of incompressible high conductivity imploding plasma. The separated equation of motion independently for electrons, ion and neutrals of fast flowing plasma in case of non-linearized equation of motion becomes so complex. In steady state condition the electrostatic potential of electron cloud which affects charged particles inside PVR is described by Eq.(2.62a). The intense electric field at steady state is generated by collapsing dynamical boundary of PVR, that is verified from Eq.(2.62b) of collapsing or growing PVR.

$$\vec{E} = -\frac{m_e}{e} \left[\frac{k}{m_e} \frac{\partial T_e}{\partial l_e} + \frac{kT_e}{m_e n_e} \frac{\partial n_e}{\partial l_e} + \beta^2 \nu u_e - \frac{2\mu}{l_e} \left[\frac{\partial u_e}{\partial l_e} + \frac{\cot \theta}{2l_e} \frac{\partial u_e}{\partial \theta} - \frac{u_e}{l_e} \right] \right] \hat{r} \quad (2.63)$$

The electron density distribution increases at convergence region during collapsing process while ion number density increases near electron beam boundary layer. However, the radial moving out ions are engulfed by imploding shock waves at the electron beam layer. The engulfed ions have not waiting time there, since they have gained enough kinetic energy from shock surface, they are accelerated suddenly and leave the electron beam region quickly.

2.9.4. Evolution of electrostatic potential inside dynamic PVR

Let consider PVR is surrounded by high density imploding ambient plasma fluids. The PVR plasma is assumed to be at thermal equilibrium condition relatively, before electron runaway or ion runaway condition is fulfilled. When the imploding ambient high density plasma diffuses through PVR, electrons and ions are accelerated near the boundary region. Let the density of plasma inside PVR is surrounded by high density plasma are given by ρ_{in} and ρ_{ex} respectively. Assume $\rho_{in} \ll \rho_{ex}$ that the collapsing PVR is surrounded by high density double current layers followed by ambient dense plasma. The inner surface electron charge density of collapsing electron beam layer is also given by ρ_s produces strong electrostatic potential, ϕ , inside PVR. The imploding electron current layer is an oscillating electron beam due to effects of moving ions behind of them. The strong pressure difference between center of convergence and dynamic boundary surface is arisen due to the following cases. These are difference in plasma density and plasma temperature between the convergence point and dynamic boundary layer. As soon as a negative dynamic pressure at convergence point is developed, the local cavity will suddenly collapsed due to strong VP of convergence point. Velocity of shock surface is much higher than acoustic sound speed $\vec{V} \gg \vec{c}_s$ and much less than speed of light, $V \ll c$ during collapsing of PVR where c_s is speed of sound and also c is speed of light. The electron and ion distribution inside PVR under the influence of surface electrostatic potential can be described in Max-wellian distribution before collapsing.

$$n_e(x, t) = n_0 e^{-e\phi(x,t)/k_B T_e(x,t)} \quad (2.64a)$$

$$n_i(x, t) = n_0 e^{ze\phi(x,t)/k_B T_i(x,t)} \quad (2.64b)$$

Where $\vec{x}$ is measured from dynamic surface of electron beam to an arbitrary point inside PVR or outside of PVR. It is expected that mass density of electron beam layer is much higher than

plasma density of PVR, $\rho_s \gg \rho_{in}$ thus, negative pressure is developed at convergence point. Inside the cavity, position where $\vec{r}(x, t)$ located at position of $\vec{r} = \vec{r}_0 - \vec{x}$ thus $\vec{x} = \vec{r}_0 - \vec{r}$ where the position $\vec{r}$ is measured from center of convergence to the interest point and $\vec{r}_0$ is the maximum radius of PVR before collapsing has been started. The function $U(x, t)$ represents the electrostatic potential energy at position of $\vec{r}$ measured from center of convergence. At a displacement $\vec{x}$ from surface electron charges, ρ_s , electron and positive ion will have potential energy of $q\phi(x, t)$ at instant of time where $q = -e$ for electron and $q = ze$ for ion and the value of z is positive real number.

$$U(x, t) = ze\phi(x, t) \quad (2.65a)$$

$$U(x, t) = -e\phi(x, t) \quad (2.65b)$$

The surface electrostatic potential inside PVR is assumed as negative electrostatic potential, $-\phi$, surface induced electrostatic potential inside PVR. At equilibrium the density of ion and electron is equal, $n_i = n_e = n_0$ and the instant ion density and electron density are given by Eqs.(2.64a) and (2.64b) inside PVR. Let assume that time independent isothermal temperature, $T(x) = T$ inside PVR. The Eqs.(2.64a) and (2.64b) show that electrons are repealed to center of PVR while ions are attracted to nearby dynamic boundary layer respectively. The total charge density at a distance x from dynamic boundary surface, the electron number distribution and ion number distribution inside PVR is defined by summing Eqs.(2.64a) and (2.64b). We consider the limit case in which the electrostatic potential is small or temperature is high. Using the approximation of $e^{-ze\phi/k_B T_i} = 1 - ze\phi/k_B T_i$, and, $e^{e\phi/k_B T_e} = 1 + e\phi/k_B T_e$ for $k_B T_e \gg e\phi$ at large distance from dynamic boundary inside the cavity. For single charge of different electron and ion temperature $z = 1$ for simple hydrogen plasma, the Poisson's equation inside low density region is described by Eq.(2.66).

$$\frac{\partial^2 \phi(x, t)}{\partial x^2} = \frac{1}{\lambda_D^2} \phi(x, t) \quad (2.66)$$

The quasi-neutrality condition, $n_{0i} = n_{0e} = n_0$ beyond the Debye length for different temperatures of electron and ion inside PVR is given by Eq.(2.67).

$$\lambda_D = \left(\frac{\epsilon_0}{e^2 n_0} \frac{k_B T_i T_e}{(T_i + T_e)} \right)^{1/2} \quad (2.67)$$

If we assume that $x \ll \lambda_D$ the potential coincides with Coulomb potential in free space, while $x \gg \lambda_D$, potential is much less because of the plasma shielding effect. If we assume that the mass ratio tends to infinity, $m_i/m_e \rightarrow \infty$, so that the ions do not move anymore and just form a uniform background of positive charge around the probe charge, so called cold ion approximation. The space charge density is defined by Eq.(2.68) for non-radiative steady PVR surrounded by thin dense electron cloud layer and using the idea of $e\phi/k_B T_e < 1$ for Coulomb force is smaller than thermal force for ρ total charge density inside the cavity.

$$\rho = en \left[z - \frac{e\phi}{k_B T_e} \right] \quad (2.68)$$

The graphs of Fig.2.12a and Fig.2.12b describe the exponential variation of time dependent electrostatic potential inside collapsing or growing PVR of high conductivity plasma medium.

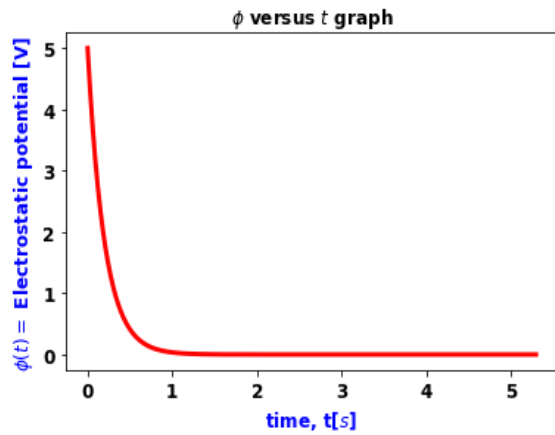


Fig.2.12a Time dependent ϕ for collapsing cavity

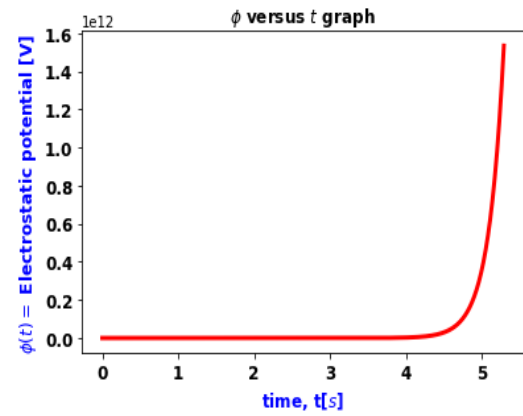


Fig.2.12b Time dependent ϕ for growing cavity

The value of instantaneous surface electrostatic potential, ϕ , inside PVR is assumed to be negative. Let us assume that electrons and ions are at the same temperature inside PVR in the absence of external force except the negative dynamic pressure. The electric potential decreases by a factor of $1/e$ each time the distance by λ_D , is the Debye length of electron layer which is surrounded by oscillating ions at distance of $r_0 - \lambda_D$ that is outer pre-electric current inside PVR. If we know the surface charge density ρ_s of electron current layer; we can specify $E_r = E_r(x=0) = E_r(0)$ is radial electric field of inner surface current at dynamic boundary layer. The radial instantaneous electric field arises due to steep gradient of surface electrostatic potential, $\phi(x, t)$ which is obtained by solving Poisson's Eq.(2.66) inside PVR.

$$\phi(x, t) = \phi_0 e^{-Vt/\lambda_D} \quad (2.69)$$

The surface electrostatic potential of PVR is determined by the ratio of shock front velocity and Debye wave length, V/λ_D during collapsing. When the value of Debye length is varying during collapsing of PVR even if the collapsing velocity is remains constant, the surface induced electrostatic potential is specified by its non-linear behavior, see Fig.2.13a and Fig.2.13b.

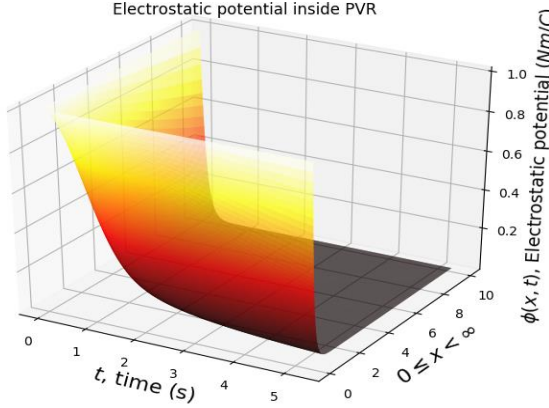


Fig.2.13a Imploding shock induced electrostatic potential

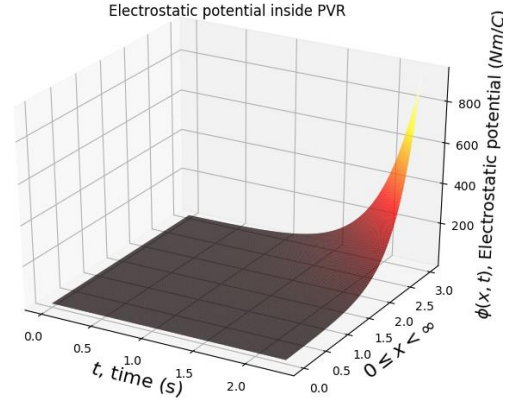


Fig.2.13b, Exploding shock induced electrostatic potential

In Fig.2.13a and Fig.2.13b , the variable $x \approx V/\lambda_D$ and Fig.2.13a and Fig.2.13b shows that the non-linear nature of electrostatic potential in case of implosion and explosion of surface electron beam of dynamic boundary of PVR respectively. The graph of Fig.2.13a and Fig.2.13b tells that the non-linear electrostatic potential inside PVR decays or grows exponentially. The quantity of $\phi_0 = \rho_s \lambda_D / \epsilon_0$ is surface electrostatic potential at initial position and V is constant shock wave velocity. If electron number density $n_e > 5.44 \times 10^{-4} n_i$ is coupled with shock wave fronts, the quasi-neutrality principle is strongly violated due to instantaneous strong charge separation that leads to introduction of electron runaway condition or ion runaway condition inside PVR. Generally, the sudden collapsing velocity of PVR is approximated by the velocity of the imploding strong shock wave fronts in non-relativistic sense. This generates strong point explosion inside the high conductivity continuum medium. The total developing electrostatic potential energy density inside PVR at a distance x away from surface dynamic boundary is approximated by Eq.(2.70a) described in terms of electron Debye length.

$$u(x) = -\frac{1}{2} \epsilon_0 \phi^2 \left[\frac{1}{\lambda_{Di}^2} + \frac{1}{\lambda_{De}^2} \right] \quad (2.70a)$$

Where λ_{Di} and λ_{De} are Debye length for ion and electron respectively. Additional shock surface is created inside the PVR due to sudden change of state or an abrupt acceleration of hot electrons and ions under the electron *runaway* and ion *runaway* phenomena. When the PVR is shrunk a distance of $\delta\vec{r} = -\alpha l_e \hat{r}$, another additional radial current is created inside the PVR before surface electron current collapse. However, the average current of the local system may be zero except at electron beam dynamic boundary layer if and only if exploding of ion flux would be balanced by imploding electron flux simultaneously. When we assumed the collapsing PVR is in isothermal condition, the collapsing radial velocity field of electron dynamic boundary layer is obtained by integrating over the travelled radial distance in the absence of collision and viscosity before electron enters to stagnation region is given by Eq. (2.71b) equivalent to Eq.(2.58a).

$$\vec{v}_e = (2)^{1/2} c_{se} \left[\frac{1}{2} + \ln \left(\frac{n_e}{n_0} \right) - \frac{e\phi_s}{kT_e} \right]^{1/2} \hat{r} \quad (2.71b)$$

At initial state inside PVR, plasma is at thermal equilibrium and the initial plasma density is $n_0 = n_{0e} + n_{0i} = 2n_0$, if electron and ion are at the same temperature $T = T_e \approx T_i$ during collapsing. Imploding ions form temporary ion beam layer behind the moving electron beam is created. Thus, temporary double current sheet is created behind dynamic boundary of PVR of hot plasma. When the temporary ion beam is following the imploding electron beam, the undisturbing ions have velocity field of $\vec{v}_i$ in the absence of *collision* and *viscosity* expressed by Eq.(2.71c) is equivalent to Eq.(2.28b).

$$\vec{v}_i = (2)^{1/2} c_{si} \left[\frac{1}{2} + \ln \left(\frac{n_i}{n_0} \right) + \frac{ze\phi}{kT_i} \right]^{1/2} \hat{r} \quad (2.71c)$$

In the absence of external forces, initial velocity of ion is specified by its initial thermal velocity. Since ions are moving towards dynamic boundary layer while electrons are moving towards center of convergence region, strong body current is created inside PVR if the surface electrostatic potential is dominant over negative dynamic pressure before imploding shock waves. The initial velocity of electron and ion is given by $v_{e0}^2 = kT_e/m_e$ and $v_{i0}^2 = kT_e/m_i$, at PVR for isothermal condition in the absence of external force. Inside PVR electrons are migrating to the center of convergence due to existence of *negative pressure* and electron *runaway* condition. Let we assume that electron velocity inside the perturbing PVR is approximately the same as velocity of imploding electron beam. In steady state situation, the

equation of motion inside PVR is specified by instantaneous electric field, negative pressure and generated shock waves see Eq.(2.50).

A. Hot electron fluids passing through the immobile ion fluid

The forces exerted by surface electrostatic potential and negative dynamic pressure gradient on electron inside PVR directs radially inwards in steady state situation for incompressible ideal electron plasma fluid. Magnitude of instant electrostatic field and electron distribution at PVR if velocity is independent of position are given by,

$$E_r = -\frac{1}{en_e} \frac{\partial p_e}{\partial r} \quad (2.72a)$$

When electrons are in isothermal condition inside PVR, electron number density distribution is specified by Eq.(2.72b).

$$n_e = n_0 e^{(e\phi/kT_e)} \quad (2.72b)$$

B. Considering motion of hot ions inside the PVR

Equation motion of charged particles inside PVR is determined by intense electrostatic potential when velocity gradient is vanishing with incompressible ions plasma is considered; the electric force exerted on ions against the negative ions' dynamic pressure is given by

$$E_r = \frac{1}{zen_i} \frac{\partial p_i}{\partial r} \quad (2.73a)$$

If the hot ions are in isothermal condition, the ion number density distribution is expressed as

$$n_i = n_0 e^{(-e\phi/kT_i)} \quad (2.73b)$$

The body electron current inside PVR before shock wave propagation during the evolution of PVR for $\vec{v}_e \gg \vec{v}_i$ using Eq.(2.71a) obtained as follow.

$$\vec{j}_e = -n_e e c_{se} \left[1 + 2 \ln \left(\frac{n_e}{n_0} \right) - \frac{2e\phi_s}{kT_e} \right]^{1/2} \hat{r} \quad (2.74a)$$

If motion of ion has a significant effect on the evolution of PVR, ion body current is obtained. The sudden jump in pressure generates a strong electron and ion discharging process through

high conductivity medium after compacting of the convergence region. When ion moves in radial direction in the absence of collision and viscosity, the ion body current during evolution of PVR is described by Eq.(2.74b).

$$\vec{j}_i = n_i z e c_{si} \left[1 + 2 \ln \left(\frac{n_i}{n_0} \right) + \frac{2ze\phi_s}{kT_i} \right]^{1/2} \hat{r} \quad (2.74b)$$

When $e\phi \leq kT_i$ is fulfilled, ions diffuse to the center of convergence point and would be reflected back at the stagnation point with velocity of twice their imploding velocity. If, $e\phi > kT_i$, the surface electrostatic potential is more effective than negative mechanical pressure because of steep gradient of electrostatic potential. Most ions are moving towards the electrons dynamic boundary layer against negative pressure gradient and engulfed by imploding strong shock waves. Thus, the total body current inside low density region can be defined by Eq.(2.74a) that combines (2.74b) and (2.71b) together in its expression.

$$\vec{j} = z_i n_j q_j c_{sj} \left[1 + 2 \ln \left(\frac{n_j}{n_0} \right) + \frac{2q_j \phi_s}{kT_j} \right]^{1/2} \hat{r} \quad (2.75a)$$

The parameter $z_i = \pm 1$ for electron and single ion and the subscript $j = 1, 2$ represents for electron and ion species and, $z = -1$, for electron species and $z = 1$ also for hydrogen ion. The surface electrostatic potential ϕ_s is determined by the boundary charge density of electron beam followed by temporary ion beam [201, 202]. When there could not be a change in plasma density flux inside the PVR, electrons and ions are oscillating infinitely in the isolated local system. No electrons could move out from PVR due to effects of electric field or electrons could reflect back inside the cavity of moving electron beam layer if they are not energetic enough. If surface electrostatic potential is strong enough to push light electrons, only ions are engulfed more by the imploding dynamic boundary of PVR associated with strong imploding shock fronts. In reality, shocked electrons and ions may be injected in to PVR from nearby outside high density region. Here, we assumed that electrons and ions flux are conserved at dynamic boundary of PVR. The number of electrons and ions move out from PVR may be balanced by number of electrons and ions injected in to PVR if and only if mass flux passing through dynamic boundary is conserved.

The mechanism for electrons and ions to inject in to PVR is expected to be shock waves behind of boundary layer and electrostatic potential which reflects electrons and ions of low

inertial velocity and generation of high negative dynamic pressure or pressure singularity at convergence point or line or plane inside PVR. The radial body electric current in steady state for constant electron and ion density inside the PVR in case of $q_j\phi \leq kT_j$ and during evolution of PVR is defined by Eq.(2.75b) before propagation of imploding shock waves.

$$\vec{j} = z_i n_j q_j c_{sj} \left[1 + \frac{q_j \phi}{kT_j} \right] \hat{r} \quad (2.75b)$$

However, the body current inside PVR is perturbed as VP is developed at convergence point. Generally, inside PVR, electron current at center of convergence is collapsed. Inside the PVR, we get a critical body current where the electrostatic potential is balanced by the velocity potential due to dynamic pressure, $q_j\phi/kT_j = 1$, at isothermal condition, the critical current is verified in the absence of plasma collision and viscosity that is described by Eq.(2.76a).

$$\vec{j} = z_i n_j q_j c_{sj} \left[3 + 2 \ln \left(\frac{n_j}{n_0} \right) \right]^{1/2} \hat{r} \quad (2.76a)$$

If electron and ion density is in isothermal plasma diffusing process in radial direction, the critical body current is approximated by Eq.(2.76b) in terms of plasma acoustic speed.

$$\vec{j} = \sqrt{3} z_i n_j q_j c_{sj} \hat{r} \quad (2.76b)$$

Neutral particles are accelerated due to negative dynamic pressure in connection with imploding strong moving shock wave and reflecting exploding moving shocks in non-relativistic situation.

2.10. Oscillation of Imploding Electron Current of Dynamic Boundary

The characteristic of imploding dynamic boundary of PVR is coupled with the imploding strong shock waves toward convergence point. The collapsing velocity of radial electron current is the same with velocity of imploding strong shock wave fronts. When ions are injected in to electron beam, they gain enough kinetic energy and are accelerated quickly out of electron beam layer due to complex shock waves. This indicates that electrons are completely separated from ions and uniformly populated at dynamic boundary of PVR. However, the surrounding plasma pressure pushes or squeezes the cavity from outside. Due to strong VP of convergence point, the dynamic boundary surface which is interacting with surrounding ambient plasma is pulled. When the intense current sheet is collapsed, a huge amount of energy is liberated due to high

discharging electrons and ions that develop anomalous resistivity at convergence point. The released energy may be in the form of heat energy, kinetic energy and radiation energy and magnetic energy *see* in chapter 2.

The electron acceleration is arisen due to formation electric field at the inner surface of dynamic boundary, steep velocity gradient inside the PVR and generation of successive shock wave fronts. However, imploding ions behind of the separated electron beam shell may develop other instantaneous induced electric fields outside the PVR at a distance l_i behind of the separated electron layer. The inner electron boundary layer of PVR is in fast harmonic oscillation mode. The PVR dynamic is treated using Poisson's equation for oscillating electron plasma fluid near the stagnation point as $\vec{r}_0 \approx -\delta\vec{r}$ is the maximum travelled distance by electron shell and $\phi(r, t)$ and $n(r, t)$ at instant of time. The Poisson's equation for collapsing electron spherical shell coupled with volume density of PVR as electrostatic force is dominant over other forces is described by Eq.(2.77).

$$\frac{\partial^2 \phi}{\partial r^2} + \frac{2}{r} \frac{\partial \phi}{\partial r} = \frac{en_e}{\epsilon_0} \quad (2.77)$$

Here, we assumed that the convergence point is filled up by oscillating supper hot electrons and all ions are engulfed by imploding shock waves instantly. The shocked ions fluid exerts a dynamic pressure over the compacted electron of converging region. At this condition near the stagnation region before plasma elements instantly stops flowing, the small cavity is characterized by high gradient of instantaneous electrostatic potential associated with fast moving shock surfaces. Near the stagnation region the electrostatic potential is expected as dominant over other mechanical potentials before collapse. When the surface electric force is completely dominant over all kinds of forces at PVR, using Eqs.(2.50) and (2.76b) yields the non-linear second order equation in steady state situation given by Eq.(2.78).

$$\left(\frac{\partial v_j}{\partial r}\right)^2 + v_j \frac{\partial^2 v_j}{\partial r^2} + \frac{1}{r} \frac{\partial}{\partial r} (v_j^2) = \omega_{pe}^2 \quad (2.78)$$

By linearizing Eq.(2.78) and assuming the electron beam oscillation frequency is constant of position, collapsing velocity of electron beam is verified from Eq.(2.78) and solution is expressed by Eq.(2.79a) that describes the collapsing velocity of dynamic boundary of local cavity in the $\min_{r \rightarrow \lambda_e} r = \lambda_e$ for thickness of electron dynamic boundary layer.

$$\vec{v}_e = \left[c_{se}^2 + \frac{1}{2} \omega_{pe}^2 \lambda_e^2 + c \right]^{1/2} \hat{r} \quad (2.79a)$$

The constant of integration c is determined using boundary condition and initial state of collapsing or growing PVR. For spontaneous collapse of PVR, the collapsing velocity is approximated by electron imploding velocity given by Eq.(2.79b) for force exerted by VP is stronger than the thermal kinetic force at initial state.

$$\vec{v}_e \approx 79.75 l_e n_e^{1/2} \hat{r} \text{ s}^{-1} \quad (2.79b)$$

Magnitude of imploding velocity of oscillating electron beam is proportional to square root of surface electron number density, $v_e \propto n_e^{1/2}$ and the oscillation frequency of surface electron beam is approximated by $\omega_{pe} \approx 56.4 n_e^{1/2} \text{ s}^{-1}$ during collapsing of PVR. Generally solving the non-linear Eq.(2.78) for radial imploding velocity analytically is so complex. The non-linear equation, Eq.(2.78) introduces formation of fast moving normal shock waves at the oscillating surface of electron beam as well as inside PVR. When the radial inflowing velocity due to electrostatic potential is independent of position, the radial acceleration of local electron plasma element is obtained from Eq.(2.76b) and Eq.(2.50) in unsteady state condition.

$$\vec{a}_r = \frac{1}{2} \omega_{pe}^2 \vec{r} \quad (2.80a)$$

$$\vec{a}_e \approx 1.59 \times 10^3 n_e \vec{r} \text{ s}^{-2} \quad (2.80b)$$

The collapsing acceleration is proportional to displacement travelled by imploding electron beam, see Eq.(2.80a). From Eqs.(2.80a) and (2.80b) we understand that the imploding oscillating electron due to strong VP and surface electrostatic potential produces non-thermal electron acceleration near the convergence point of PVR. For any applied electromagnetic field of frequency less than electron plasma frequency are prevented from penetrating the plasma by spontaneous electrons response which annihilates the incident field. The spontaneous induced instantaneous magnetic field due to fast flowing electron plasma is more intense and becomes effective on the surface of parcel of plasma. The imploding or exploding plasma creates multipolar induced magnetic fields outside the shocked local system [203, 204]. For compressing electrons near the stagnation region of plasma elements, decreasing in velocity

behind of the dynamic boundary of PVR is expected if no electron mass passes the dynamic boundary of PVR or no radiation is formed inside PVR before explosion.

2.11. Formation and Propagation of Shock Waves inside PVR

When PVR sucks the ambient plasma with magnitude of imploding velocity is much higher than speed of sound, c_s , a primary shock surface is generated at dynamic boundary. A distance of r_0 is measured from the center of convergence point to initial position of PVR at initial time. The position $\vec{r}_0 = \vec{r}_0(r)$ represents static boundary position since shock fronts have been generated at this boundary layer for the first time. The imploding primary shock compresses the imploding plasma near the boundary of PVR while the exploding primary shock rarifies the surrounding inflowing plasma by engulfing and pulling the inflowing ambient plasma into convergence point. The imploding primary shock fronts propagate to a stagnation region inside the PVR and reflect at convergence point while the primary exploding propagates outward and it is called *primary exploding shock fronts*.

The region behind the primary imploding shock becomes compacted and highly dense. The maximum limit of electrostatic potential is dropped and it leads to the sudden collapse of PVR instantly. A secondary exploding shock is developed instantaneously at the stagnation region during collapsing. This secondary shock provides enough energy to explode or to burst the local system. The secondary exploding shock wave is followed by strong blast or explosive waves. However, blast waves may follow behind of the primary shock, if the accumulated energy is enough for explosion before the existence of secondary shock or burst of PVR. The released energy depends on the strength of moving shock fronts. Because of the annihilation and creation of micro-electromagnetic fields, infinite train of successive shocking process happened with in a small fraction of seconds.

2.12. Propagation of Shock Fronts in Non-magnetized Plasma

We considered continuous trains of shock fronts are propagating through high conductivity plasma of local system; there are two families of shock waves that are formed at the dynamic boundary of PVR due to high velocity shock potential and instantaneous electrostatic field. These are the imploding primary shock waves move toward the stagnation region while

exploding slow primary shock waves moving outwards are the expected continuous trains of shock fronts. Let us denote the velocity of the shock wave relative to the background of plasma is represented by $\pm V$, where V is taken as a positive real number. The " + " sign represents the primary shock wave moves inward (i.e., imploding shock waves) while the " – " sign represents the slow shock moves away from dynamic boundary PVR (i.e., exploding shock waves) and converges at infinity.

The plasma behind of the imploding primary shock fronts is heated and compressed. The imploding primary shock fronts propagate with velocity of $c_1 + V$ where c_1 speed of sound of background neutral plasma before shock front passages. The front region of the imploding primary shock fronts a head on the electron current layer characterized by disturbing electromagnetic fields. The relative velocity of the moving shock wave is given by $\vec{u}_1 + \vec{V}$ or $-\vec{u}_1 - \vec{V}$ for the imploding shock surface, while for exploding shock surface the relative velocity is given by $\vec{u}_1 - \vec{V}$ as shock wave propagates high conductivity plasma.

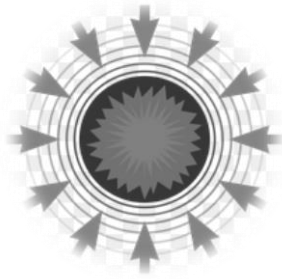


Fig.2.14a Imploding shock fronts,

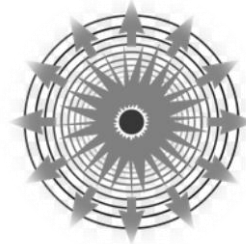


Fig.2.14b Exploding shock fronts

The thermodynamic properties of the plasma are not influenced by the motion of observers while the velocity of the shock wave is influenced. Consider the imploding shock waves, see at Fig.2.14a. The plasma in front of the imploding primary shock inside PVR is in random motion with velocity $\vec{u}_1$ before shock fronts when *electrostatic potential is dropped*. The charged particles and neutrals inside PVR are engulfed by the imploding primary propagating shock fronts, and the behavior plasma behind the shock fronts differ from the un-shocked plasma. The supersonic inflow produces a convergent spherical shock front as electrostatic potential is dropped suddenly. The primary imploding shock waves, as we have seen that $\vec{u}_1 + \vec{V}$ is the

relative shock speed, and $\vec{u}_1 + c_1 \hat{r}$ is the propagation speed of small disturbances in the plasma before the shock and $\vec{u}_2 + c_2 \hat{r}$ also the propagation radial velocity of small disturbances in the plasma behind the shock wave. Thus, the shock Mach number of moving shock wave is $M_s \gg 1$ for supersonic shock wave propagating through high conductivity fluid. So, the $V > c_1$ the shock wave travels faster than speed of sound or small disturbance. Equation of $V + u_1 < u_2 + c_2$ shows that shock wave travels slower than small pressure wave through plasma behind shock waves while equation $u_1 + V > u_1 + c_1$ shows that shock wave travels faster than small pressure waves.

Generally, the shock waves phenomena can be expressed as shock waves always overtakes continuous waves of the same family in the region a head of the shock wave, and are always overtaken by continuous waves of the same family in the region behind the shock wave. When the imploding shock wave overtakes continuous compressive waves of the same family, the continuous wave is generally absorbed in to the shock waves and the latter grows stronger. On the other hand, if the exploding shock overtakes a continuous rarefaction waves gradually are disappearing and the shock waves gradually weakening. We can determine the conditions of physical quantities across the moving normal shock in steady state situation of un-magnetized flowing plasma. The continuity, momentum and energy equations of ideal plasma are expressed by Eqs.(2.81), (2.82) and (2.83) as electrostatic potential is suddenly dropped in steady state.

$$\rho_1 V = \rho_2 [V \pm (u_1 - u_2)] \quad (2.81)$$

$$p_1 + \rho_1 V^2 = p_2 + \rho_2 [V \pm (u_1 - u_2)]^2 \quad (2.82)$$

$$h_1 + \frac{V^2}{2} = h_2 + \frac{1}{2} [V \pm (u_1 - u_2)]^2 \quad (2.83)$$

Where h_1 and h_2 are internal energy density before the shock wave and after shock wave respectively. By equating Eqs.(2.81), (2.82) and (2.83), the density ratio and pressure ratio across the fast moving shock fronts are given by Eqs.(2.84) and (2.84) in steady state situation.

$$\frac{\rho_2}{\rho_1} = \left[\frac{\gamma-1}{\gamma+1} + \frac{2}{M_s^2} \right]^{-1} \quad (2.84)$$

$$\frac{p_2}{p_1} = \frac{1-\gamma}{\gamma+1} + \frac{2\gamma}{\gamma+1} M_s^2 \quad (2.85)$$

the parameter $M_s = V/c_1$ is a sonic Mach number or shock Mach number. Velocity of the shock front can be obtained from Eq.(2.85) and the result is described by Eq.(2.86) through unmagnetized plasma.

$$V = c_1 \left[1 + \left(\frac{p_2}{p_1} - 1 \right) \frac{\gamma+1}{2\gamma} \right]^{1/2} \quad (2.86)$$

The value of shock Mach number is greater than unity for moving shock waves as we have seen from Eq.(2.86). For the primary imploding normal moving shock wave, we can approximate that $M_s \gg 1$, the magnitude ratio of p_2/p_1 is very large for strong shock wave; so the imploding shock surface is very strong and conditions across the propagating strong shock fronts can be approximated as surface electrostatic potential is dropped suddenly.

$$\frac{\rho_2}{\rho_1} = \frac{\gamma+1}{\gamma-1} \quad (2.87)$$

$$\frac{p_2}{p_1} = \frac{2\gamma}{\gamma+1} M_s^2 \quad (2.88)$$

For secondary and primary exploding slow shock waves, the pressure ratio and mass density ratio behind of moving shock wave to before shock wave is specified by Eqs.(2.89) and (2.90)

$$\frac{p_2}{p_1} = \frac{1-3\gamma}{\gamma+1} + \frac{4\gamma}{\gamma+1} M_s \quad (2.89)$$

$$\frac{\rho_2}{\rho_1} = \frac{\gamma-3}{\gamma+1} + \frac{4}{\gamma+1} M_s \quad (2.90)$$

When surrounding plasma is sucked by VP pulse that increases with time, the resulting acceleration can be approximated as a result of sudden velocity jumps. This successive sudden jump in speed creates a continuous compression wave that propagates through the plasma at velocity of moving normal shock wave is higher than local adiabatic sound speed. When the pressure and velocity increases, each successive compressing wave front propagates faster than the former created shock wave fronts as the dynamic boundary is squeezed by imploding surrounding pressure. For the sake of simplicity, we consider that the plasma is high conductivity, non-viscous fluid and collision-less. However, the real plasma is characterized by viscous fluid and plasma collision. Since the completely ionized plasma is composed of electrons

and ions only, the response of the lighter electrons to the pressure gradient terms will be different from that of the heavier ions. The electrons move faster than the ions, and thus transport energy faster, while the heavier ions transport high momentum in slower rate.

Let we consider the imploding strong shock fronts which is generated at dynamic boundary of PVR due to formation of oscillating electron cloud layer. This strong shock wave compresses the imploding ambient plasma near inner side boundary layer and accelerates electrons, ions and neutrals inside the PVR associated with electrostatic potential that is dropped suddenly. The electron current spherical shell of thickness l_e propagates to a point like region with velocity of $c_1 \hat{r} + \vec{v}$ radially inward. However, the induced intense electric field accelerates electrons and ions in front of the electron current layer before reaching the boundary layer. The imploding parcel of fast moving electron beam has a velocity given by Eq.(2.52) near the convergence point. The instantaneous collapsing radial electron current for considerable initial radial velocity due to initial density gradient and initial temperature gradient is obtained from Eq.(2.71a) coupled with the imploding moving shock fronts in the absence of collision and viscosity at isothermal condition. The corresponding imploding surface electron current is also expressed by Eq.(2.74a). The characteristic acceleration of collapsing electron current layer at non-steady state of isothermal condition can be approximated using the dimension-less parameter of β and α collapsing spherical electron shell for unsteady collapsing process.

$$\vec{a} = -\frac{1}{(\beta-\alpha)l_e} \left[\frac{1}{2} v_e^2 + \frac{e\phi}{m_e} \right] \hat{r} + \left[\frac{1}{(\beta-\alpha)l_e} + 1 \right] c_{se}^2 \hat{r} \quad (2.91)$$

For $\beta \neq \alpha$ near convergence point, the acceleration which is determined by Eq.(2.91) yields radiation of electron at collapsing dynamic boundary of PVR. Since the minimum limit of imploding shock wave front is approximated by velocity of collapsing electron plasma layer; the collapsing electron velocity is replaced by shock velocity, $\vec{v}_e = \vec{V}$ in Eq.(2.71a) during collapsing of VR in the absence of particle collision and viscosity. The velocity of imploding shock fronts corresponding imploding surface velocity in isothermal steady state condition is obtained by Eq.(2.86) that describes the minimum velocity occurred by velocity shock potential.

$$\vec{V} \geq c_{se} \left[1 + 2 \ln \left(\frac{n_e}{n_0} \right) - \frac{2e\phi_s}{k_B T_e} \right]^{1/2} \hat{r} \quad (2.92a)$$

The Eq.(2.92a) shows that minimum velocity limit of fast imploding shock wave fronts. The minimum collapsing velocity of imploding shock surfaces is given by $\vec{V} \approx c_{se}\hat{r}$, sonic imploding shock wave. This indicates that minimum limit of imploding shock wave is approximated by small disturbance wave speed before shock passage.

2.13. Electric Field Generated by Dynamics Boundary of PVR

Let consider high density ambient plasma is imploding to convergence point from all directions so as to destroy the PVR of local system. A dense oscillating electron beam is created at the dynamic boundary PVR during collapsing. The radial electron current of spherical shell with thickness $l_e(t)$ propagates to convergence region. The radial propagating velocity field is given by $c_1\hat{r} + \vec{V}$ through high conductivity medium before shock fronts. In simple and feasible reasoning, the velocity of imploding shock front is same as radial velocity of electron beam followed by ions and neutrals. However, the developing Coulomb forces across shock surface influence the velocity of charged particles. In general the collapsing velocity of VPR is determined by the density and temperature of spontaneous imploding surrounding plasma before shock wave formation. The velocity of imploding shock front in steady state is approximated by charged particle velocity.

$$\vec{V} \geq c_{sj} \left[1 + 2 \ln \left(\frac{n_j}{n_0} \right) + \frac{2q_j\phi_s}{k_B T_j} \right]^{1/2} \hat{r} \quad (2.92b)$$

For separated electrons, ions and neutrals Eq.(2.92b) is used, for j represents electron, ion and neutral species. When the dynamic boundary of PVR is characterized by fast moving electrons followed by ions, using the assumption of $\vec{v}_e \gg \vec{v}_i$ during collapsing, velocity of imploding shock wave is approximated by Eq.(2.92b). When the spherical electron beam layer shrinks to point like small region with constant velocity, the electron potential has maximum value near the stagnation region. When velocity of imploding shock wave is nearly the same as velocity imploding parcels of electron beam, from Eqs.(2.92a) and (2.92b) we can evaluate the induced instantaneous electric field inside the PVR which is responsible for *electron runaway* and ion runaway condition. This kinds of electric field results instantaneous body current inside PVR in front of collapsing electron current layer.

We assumed that evolution of induced electric field is associated with the evolution of moving shock waves. The source of electric field is vanished before shock wave and after shock wave far away from electron beam or ion beam layer. The main source of shock waves is formation of VP associated with charge separation process. The intense electrostatic field is obtained from Eq.(2.92a) in case of spontaneous imploding surrounding plasma. The induced electric field is described by Eq.(2.93) during imploding.

$$\vec{E} = \frac{m_j V^2}{2q_j(\beta-\alpha)l_e} \hat{r} - \frac{k_B T_j}{q_j(\beta-\alpha)l_e} \left[\frac{1}{2} + \ln \left(\frac{n_j}{n_0} \right) \right] \hat{r} \quad (2.93)$$

The first term on right hand side of Eq.(2.93) is shock wave induce radial electric field during collapsing of PVR. The second term of Eq.(2.93) on right hand side is electric field induced by temperature gradients and density gradient of high conductivity plasma in the absence of collision and viscosity. At isothermal condition when plasma density is constant, the second term of Eq.(2.93) on the right hand side is vanished. The fast moving imploding shock surface inside PVR creates an instantaneous strong electric field. The induced electric field inside PVR is directly proportional squared of shock wave velocity see Eq.(2.93).

When shock wave propagates through high conductivity plasma, an instantaneous electrostatic field is produced. The induced surface electric potential across the imploding trains of shock fronts is specified in terms of pressure before and behinds of shock wave trains. The surface electrostatic potential and corresponding electric field provided by the fast moving shock wave is obtained from Eqs.(2.86) and (2.92b) which shows that the lower limit of fast moving shock fronts assuming all quantities of Eq.(2.92b) are before shock fronts to fulfill the lower limit of shock velocity.

$$\phi_s = \frac{1}{2} \frac{m_j}{q_j} c_1^2 \left[1 + \left(\frac{p_2}{p_1} - 1 \right) \frac{\gamma+1}{2\gamma} \right] - \frac{k T_j}{q_j m_j} \left[\frac{1}{2} + \ln \left(\frac{n_j}{n_0} \right) \right] \quad (2.94a)$$

$$\vec{E} = \frac{1}{2} \frac{1}{q_j} \frac{m_j c_1^2}{(\beta-\alpha)l_e} \left[1 + \left(\frac{p_2}{p_1} - 1 \right) \frac{\gamma+1}{2\gamma} \right] \hat{r} - \frac{k T_j}{q_j m_j (\beta-\alpha)l_e} \left[\frac{1}{2} + \ln \left(\frac{n_j}{n_0} \right) \right] \hat{r} \quad (2.94b)$$

Since the imploding shock front is expected as strong moving shock wave, it generates instant electric field in front of collapsing electron beam. Using Eq.(2.88) the electrostatic potential and

corresponding electric field are generated by imploding shock fronts obtained from Eqs.(2.94a) and (2.94b) as plasma before shock front and behind shock front suffices adiabatic condition

$$\phi_s = \frac{1}{2} \frac{m_j}{q_j} c_1^2 \left[M_{s1}^2 + \frac{\gamma-1}{2\gamma} \right] - \frac{c_1^2}{q_j} \left[\frac{1}{2} + \ln \left(\frac{n_j}{n_0} \right) \right] \quad (2.95a)$$

$$\vec{E} = \frac{1}{2} \frac{1}{q_j} \frac{m_j c_1^2}{(\beta-\alpha)l_e} \left[M_{s1}^2 + \frac{\gamma-1}{2\gamma} \right] \hat{r} - \frac{c_1^2}{q_j(\beta-\alpha)l_e} \left[\frac{1}{2} + \ln \left(\frac{n_j}{n_0} \right) \right] \hat{r} \quad (2.95b)$$

Here, we assumed the $kT_j/m_j \approx c_1^2$ in the above expression before shock passage. The shock Mach number is given by $M_{s1} = V/c_1 \gg 1$ for fast moving shock front. When ion density remains constant inside the collapsing PVR and they are assumed to be relatively at rest. Only the shocked electrons generate intense electric field in front of the moving plasma in response to static ions. The absence of collision and viscosity shows that induced electric field is much higher than Direicer electric field; see Eq.(2.94b) and (2.95b).

Inside PVR, except at the stagnation region the collisional force is vanishing due to radial aligned electron motion which is controlled by local VP. However, if the plasma density inside PVR is high enough, plasma collision has significant effect on the local collapsing system. Accelerated electrons and ions penetrate the electron layer of thickness l_e when the accelerated particles gain much higher frequency than frequency of electron beam layer. A sudden disturbance of electromagnetic wave during collapsing of electric current creates electromagnetic radiation pressure at small local region. Even electron density gradient may be vanishing across the electron beam layer; instantaneous electrostatic potential is generated due to formation of strong imploding shock fronts see Eqs.(2.95a) and (2.95b) and electric field is approximated by Eq. (2.96).

$$\vec{E} = -\frac{1}{2e} \frac{m_e c_1^2}{(\beta-\alpha)l_e} \left[M_{s1}^2 + \frac{\gamma-1}{2\gamma} \right] \hat{r} \quad (2.96)$$

Let determine characteristic electrostatic potential at dynamic boundary layer of PVR which produce on its nearby electrons and ions. The radial characteristic electrostatic potential is given by $E_r \approx \phi/\alpha l_e$ where the value of constant parameter $0 < \alpha \leq \infty$ in the range position between initial boundary of collapsing PVR and stagnation region. This shows that effect of electric field and micro-magnetic field far away from boundary region is negligible. When the electron beam

layer is heated due production of fast moving shock waves, $T_e \gg T_{e0}$ when T_e and T_{e0} are electron temperature behind moving shock and before moving shock respectively. Electron number density before moving shock wave and behind the moving shock wave is also given by n_0 and n_e respectively. From Eqs.(2.93) and (2.96) we can understand that instantaneous electrostatic field is produced by moving shock waves associated with electron beam density gradient at compacted plasma region.

Let we assumed that p_2 is pressure of plasma behind of normal shock surface and p_1 is plasma pressure before shock wave. For imploding strong shock when $T_e \gg T_{e0}$ is to be assumed as adiabatic principle is violated across moving normal shock surface. When imploding shock wave is reflected at convergence point, it propagates radial outward accompanied with the exploding primary shock wave fronts. When exploding shock waves are passing through the electron beam layer, the expected instantaneous electric field is generated due to slow shock fronts. In case of slow shock, when $T_e \gg T_{e0}$ electron induced electric field is obtained as follow.

$$\vec{E} = \frac{m_j c_1^2}{q_j (\beta - \alpha) l_e} \left[M_s - \frac{1}{4} - \ln \left(\frac{n_l}{n_0} \right) \right] \hat{r} \quad (2.97)$$

From Eq.(2.97), we can understand that the instantaneous induced electric field is produced due to slow shock fronts coupled with high density gradient is proportional to sonic Mach number. The velocity of bouncing normal slow shock wave may produces localized electron induced instantaneous electric field, see Eq.(2.93). However, density of plasma element could not be constant across the moving shock wave due to irreversible and non-adiabatic nature of shock fronts. When a primary imploding and primary exploding shock waves are generated at dynamic boundary position of $r_0(r, t)$ far away from the center of convergence point initially; dynamic boundary of PVR moves to convergence point followed by imploding ambient plasma. The center of convergence point is characterized by strong radiation process, see Eq.(2.55b). The local imploding plasma becomes super-hot plasma behind the fast imploding and exploding shock fronts. Due to accelerating electrons and ions, electromagnetic waves are created at this local region suddenly (i.e., Electromagnetic wave burst is occurred). In this case the mass flux across the dynamic boundary is not conserved. Plasma density of the PVR decreases extremely because charged particles are accelerated in the form of radiation. The convergence point sucks ambient plasma due to local VP; finally the cavity is collapsed.

The shock wave induced electric field which is described by Eqs.(2.96) and (2.97) has non-linear nature in steady state situation. Its non-linearity is specified in terms of varying sonic shock number and corresponding position vector. The shock wave induced electric field in steady state as function two variables, position and corresponding velocity, is well described by Fig.2.15a as functions of position and squared of Mach number and Fig.2.15b as function of position and Mach number across the fast moving shock wave. Fig.2.15a and Fig.2.15b illustrates the fast propagating shock wave can generates position dependent electrostatic potential inside the collapsing and growing cavity respectively.

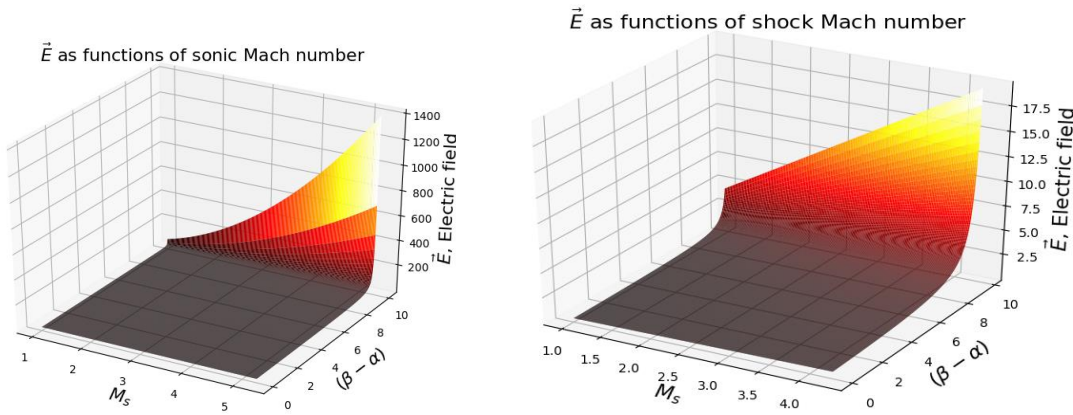


Fig.2.15a Imploding shock induced electric field

Fig.2.15b Exploding shock induced Electric field

2.14. Formation of Secondary Shock Wave Fronts

When the primary imploding shock fronts propagates to a point like convergence region, the increment of induced electrostatic potential cease at very small stagnation region. The propagating imploding primary shock fronts followed by imploding blast waves is bounced at the central convergence. The reflected primary shock surface interacts with the incident imploding shock surface. When the reflected shock wave coupled with particles collision and next imploding shock waves, plasma is so compressed there. The imploding primary shock changes its nature near the stagnation point because of reflection and interfacing with other wave fronts. The imploding plasma elements behind of the electron current layer are compressed continuously by exploding primary shock surfaces. A secondary shock fronts exist due to overloading of the same families wave phases. The secondary shock front engulfs and compact the imploding plasma followed by explosion.

The intensity of electromagnetic field burst depends on the strength of compressive shock and presence of strong magnetic field associated with high plasma density gradient. The radially collapsing electron current at the inner side of PVR is directly proportional to shock Mach number. When electric current sheet of spherical shell passes through strong shock surface, the instantaneous electron current sheet is generated due to strong shock wave. It is calculated using Eq.(2.86) resulting Eq.(2.98), minimum collapsing electron current associated with imploding strong shock waves.

$$\vec{j} \approx -n_e e c_1 M_s \hat{r} \quad (2.98)$$

The radial electric field which is produced by slow shock before explosion of local system is proportional to square root of shock Mach number. The propagating slow shock wave creates electron current which is dissipated by anomalous plasma resistivity, described by Eq.(2.99).

$$\vec{j} = -n_e e c_1 [1 + 2M_s]^{1/2} \hat{r} \quad (2.99)$$

From Eqs.(2.98) and (2.99), radial instantaneous current field produces non-radial micro magnetic field, an instantaneous magnetic field may be propagated behind of fast moving shock fronts. The radial converging flow of plasma element creates instantaneous strong electric current. Let we consider the collapsing spherical electron current shell that creates non-radial induced micro magnetic field $\vec{B}$, which compresses and compacts the imploding plasma. Magnetic energy is stored at small region of collapsing cavity. The inflowing plasma elements never bounce back before it reaches at stagnation region due compressing effects of non-radial magnetic field behind it. The shock wave induced non-radial magnetic field behind of imploding and exploding shock surface prevents the ambient surrounding plasma from imploding to convergence point. The compacted region is prepared for explosion because of developing anomalous resistivity. As soon as secondary shock wave is developed at stagnation region after imploding primary shock fronts, explosion has been appeared at this small local region instantly.

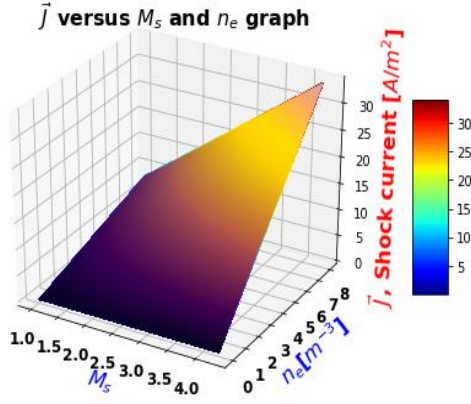


Fig.2.16a Strong shock induced electron current associated with Mack number

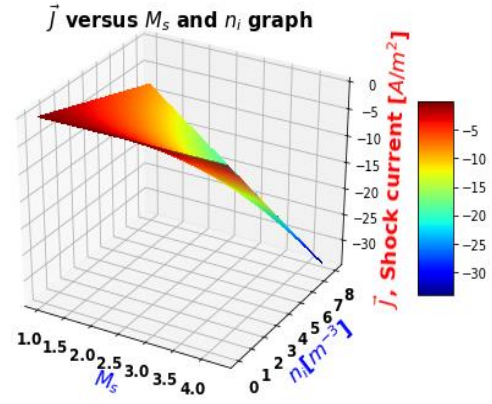


Fig.2.16b Strong shock induced ion current associated with Mack number

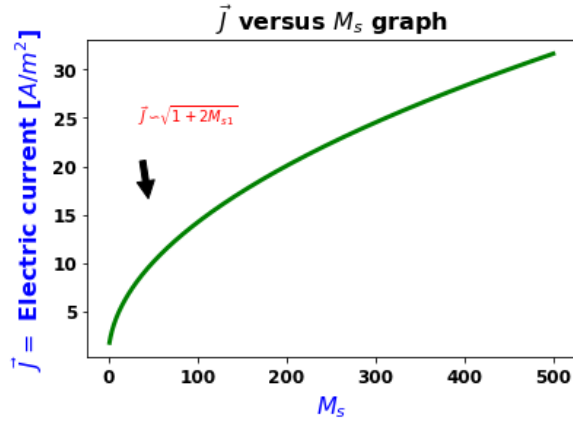


Fig.2.16c Slow shock induced electron current of constant electron flux

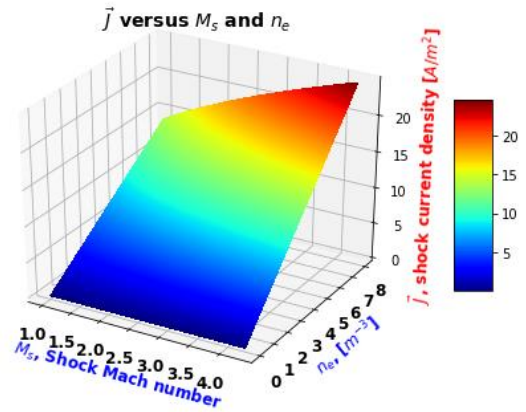


Fig.2.16d Slow shock induced electron current of variable electron flux

The figures of Fig.2.16a and Fig.2.16b describes the non-linearity of strong shock currents of imploding electron current and followed ion current in steady state respectively while Fig.2.16c shows the non-linear linear behavior of imploding electron having constant electron number density across slow shock waves. Fig.2.16d describes the non-linear nature of shocked electron current across slow shock surfaces for varying electron flux on position. The induced magnetic field of compacted region due to radially separated electron is obtained from $\vec{\nabla} \times \vec{B} = \mu_0 \vec{j}$ and $\vec{\nabla} \cdot \vec{B} = 0$ at local isolated spherical coordinate using Eq.(2.98), the imploding electron induces non-radial magnetic field that is specified by Eq.(2.100a), is purely non-radial magnetic field.

$$\vec{B} \approx -\frac{3}{8}\pi^2\mu_0ec_1M_{s1}n_er\hat{\theta} + B_\varphi\hat{\phi} \quad (2.100a)$$

We assumed that n_e and $\vec{V}$ are position independent and B_φ and B_θ are only φ dependent at steady state to minimize complexity. The magnitude of azimuthal components of induced magnetic fields is assumed to be constant and the polar component of magnetic field depends on sonic Mach number. For very strong imploding moving shock waves, induced magnetic field is given by Eq.(2.100a) during electron implosion. The exploding electron beam across the moving slow shock is derived from Eq.(2.99) using the assumption of curl and divergence of magnetic fields similar to Eq.(2.100a) in case strong shock waves. The polar component of induced micro-magnetic field is proportional to square root of sonic Mach number using this assumption, it is specified by Eq.(2.100b) also purely non-radial.

$$\vec{B} \approx -\frac{3}{8}\pi^2\mu_0ec_1[1 + 2M_s]^{1/2}n_er\hat{\theta} + B_\varphi\hat{\phi} \quad (2.100b)$$

The micro-magnetic field which is generated by imploding shock wave that is described by Eq.(2.100a) interact with micro-magnetic field which is generated by exploding (i.e., reflected shock waves) that is described by Eq.(2.100b) through high conductivity plasma make the system is so complex. The induced micro-magnetic field across the moving shock exerts a magnetic pressure against the VP pressure. Suddenly, complex magnetic energy is generated due to non-linear effects of density gradient and pressure gradient, associated with the existed shock surfaces in radial convergent electron flowing. The velocity of fast moving shock is in the interval of sound speed and light speed. However, we are now interested in non-relativistic fast moving shock surfaces. We theorized here that plasma elements behind of collapsing electron shell become instantly magnetized. When induced local magnetic field becomes so intense, it prevents slowly accelerated particles from moving away and also it intensifies the shock intensity, see chapter 3.

Thus, those charged particles and even neutrals are heated and compressed by shock fronts instantly. In next chapter 3, we will study shock surface in strongly magnetized high conductivity plasma. Generally, radial imploding or exploding plasma elements associated with imploding primary normal shock waves and exploding primary normal shock waves behind of electron beam spherical surface layer produces instantaneous electric field, current and radial,

azimuthal and polar components of magnetic field. When the spontaneous induced magnetic field is strong enough, some of plasma particles tries to move along the induced magnetic field lines and produces other induced micro-magnetic field. The local system produces toroidal micro-magnetic fields and poloidal micro-magnetic field behind fast moving shock surfaces. The radial imploding electrons accompanied with imploding strong shock fronts are tried to reflect at the convergence region. When the stored energy reaches its maximum limit, it is released suddenly. Due to continuous production of magnetic field at small local region, highly magnetized local plasma is blown out from lower region of stellar atmosphere in the form of CMEs, prominences and magnetic flux tubes.

As flares and CMEs are released, electrons and ions are accelerated spontaneously in non-thermal manner from moving CMEs and its boundary with ambient surrounding plasma. When the compacted small local region contains huge amount of magnetic energy, the compacted magnetized plasma which carries huge magnetic energy may be ejected out before formation of anomalous plasma resistivity. Based on this theory CMEs can be appeared independent of flares. However, due to dynamics of high conductivity plasma and particle-wave or particle-field interaction, the floating CMEs can create flares and electromagnetic burst due high disturbance of fields coupled with continuous generation of fast moving strong and slow shock fronts.

However, the electron beam of fast moving plasma passes successive continuous trains of shock wave fronts. From Eqs.(2.100a) and (2.100b), we can understand that because of the entrance of fast moving shock wave, kinetic energy is converted in to magnetic energy across fast moving normal shock waves. We assumed that no plasma particle rotation or no rotation of velocity field for the sack of simplicity. The minimum limit of bouncing velocity is twice velocity of imploding strong shock. The minimum limit of kinetic energy of reflected electrons at the convergence region for negligible plasma collision and viscosity is given by Eq.(2.101) that describes the generated kinetic energy of energetic particles.

$$E_{km} = 4\rho_e c_1^2 (2M_s - 1) \quad (2.101)$$

where, E_{km} , is the minimum limit of reflected kinetic energy carried by reflected shock wave at the convergence region coupled with moving plasma elements. The radiation frequency is

generated by the reflected electrons at convergence point or line or plane. Now, we calculate radiation frequency corresponds to kinetic energy given by Eq.(2.101).

$$\nu_r = \frac{2}{h} \rho_e c_1^2 (2M_s - 1) \quad (2.102)$$

The quantities, h is plank's constant and ν_r is radiation frequency from shocked electron beam. The electron temperature is produced by moving shock fronts in connection to kinetic energy near convergence region for collision-less and non-viscous plasma is given by Eq.(2.103).

$$T_e = \frac{2\rho_e}{k_B} c_1^2 (2M_s - 1) \quad (2.103)$$

When shock wave fronts move at high velocity in high conductivity plasma medium, huge amounts of heat energy is generated due to shock wave formation process.

2.15. Spherical Velocity Shock Potential (Mechanism of Flares and CMEs)

The instability of scalar explosive potential field produces a strong disturbance in local plasma fluid of solar atmosphere. When plasma element is accelerated suddenly through background plasma with its velocity magnitude is greater than background acoustic velocity field $\vec{v}_r \gg c_s \hat{r}$, it generates shock wave fronts through the back ground high conductivity plasma. Where, $\vec{v}_r \approx \vec{v}$ is the radial particles velocity during imploding or exploding and c_s is sound speed. When the speed of flowing particles approaches to the speed of light, the formed shock is known as a *relativistic shock*.

However, we are now concentrating on non-relativistic shock waves. The continuous generation of shock wave fronts creates implosive or explosive blast wave. Plasma particles at stagnation region increase their internal energy and entropy because they absorb energy from imploding shock wave fronts. The plasma particles at convergence region gets rest instantly due to compressing shock fronts associated with confining micro magnetic field and imploding blast waves. Let us consider the medium is shocked by a continuous train of shock fronts in irreversible manner. Here, we assumed that the shocked medium passed N times of a successive constant shock wave fronts with in small fraction of seconds. When the stored energy reaches its maximum limit, it is burst. Electrons and ions are accelerated by shock waves at local region. A nuclear reaction can be created in very dense plasma due to these kinds of shock waves

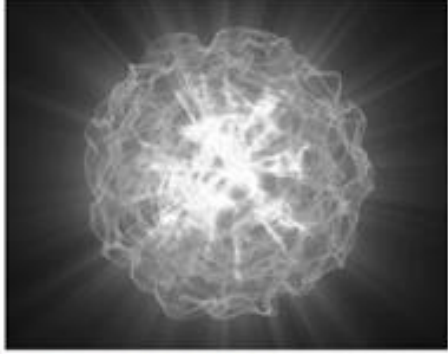


Fig.2.17 Radiative blast wave

During explosion at stellar (solar) atmosphere electrons, ions and neutrals are accelerated by shock surfaces to surrounding environment. This situation at local region of stellar atmosphere leads to the formation of electromagnetic wave burst. Because the local shocked system is dominated by collision-less shock at upper stellar atmosphere, VSP field is also dominant over other potentials. Collapsing of PVR at stellar surface region is expected as dominated by

collisional shock process at deep stellar atmosphere. The strong released energy swept out the surrounding mass due to explosive waves. Behind the propagating shock front a sudden increase in temperature of electrons, ions and ionization process is occurred. The accumulated mass and magnetic field are the source of energy that is released abruptly. A blast wave drove out the accumulated mass behind of secondary shock waves. The maximum instantaneous stored energy, E_0 in very small region relative to size of star.

We can calculate the VSP, $\psi(X, t)$, which produces a blast waves that may be implosive or explosive waves behind of moving shock fronts. Let us assumed that blast wave is in spherical harmonic expansion mode, see Fig.2.17. The quantity $\psi(X, t)$ is scalar velocity shock potential satisfying the source free implosive and explosive wave equation defined by Eq.(2.105). Using the Fourier – analyzed in time-space coordinate,

$$\psi(X, t) = \int_{-\infty}^{\infty} \psi(X, \omega) e^{-i\omega t} d\omega \quad (2.104)$$

with each Fourier component satisfying Helmholtz wave equation, Eq.(2.105) explained below,

$$(\vec{\nabla}^2 + k^2) \psi(X, \omega) = 0 \quad (2.105)$$

with $k^2 = \omega^2/v^2$, the separation of angular and radial variables follow the following well known expression. The VSP is specified by spherical harmonics $\psi(X, \omega) = \sum_{l,m} f_{lm}(r) Y_{lm}(\theta, \varphi)$ where $X = (r, \theta, \varphi)$ is space coordinate. The radial function $f_{lm}(r)$ satisfies the radial equation independent of m and yields Bessel equation of Eq.(2.106) expressed below.

$$\left[\frac{d^2}{dr^2} + \frac{2}{r} \frac{d}{dr} + k^2 - \frac{l(l+1)}{r^2} \right] f_l(r) = 0 \quad (2.106)$$

With the substitution of $f_l(r) = r^{-1/2} u_r(r)$ Eq.(2.106) is transformed in to,

$$\left[\frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr} + k^2 - \frac{(l+\frac{1}{2})^2}{r^2} \right] u_l(r) = 0 \quad (2.107)$$

This is Bessel equation with, $v = l + 1/2$ the solution for $f_{lm}(r)$ and $u_l(r)$ is radial function

$$f_{lm}(r) = \frac{A_{lm}}{r^{1/2}} J_{l+\frac{1}{2}}(kr) + \frac{B_{lm}}{r^{1/2}} N_{l+\frac{1}{2}}(kr) \quad (2.108)$$

$$\psi(X) = \sum_{l,m} \left[A_{lm} h_l^{(1)}(kr) + B_{lm} h_l^{(2)}(kr) \right] Y_{lm}(\theta, \varphi) \quad (2.109)$$

$$\psi(X, t) = \sum_{l,m} \left[A_{lm} h_l^{(1)}(kr) + B_{lm} h_l^{(2)}(kr) \right] Y_{lm}(\theta, \varphi) e^{i\omega t} \quad (2.110)$$

The coefficient A_{lm} and B_{lm} will be determined by initial value and boundary conditions, $h_l^{(1)}$ and $h_l^{(2)}$ are Henkel's function first and second kind. The velocity shock potential arises due to formation of gradients of negative total pressure of the local system.

2.15.1. Boundary value problem of velocity shock potential

Nonlinear waves are specified by nonlinear wave equations, the superposition principle does not work in nonlinear system. The nonlinear wave equation does not have general mathematically analytic solution. It is a good method that using the numerical approximation in connection with boundary conditions and initial value of physical quantities at local system. In fully ionized local un-magnetized plasma, electrons and ions are accelerated suddenly if their inertial speed is higher than thermal speed, $v_j > v_{j,th}$ near equilibrium situation. Here, we establish a simple and important model of solar flares in weak magnetic field regions, solar quiet region. This model gives a clear understanding for future study about stellar (solar) flares, explosive events, CMEs and active solar phenomena.

As the shock wave engulfs ambient plasma, plasma particles suddenly gain enough energy which enables them to accelerate intensely. Those energetic electrons oscillate repeatedly inside the shocking and compressing region in spherical harmonic oscillation mode. A strong

shock waves and particle interaction is occurred inside the shocking region. An explosive wave is developed and propagates in spherical harmonic expansion until the source of current over flow is stopped. This creates electromagnetic field burst in fractions of seconds. To model the explosive waves in fully spherical harmonic oscillation mode is natural. However, to solve this natural model numerically is very difficult due to its sophisticated nature. The radial component of velocity shock wave function is taken by $\psi(r, t)$ as a function of radial space-time coordinate. For small motion of electron beam layer coupled with VSP, we obtain the equation of shock waves followed by blast wave that depends on radial space-time coordinate expressed by Eq.(2.111).

$$v^2 \left[\frac{\partial^2 \psi}{\partial r^2} + \frac{2}{r} \frac{\partial \psi}{\partial r} \right] = \frac{\partial^2 \psi}{\partial t^2} \quad (2.111)$$

Where $v = c_s + V$ propagation relative velocity field of shock wave, c_s , is sound speed, if $c_s \gg V$ for slowly propagating shock waves, Eq.(2.111) is expressed as,

$$c_s^2 \left[\frac{\partial^2 \psi}{\partial r^2} + \frac{2}{r} \frac{\partial \psi}{\partial r} \right] = \frac{\partial^2 \psi}{\partial t^2} \quad (2.112)$$

Based on Eq.(2.112) a shock wave is not generated due to flowing of high conductivity plasma fluids when flowing velocity is less than acoustic plasma velocity. However, when the high conductivity plasma moves with $\vec{v} \geq c_s \hat{r}$ in radial direction, a moving shock of velocity field $\vec{V}$ is generated through high conductivity plasma fluids. For $0 < \vec{r} < \vec{r}_0$ the shock front travel a distance of $\delta \vec{r} = -\alpha l_e \hat{r}$ between the initial static boundary position of $\vec{r}_0$ and $\vec{r} \rightarrow 0$ for imploding shock surfaces. The imploding shock surface is reflected at the convergence center $\vec{r} \rightarrow 0$ or sinks at the stagnation region. We assumed that dynamic boundary of PVR, first boundary and the center of convergence is also the second boundary. Initially at the first static boundary of PVR, the value of α is zero while at final state, secondary boundary, when imploding shock wave is reflected or sunk at center of convergence the value of α is large and its value approaches to β . The exploding primary shock surface originates from dynamic boundary of PVR as well as from center of convergence which propagates a distance $\vec{r} \gg \vec{r}_0$ beyond dynamic boundary of PVR. The exploding shock wave is disappeared at distance $r \approx \infty$ far away from center of PVR. The final state of exploding primary shock surface is assumed to be at infinite $r \gg r_0$. The boundary condition tells us that we assume that the explosive

secondary shock wave function followed by blast wave to be position independent at moving boundary $\psi(r_0(t), t) = \text{constant}$, it may be zero for primary explosive shock wave, $\psi(r, 0) = f(r)$ and $\partial\psi/\partial t|_{t=0} = g(r)$; $0 < r < r_0$ is considered as imploding shock. Using separation of variable, $\psi \equiv R(r)T(t)$, Eq.(2.111) transform in to Eq.(2.113) that represents blast wave.

$$\frac{R''}{R} + \frac{1}{r} \frac{R'}{R} = \frac{T''}{c_s^2 T} = -\lambda \quad (2.113)$$

The parameter λ is constant real number which connects the two independent partial differential equations. Because of the radial oscillation nature of the problem, let we choose, $\lambda = k^2 > 0$: $k > 0$ of Bessel differential equation order of zero, $\nu = 0$ integer value. The general solution of radial differential separated equation for $r > 0$ is given by Eq.(2.114). Since $J_\nu(kr)$ and $Y_\nu(kr)$ are respectively, the Bessel function of first and second kind order of ν and A_1 and A_2 are constant parameters which are determined by boundary conditions. Moreover, $\lim_{r \rightarrow 0^+} R(r)$ is finite if and only if $A_2 = 0$ and so $R(r) = c_1 J_\nu(kr)$. Recall, $J_\nu(0) = 0$ if $\nu > 0$ and $J_0(0) = 1$ where $Y_0(kr) \rightarrow \infty$ as $r \rightarrow 0^+$, this implies that velocity shock potential $\psi(r, t)$ should be bounded at $r = 0$ or $r = \beta l_e = r_0$, for imploding shock wave followed by imploding blast wave if the solution is bounded in the interval $(0, r_0)$ for $r_0 > 0$, which forces as to define $A_2 = 0$, thus $R = A_1 J_0(kr)$. Since the boundary condition $\psi(r_0, t) = 0$ is equivalent to $R(r_0) = 0$, we must have $R = A_1 J_0(kr) = 0$. We rule out $A_1 = 0$, so consequently $J_0(kr_0) = 0$. When $x_n = k_n r_0$ are positive roots of $J_0(kr_0) = 0$, then $x_n = k_n r_0$ and the Eigen values of the problem are $\lambda_n = k_n^2 = x_n^2 / r_0^2$ and Eigen value functions are $A_1 J_0(k_n r)$.

$$\psi(r, t) = \sum_{n=1}^{\infty} [A_n \cos(kx_n t) + B_n \sin(kx_n t)] J_0(k_n r) \quad (2.114)$$

Using initial conditions to determine coefficients of A_n and B_n ; set $t = 0$; and using $\psi(r, 0) = u(r, 0) = f(r)$ yields that $f(r) = \sum_{n=1}^{\infty} A_n J_0(k_n r)$. This last result is recognized as a Fourier-Bessel equation of function of the interval $(0, r_0)$. Hence by direct substitution we obtain that

$$A_n = \frac{2}{r_0^2 J_0^2(k_n r_0)} \int_0^{r_0} r J_0(k_n r) f(r) dr \quad (2.115)$$

Differentiating the function of $f(r)$ with respects of t and set $t = 0$, and use $u_t(r, 0)|_{t=0} = g(r)$ yields that $g(r) = \sum_{n=1}^{\infty} c k_n B_n J_0(k_n r)$ and the second coefficient is given by,

$$B_n = \frac{2}{cr_0^2 J_1^2(k_n r)} \int_0^{r_0} r J_0(k_n r) g(r) dr \quad (2.116)$$

We can understand that the imploding shock waves followed by implosive waves are bounded between the boundary of PVR, and center of convergence before reflection. This kind of shock wave is converging shock waves. The imploding shock decelerates electrons and ions at the center of PVR suddenly. Thus, motion of plasma particles stopped suddenly and plasma is compacted instantly. However, the exploding waves are bounded between the boundary of PVR or convergence point and at infinite value of $\vec{r} \rightarrow \infty$ or bounded between center of convergence point and infinite radial distance in case of exploding and reflection of imploding shocks.

2.15.2. Velocity shock potential (VSP) followed by blast waves

The form of unknown potential energy which produces a moving shock surfaces in continuum medium is known as *velocity shock potential*(VSP). This kind of shock potential energy is observed in high explosive phenomenon such as human made explosive weapons [205], natural explosive events such as atmosphere blast waves and thunder storm during raining time [206] and astronomical explosive events such as solar flares and CMEs [207, 208]. The VSP can be existed in all kinds of material state. However, now we are concentrated on VSP which appeared in hot plasma state at stellar surface and supper hot stellar atmosphere plasma medium. Behind the moving shock surface, velocity potential becomes a source of blast waves which propagates with velocity $\vec{v} = \vec{V} + c_1 \hat{r}$.

Here, we assumed that the source of sudden implosion or explosion of high conductivity plasma associated with normal propagating shock waves at velocity $\vec{V}$ is known as VSP. Across normal moving shock fronts, electrons and ions are accelerated or decelerated in random direction. Electrons, ions and neutral particles gain enough energy from shock fronts due to shock wave and particle interaction principle [209, 210]. When neutral particles cross continues train of shock fronts, they become heated, ionized and accelerated. Due to development of highly negative VSP, the PVR sucks the ambient plasma to its convergence point. The VSP is denoted by $\psi(r, t) = -\psi(r, t)$, is negative for imploding shock wave of local system to differentiate it from exploding shock potential outside of PVR. Plasma elements which reach at stagnation region (center of PVR when $\vec{v}_r \rightarrow 0$) suddenly stop their motion before bounce. For exploding

local system, plasma elements are blown out due to sudden formation of positive VSP, $\psi(r, t)$, at local compacted region. By imploding local system, we do not meant imploding shock wave fronts. For the imploding local system, the VSP outside of PVR is denoted by $\psi(r > r_0, t)$, also a negative behind the dynamic boundary surface of PVR and it pulls or sucks the ambient plasma towards the center of convergence. The VSP at instant boundary of PVR is given by $\psi(r_0, 0)$. The high negative VSP inside PVR is $\psi(r < r_0, t)$, provides negative VSP. This VSP of local hydrodynamic system which is coupled with particle kinematics is constant of polar and azimuthal space components in this special case.

When the PVR is burst or collapsed, we can defines, $\psi(r(t) = 0, t = \tau) = \psi(0, \tau)$ is the condition of final state for imploding shock waves followed by implosive blast waves. The convergence point can be considered as transition from implosive to explosive nature of the system where, τ is the time required to collapse the PVR. As the cavity is collapsed, the negative velocity potential is annihilated, at the stagnation region, $\psi(0, \tau)$, is provided. This is only true if collision of imploding plasma particles with reflected plasma particles is negligible. As soon as PVR is collapsed, a positive VSP is developed instantly associated with secondary shock waves. The positive VSP at the stagnation region is expressed as $\psi(0, t \rightarrow \tau^+)$ is a mechanism for secondary explosive shock fronts which create constant positive shock acceleration potential instantly. The positive VSP decreases away from its center during explosion. A sudden explosion of this compacted local system creates intense explosive shock fronts followed by blast waves.

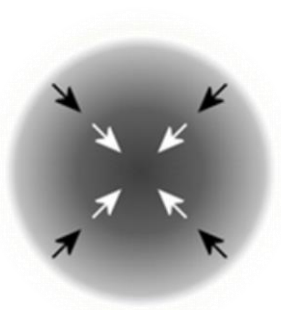


Fig.2.18a Implosive shock wave process

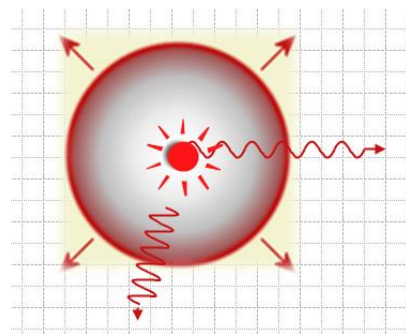


Fig.2.18b Explosive shock wave process

The exploding primary and secondary VSP vanishes far away from stagnation region or point like source, $\psi(r \rightarrow \infty, t \rightarrow \infty) \approx 0$, for both negative and positive VSP. The presence of induced micro-magnetic field pressure affects the disseminating and bouncing of shock fronts.

When PVR is once created inside a continuous high conductivity plasma medium, the ambient plasma gives a tendency to fill up the PVR so as to keep the system in equilibrium situation. An instantaneous dynamic boundary layer is created between the PVR and high density region of continual medium. The PVR and high density plasma region from outside interacts due to moving shock waves at dynamic boundary layer. Generally, we expect the dynamic boundary layer between two regions inside continuum medium is described as follow.

1. Boundary layer between non-magnetized plasma and strong magnetized plasma.
2. Boundary layer between warm plasma and hot plasma.
3. Boundary layer between high density plasma and low density.
4. Boundary between plasma and vacuum region.

2.15.3. VSP in the absence of electrostatic potential generates blast wave

The VSP is necessarily existed in high conductivity plasma when local cavity is created inside the continuum medium as magnitude of aligned flowing velocity field is greater than background sound speed. For the sake of simplicity, let we assumed that imploding velocity field as well as exploding velocity field coupled with moving shock wave is radial velocity. The radial imploding or exploding velocity is assumed here as ir-rotational velocity. Vorticity of the local imploding plasma element is given by $\vec{\omega} = \vec{\nabla} \times \vec{u} = -\vec{\nabla} \times \vec{\nabla}\psi = 0$ during collapsing of PVR and explosion of local plasma in connection with radially moving normal shock fronts may be occurred behind collapsing cavity. If plasma has both ir-rotational and incompressible behavior, then we have a velocity shock potential field of imploding plasma elements as $\vec{V} = -\vec{\nabla}\psi$ and $\vec{\nabla} \cdot \vec{V} = 0$ inside high conductivity background plasma fluid. Since the imploding or exploding velocity is approximated by $\vec{V}$, using the assumption of $\vec{V} = \vec{V}(\vec{r}, t)$ and ψ , is function of space-time coordinates described by Eq.(2.110) in spherical harmonic mode. The velocity shock potential function provides a strong blast wave behind of the dynamic boundary of PVR, and it can be described by Laplace equation of VSP at steady state situation.

$$\vec{\nabla}^2\psi = 0 \tag{2.117}$$

Formation of VP is the main mechanism for existence of VSP at small local region. Since we have $\psi(r, t)$ is the total VSP of local system with no sink or source of shock wave as observed

from Eq.(2.117), this Laplace equation determines the nature of VSP and its solutions are specified by *boundary conditions* in steady state. When flow potential creates a shock surface, its velocity is equivalent to velocity field of shock fronts followed by blast waves (i.e., $\vec{u} = \vec{V}$ during collapsing of PVR or during explosion coupled with exploding shock waves) in the absence of viscosity, collision and external field of local isolated system. Since ρ is plasma density that shock wave passes over it and $\vec{\nabla} \cdot \vec{V} = 0$, for fast flowing plasma, and p is the negative dynamic pressure of PVR, local system before shock passage or before collapsing. During collapsing or explosion of local system when the dynamic boundary layer is characterized by constant electrostatic potential, we approximate the imploding shock velocity from Eq.(2.50) in the absence of collision and viscosity that yields

$$\vec{V} \geq \left[\frac{2k}{m_j} \left[T_j - \frac{1}{2} T_{j0} \right] + \frac{2k}{m_j} \int T_j \frac{dn_j}{n_j} + c \right]^{1/2} \hat{r} \quad (2.118a)$$

The quantity c is integration constant that is determined using boundary condition at steady state situation. If the collapsing or growing process of PVR is spontaneous, the integration constant is vanished. In case of sudden collapsing of or strong explosion from point, line or plane, the velocity of fast propagating shock front is predicted from the concept of $V \gg c_s$ and the shock velocity is constant for non-variable shock fronts. The expected minimum value of shock velocity is obtained from Eq.(2.118a) for imploding neutral collapsing plasma spontaneously.

$$V \approx c_s \sqrt{\frac{2}{\gamma}} [1 + \ln \rho]^{1/2} \quad (2.118b)$$

For $\gamma = 4/3$ for all relativistic gases we get that

$$\vec{V} \approx 1.22 [1 + \ln \rho]^{1/2} \vec{c}_s \quad (2.118c)$$

For $\gamma = 5/3$ for non-relativistic monoatomic gases we get that

$$\vec{V} \approx 1.5 [1 + \ln \rho]^{1/2} \vec{c}_s \quad (2.118d)$$

Since $p(r, t)$ is the instantaneous dynamic pressure at radial arbitrary position $\vec{r}$ and time t of collapsing or growing PVR, at initial state it is denoted by $p(r_0)$ at dynamic boundary of PVR. The shock velocity is defined by gradient of velocity shock potential. Thus, $\vec{V} = -\vec{\nabla}\psi$, for

$\psi = \psi(r, t)$ and let we assume the process is spontaneous, $u_{r0} \approx 0$, for the sake of simplicity. Now, we can calculate the value of *velocity shock potential* $\psi(r, t)$ for imploding shock waves followed by imploding blast waves. The positive VSP is approximated from Eq.(2.118a), the imploding or exploding velocity shock potential is given by Eq.(2.119a).

$$\psi = \pm[Kt - V^2t] \quad (2.119a)$$

$$K = \frac{\partial \psi}{\partial t} + \frac{p}{\rho} + \frac{c_s^2}{\gamma} \ln \rho = \text{constant} \quad (2.119b)$$

The quantity K is position independent function for $K \ll V^2$, Eq.(2.119a) results Eq.(2.119c).

$$\psi \approx \pm V^2 t \quad (2.119c)$$

The velocity shock potential given by Eq.(2.119c) can be specified in terms of radial position vector. If we consider the ratio of change in dynamic pressure to density and $\ln \rho$ is constant of the integration Eq.(2.119c) can be expressed by Eq.(2.119d) in terms of position.

$$\psi \approx -rV \quad (2.119d)$$

From Eqs.(2.119c) and (2.119d) we understand that strong VSP depends of propagating velocity through high conductivity medium.

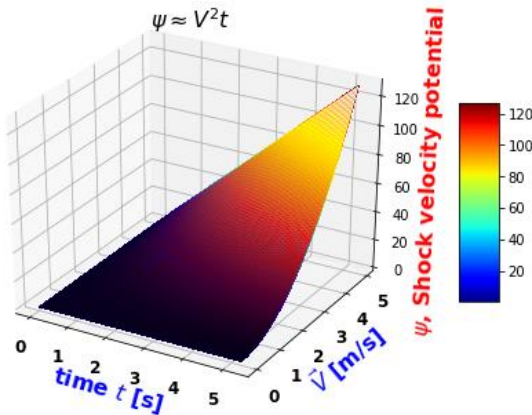


Fig.2.19a Implosive shock velocity potential

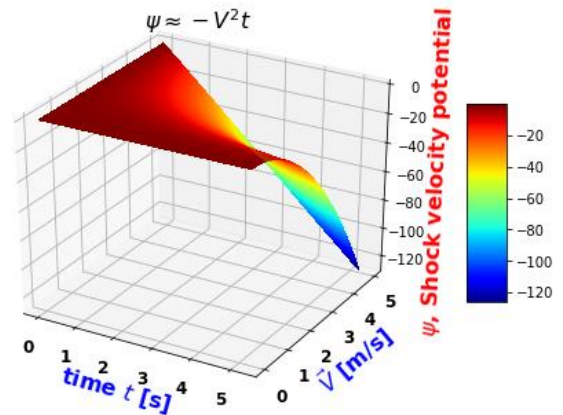


Fig.2.19b Explosive shock velocity potential

From Fig.2.19a and Fig.2.19b, we understand that due to non-linear behavior of shock wave, the process is ceased at large time for both strong and weak shock process. Fig.2.19a shows the strength of shock velocity potential is in maximum limit at convergence point that leads to

sudden collapse of local PVR; the shock velocity potential is connected with strong VP at convergence point. While Fig.2.19b shows the maximum limit of shock velocity potential at initial time in the compacted local region after collapse. When we consider the imploding or exploding plasma suffices quasi-neutrality condition. The shock velocity and corresponding VSP are obtained Eq.(2.50) and using $\vec{V} = -\vec{\nabla}\psi$ in steady state condition, given by Eqs.(2.120) and (2.121) near the convergence point associated with position dependent electrostatic potential.

$$\vec{V}(r) = A_1 \exp \left\{ \frac{1}{2\mu} \left(\frac{1}{2} v r^2 + 2\mu \ln r \right) \right\} \hat{r} - A_1 \exp \left\{ \frac{1}{2\mu} \left(\frac{1}{2} v r^2 + 2\mu \ln r \right) \right\} \int^r \left[\frac{r}{2\mu} \left[\frac{q}{m} \frac{\partial \phi}{\partial r} + \frac{1}{\rho} \frac{\partial p}{\partial r} \right] \exp \left\{ -\frac{1}{2\mu} \left(\frac{1}{2} v r^2 + 2\mu \ln r \right) \right\} \right] dr \hat{r} \quad (2.120)$$

$$\psi = - \int \left(A_1 \exp \left\{ \frac{1}{2\mu} \left(\frac{1}{2} v r^2 + 2\mu \ln r \right) \right\} \right) dr + \int \left(\exp \left\{ \frac{1}{2\mu} \left(\frac{1}{2} v r^2 + 2\mu \ln r \right) \right\} \int^r \left[\frac{r}{2\mu} \left[\frac{q}{m} \frac{\partial \phi}{\partial r} + \frac{1}{\rho} \frac{\partial p}{\partial r} \right] \exp \left\{ -\frac{1}{2\mu} \left(\frac{1}{2} v r^2 + 2\mu \ln r \right) \right\} \right] dr \right) dr \quad (2.121)$$

The value of constant function, A_1 , is determined using the boundary condition concept. The shock velocity and corresponding VSP function given by Eqs.(2.120) and (2.121) are not simple to understand. The presence of plasma viscosity and collision of plasma particles makes the process is so complex. Thus, the propagating shock wave may create turbulence behind of it in steady state condition. The shock wave acceleration coupled with constant plasma density in case of collision-less process is obtained from Eq.(2.119a) and is described by Eq.(2.122a) in terms of shock wave velocity radially.

$$\vec{a} = \frac{1}{2t} \left[\frac{p-p_0}{\rho V} + \frac{K}{V} - V \right] \hat{r} \quad (2.122a)$$

The shock acceleration is inversely proportional to time, see Eq.(2.122a) and the collapsing shock acceleration is arisen due to time dependent velocity shock potential. The shock wave acceleration is given by $\partial \vec{V} / \partial t = \vec{a}$ at non-steady state situation has non-linear behavior, see Eq. (2.122a). If the position constant function K given by Eq.(2.119b) is highly time-dependent, the shock wave acceleration is described by Eq.(2.122b) in unsteady state during collapsing.

$$\vec{a} = \frac{1}{2t} \left[\frac{2c_s^2}{\gamma V} - V + \frac{K}{V} - \frac{t}{V} \frac{\partial K}{\partial t} \right] \hat{r} \quad (2.122b)$$

The imploding shock acceleration is inversely proportional to collapsing radial distance. This shows that at stagnation region, the acceleration of shock wave front is smaller as it travels maximum distance. To predict the intensity of VSP, $\psi(r, t)$, it is important to determine the value of dynamic pressure as functions of density and time at fixed position, $p(\rho(r), t)$ of dynamic boundary. Since, $p(r, 0) = p_0$ at static boundary of PVR, a distance of r away from center of convergence point and value of $\psi(r, t)$ at initial condition $\psi(r, 0) = f(r)$ at electron beam layer boundary. When surface electrostatic potential plays a crucial role for accelerating of charged particles, the VSP given by Eq.(2.119a). In the absence of particle collision, viscosity and other external forces for constant plasma motion, velocity of shock is approximated by

$$\vec{V} = \left[c_0^2 + \frac{2q\phi}{m} + \frac{2}{\rho}(p - p_0) + 2\gamma c_s^2 \ln \rho \right]^{1/2} \hat{r} \quad (2.122b)$$

If the shock velocity is equal to acoustic velocity in aligned radial motion of plasma elements, the VSP is known as *sonic velocity potential*. Near the stagnation region or convergence region the VSP can be included the *viscosity* and *collision* term of incompressible high density plasma. Thus, fast moving shock fronts inside the PVR reflected back and forth many times between the moving boundary and center of PVR before complete collapse of local system. When, $|\vec{v}| = c_s$ speed of sound behind moving shock wave the quantity $\psi = \psi(r, t)$ become sonic shock potential (SSP). The solution of Eq.(2.111) radial component VSP is obtained for both radial imploding shock and exploding shock waves followed by blast waves in terms of velocity shock wave function given by Eq.(2.123a).

$$\psi(r, t) = \frac{1}{r} [f(r + vt) + f(r - vt)] \quad (2.123a)$$

The functions $f(r + vt) = Ee^{ik(r+vt)}$ and $f(r - vt) = Fe^{ik(r-vt)}$ denote the shock wave function and also $\vec{r}$ is measured from the source of shock wave fronts to interest point. The constants E and F are determined using the boundary condition and initial value. The functions $f(r + vt)$ and $f(r - vt)$ are arbitrary shock functions. The function $f(r + vt)$ represents the imploding shock waves to a point while $f(r - vt)$ is exploding shock wave from a point to infinity or from dynamic boundary layer to infinity.

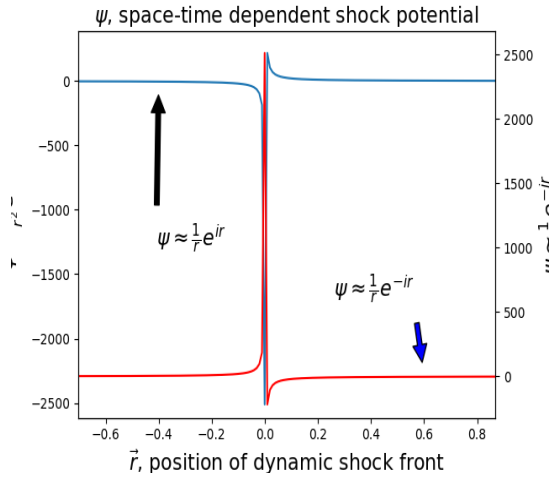


Fig.2.20a Solutions of VSP as solid shock

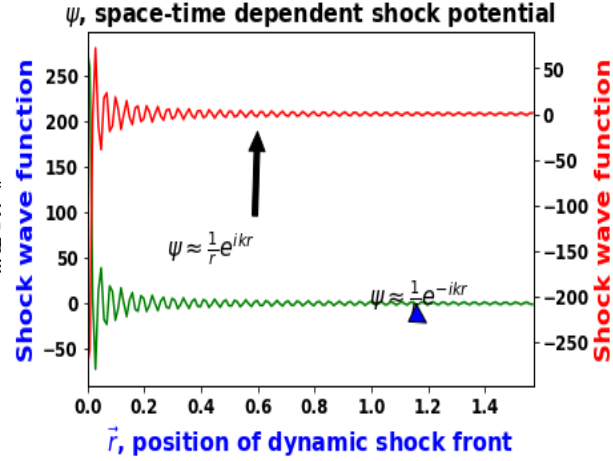


Fig.2.20b Solutions of VSP produces shock trains

As we see from Fig.2.20a, the velocity shock potential has a rapid change near its source or at convergence point. The factor $1/r$ affects only the shock wave magnitude and represents the spreading of the wave energy over larger surface as it propagates away from the source. Fig.2.20b explains that the oscillating amplitude of shock wave increases at convergence region. Thus, the un-stability condition is increasing. Equating Eq.(2.119a) in to Eq.(2.123a) for imploding velocity shock potential, the arbitrary shock wave function of $f(r + vt)$ that is described by Eq.(2.123a) can be expressed as follow.

$$f(r + vt) = [K - V^2]rt \quad (2.123b)$$

We assume that the imploding blast wave has radial component of constant phase velocity $\vec{v}$ behind the imploding blast wave. The shock surface is followed by trains of implosive or exploding blast waves if $\vec{v} \geq \vec{u}_r$ only. The implosive blast wave travels a distance $x = r_0 \pm vt$ where x is the distance travelled by shock surfaces which produces a blast waves with relative to initial distance r_0 boundary position. The relative velocity of blast wave is given by $\vec{u}_r + c_2 \hat{r}$ which implies the moving shock is followed by blast wave. Fig.2.20a represents the behavior of radial functions of shock potential for unity of shock wave number. In Fig.2.20a the red line represents the exponentially growing shock wave function while the blue line represents the exponentially decaying shock wave function. The solution of shock velocity potential that is defined by Eq.(2.123a) for both implosive and explosive shock velocity potential is well illustrated in Fig.2.20a and Fig.2.20b. The graphs of Fig.2.20a and Fig.2.20b show for both

implosive and explosive cases. The shock velocity potential has maximum strength at initial time and finally vanished as time is progressed.

2.15.4. Analytical solution of implosive and explosive waves

When the collapsing cavity is filling up with highly shocked dense compacted plasma, the imploding plasma bounces back or ceases its motion at convergence point instantly. The secondary shock wave fronts are generated and followed by strong explosive blast waves at the compacted plasma region. The surrounding plasma continuous it's imploding to center of convergence until VP is disappeared. Interaction of imploding shock waves with reflected imploding shock waves makes the process is more dynamic and complex. If we assumed that the collapsing process is collision-less and there is no effects of plasma viscosity, ions and electrons of compacting plasma enter to charged particle runaway condition quickly. Thus, the collapsing and compacting plasma is highly unstable. The reflected high pressure plasma element continuously changes its behavior across the shock waves. This shock discontinuity creates the front of advancing blast wave system as it progresses further outward.

Let us consider the radially expanding shock wave followed by the sudden release of some large amount of energy E from a small cell volume, as in an explosion of detonation. Let us further consider that the shock wave at times t after the time of the energy release $t_0 = 0$, has propagated to some radial distance $\vec{r}$ that is large compared to the original radius of small compacted region that total energy is deposited. We will find that the motion is determined solely by the explosion energy, and the initial density and thermodynamic characteristics of the plasma into which the shock wave is propagating. This problem was first considered and solved by Sedov in 1946 for neutral explosive plasma or gas particles. At that time, the Sedov blast wave has reached a radius, $\vec{R}$, contained within the volume behind the blast wave is a mass of plasma element and density of small compacted region before explosion shock is denoted by ρ in Eq.(2.124). Let consider the collapsing cavity of PVR is created inside a dense perturbed plasma fluid at stellar atmosphere. The collapsed cavity was a sphere of initial radius position $\vec{r}_0$ of isolated local region. Thus, we obtain a compacted mass, M , is described by Eq.(2.124).

$$M = \frac{4}{3}\pi R^3 \rho \quad (2.124)$$

We can calculate the shock speed associated with blast wave due to dynamic pressure difference between the convergence point of PVR and high density surrounding plasma. The VSP creates a high blast wave or explosive wave that swept out plasma mass to surrounding. In spherical symmetric, the linear wave Eq.(2.112) of isolated system has solution given by Eq.(2.123a) analytically. For supersonic flow, the minimum velocity of flowing plasma associated with shock wave is equals to plasma acoustic velocity $\vec{v} \geq c_0 \hat{r}$, and $\psi = \psi(r, t)$ is the VSP for imploding cavity. Sonic VSP is also the source of shock waves and it accelerates electrons and ions non-thermally across shock fronts. Where, $r(t) = r_0 \pm R(t)$, r_0 is initial radius of the collapsed cavity which VSP is independent position and time at initial state. The general solution of Eq.(2.112) is given by Eq.(2.125) in terms of shock wave functions.

$$\psi(r, t) = r^{-1}[f(r + c_s t) + f(r - c_s t)] \quad (2.125)$$

The solution $r^{-1}[f(r + c_s t)]$ represents for sonic wave is propagating radially inward while $r^{-1}[f(r - c_s t)]$ is propagating radially outward. The source of shock wave is at small point in case of explosive secondary shock fronts while at the initial dynamic boundary of PVR for primary shock fronts. Let we considered speed of sound is constant at background plasma fluid is c_s , of the unperturbed media. The mass of fast flowing plasma jet is negligible when we compare to mass of the whole plasma of star.

Our focus is at small local system or micro system of huge global plasma system. The velocity and change in pressure of local system for imploding primary shock fronts and exploding shock waves followed by blast wave can be calculated by Eqs.(2.126a), (2.126b) and (2.126c) describe sonic shock wave. When plasma number density remains constant across the non-radiative moving shock wave, only heat energy and magnetic energy may be generated by the moving shock wave. From Eq.(2.50), replacing velocity of flowing plasma by velocity of shock front to fulfill its minimum requirement of shock wave propagation through high conductivity plasma, we get Eqs.(2.126a) and (2.126b) in terms of electron temperature gradient and ion temperature gradient respectively.

$$\vec{V} \approx 1.52 \times 10^6 \vec{\nabla} [\int T_e(r, t) dt - T_e(r) t] \quad (2.126a)$$

$$\vec{V} \approx 8.25 \times 10^3 [\int \vec{\nabla} T_i(r, t) dt - \vec{\nabla} T_i(r) t] \quad (2.126b)$$

The Eqs.(2.126a) and (2.126b) show that steep temperature gradient is the cause of sonic shock during spontaneous plasma flow. To find velocity of moving shock arises from spontaneous plasma flow, let we define the traveled distance by shock fronts in terms of dimension-less parameter, α using Eq.(2.125) and $V = -\partial\psi/\partial r$ the shock velocity is given by Eq.(2.126c) for imploding shock waves followed by blast waves for negligible radiation effect.

$$\vec{V} = \frac{\alpha^3 c_s}{1-\alpha^2} \left[\left(1 + \frac{1}{\alpha}\right)^2 - 2 \left(1 + \frac{1}{\alpha}\right) \right] \hat{r} \quad (2.126c)$$

Where, $\alpha c_s t = Vt$ and $\alpha \gg 1$, for $V \gg c_s$, the dimensionless parameter α relates the distance travelled by moving shock surface with distance travelled by small pressure disturbance waves.

$$\psi = \frac{\alpha^4 c_s^2}{1-\alpha^2} t \left(1 + \frac{1}{\alpha}\right)^2 \quad (2.127)$$

$$p - p_0 = \frac{\rho \alpha^4 c_s^2}{\alpha^2 - 1} \left(1 + \frac{1}{\alpha}\right)^2 \quad (2.128)$$

The shock wave function and difference in dynamic pressure can be defined in terms of the dimensionless parameter. This helps to simulate the propagating shock wave followed by blast wave through high conductivity plasma fluid during implosion or explosion. We consider that the radial flow from a point, to simulate the explosion, we assumed that the exploding shock front is to be spherical shell which suffices spherical symmetry of radial flow. The blast wave or explosive wave propagates behind of shock fronts that pushed the surrounding plasma which was engulfed by the headed moving shock fronts. The blast waves which moves behind of the moving shock wave is described by linearized form Eq.(2.111) and its solution is given by Eq.(2.123a) propagating behind the fast moving shock fronts. The blast wave or explosive wave fronts may propagate in front of the small disturbance or behind the small disturbance inside the shocked spherical region.

2.15.5. Propagation of slowly and fast exploding blast wave

Let us consider the blast wave or explosive wave fronts that are propagating before the small disturbance or behind the small disturbance. The exploding shock front travels a radial distance of $\vec{R}(t)$ before the imploding or exploding blast wave. The position of blast wave inside the shocked spherical region is denoted by $\vec{r}(t) = \vec{v}t = \alpha c_s t \hat{r}$ implies that $0 < \alpha < 1$ for slow

propagation of blast wave behind shock while $\alpha \gg 1$ for fast imploding or exploding shock waves which is followed by blast waves, the fast moving shock wave propagates before small disturbance. The relative position of exploding blast wave behind shock front is $\vec{w} = (\alpha - 1)c_s t$ inside exploding sphere. The relative velocity of slow blast wave for constants α and c_s is specified by $d\vec{w}/dt = \vec{w}/t$ that yields $d\vec{w}/dt = (\alpha - 1)c_s < c_s$ for slow blast waves and $d\vec{w}/dt = (\alpha - 1)c_s > c_s$ for fast propagating imploding or exploding blast waves preceded by fast moving shock waves. When the dimension-less parameter $\alpha(r, t)$ is position and time dependent, acceleration of implosive or explosive blast wave is given by $d^2\vec{w}/dt^2 = c_s d\alpha(r, t)/dt$ behind of moving shock front. This shows acceleration of imploding or exploding blast waves behind the fast moving shock fronts. Acceleration of blast wave through high conductivity completely ionized plasma creates discharging of electrons and ions. The discharging process arises due to absence of plasma viscosity and collision. The bulk accelerating plasma creates out flowing plasma jet from small local region.

The undisturbed ambient plasma outside of the first propagating shock front with $\vec{v} = 0$ and $p = p_0$ at position $\vec{r}(t) = \vec{u}t$ remains undisturbed at infinity large distance far away from center of explosion. The blast wave potential, velocity of blast waves inside the imploding or exploding sphere and change in pressure between shocked plasma and dynamic boundary are described by Eqs.(2.129a) to (2.130c). For $\alpha \ll 1$ the velocity shock potential is approximated as

$$\Psi \approx \frac{\alpha^2}{1-\alpha^2} c_s t \quad (2.129a)$$

$$V \approx \frac{\alpha}{1-\alpha^2} c_s \quad (2.129b)$$

$$p - p_0 \approx \frac{2\alpha^2}{1-\alpha^2} \rho_0 c_s^2 \quad (2.129c)$$

For $\alpha \gg 1$ corresponding fast exploding blast shock propagates behind of small disturbance

$$\Psi \approx \frac{c_s \alpha^4}{1-\alpha^2} t \quad (2.130a)$$

$$V \approx \frac{c_s \alpha^3}{\alpha^2 - 1} \quad (2.130b)$$

$$p - p_0 \approx \frac{2\rho_0 c_s^2 \alpha^3}{\alpha^2 - 1} \quad (2.130c)$$

The relationship between velocity shock potential of implosive and explosive process can be described by the following velocity shock potential versus time, velocity and pressure graphs.

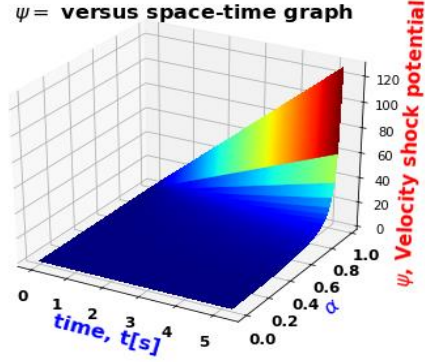


Fig.2.21a Non-linear behavior of velocity shock potential generates slow propagating shock

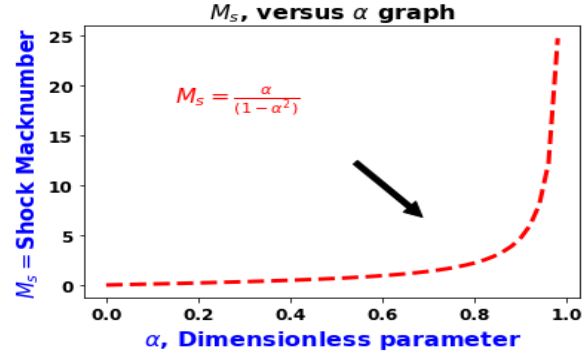


Fig.2.21b Velocity of blast wave behind slow propagating shock wave

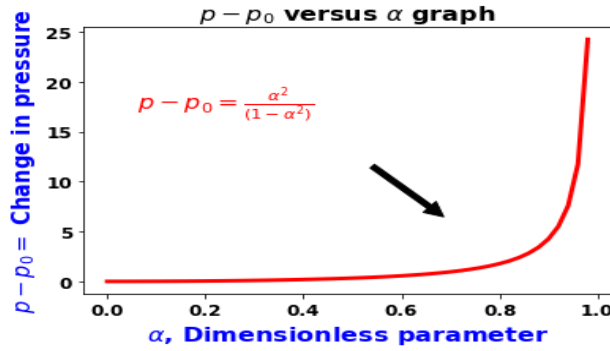


Fig.2.21c Change of dynamic pressure across slow propagating shock wave front

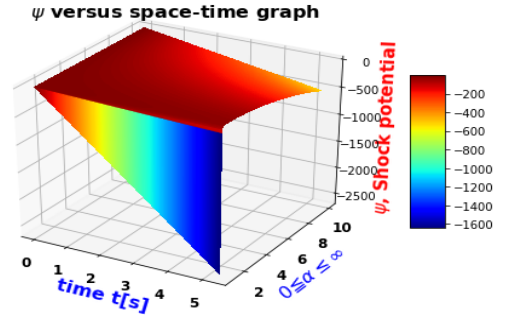


Fig.2.21d Non-linear behavior of velocity shock potential generates fast propagating shock wave

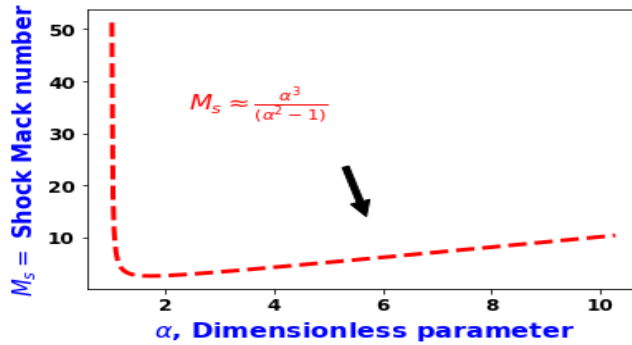


Fig.2.21e Velocity of blast wave behind fast propagating shock wave

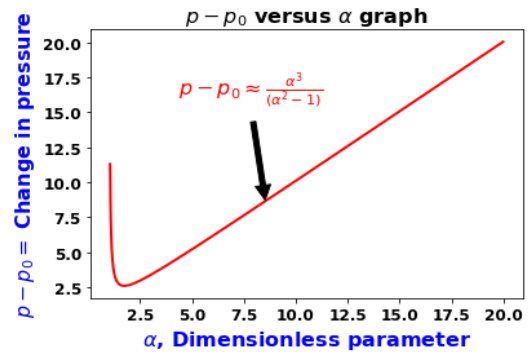


Fig.2.21f Change of dynamic pressure across fast propagating shock wave front

These plots are illustrated from Eqs.(2.129a) - (2.130c) which describes the behavior of shock induced blast waves, associated dynamic pressure change and corresponding velocity of shock. Fig.2.21a shows the non-linear relation of velocity shock potential in space-time coordinate in non-relativistic sense in slow exploding sonic shock process (i.e., during explosion). The graphs of Fig.2.21b and Fig.2.21c show the non-linear relation of shock Mach number with position and change in dynamic pressure with position respectively in case of slow shock wave process. In similar manner, the graph of Fig.2.21d indicates the shock velocity potential so complex in space-time coordinate for fast shock process (i.e., during explosion). The relationship between shock Mach number and position, and change in dynamic pressure and position during explosion process is well described by graphs of Fig.2.21e and Fig.2.21f respectively. In Fig.2.21a - Fig.2.21f the dimensionless parameter α represents the ratio of distance travelled by shock front to Debye length.

2.16. Energy Estimation of Explosive Instant Compacted Local Region

The source of explosion energy is the internal energy of compacted high conductivity non-magnetized plasma fluid. Even in the absence of plasma resistivity, huge amount of stored energy is released in the forms of kinetic energy, heat energy, and radiation energy and magnetic energy due to anomalous resistivity across shock wave fronts. The released amounts of energy can be approximated by using the power law energy distribution behind the shock fronts in connection with blast waves. The total energy is stored at high conductivity compacted plasma of local system. It is represented by E_t and would be stored at small local region of radius, r_c due to imploded strong shock followed by imploded blast wave. As the total energy is released, it is time dependent as we see from Eq. (2.131) for real parameter $n \geq 0$ during explosion.

$$E_t = E_0 t^n \quad (2.131)$$

The quantity E_0 is initial constant energy before exploding of blast waves and n is constant real number. The case $n = 0$ corresponds to the shock wave followed by blast wave or explosive wave has constant energy. When $n \geq 0$ in case of imploding or exploding events, the total energy increases with time. The dissipation effect is ignored in the absence of particles collision and viscosity for the sake of simplicity behind the moving normal shock fronts. The radial flow suffice in spherical symmetry unsteady inflow behind shock fronts relate to VSP in connection

with blast wave can be expressed by the following equations behind of imploding or exploding shock waves:

$$\frac{\partial \rho}{\partial t} + \rho \frac{\partial v}{\partial r} + v \frac{\partial \rho}{\partial r} + \frac{kv\rho}{r} = 0 \quad (2.132a)$$

$$\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial r} + \frac{1}{\rho} \frac{\partial p}{\partial r} = 0 \quad (2.132b)$$

$$\frac{\partial}{\partial t} (p\rho^{-\gamma}) + v \frac{\partial}{\partial r} (p\rho^{-\gamma}) = 0 \quad (2.132c)$$

The variable functions ρ , v , and p are mass particle density, particle velocity and pressure behind shock wave respectively, are position and time dependent. The value of $k = 0, 1, 2$ represent for plane, cylindrical and spherical coordinates respectively in Eq.(2.132a). In case of imploding shock waves, the distance traveled by shock front is $|\vec{r}| < |\vec{r}_0|$ converges at a point while for primary and secondary exploding shock, $|\vec{r}| > |\vec{r}_0|$ converges at infinity. If we consider the energy stored in small local region include electrical energy and magnetic energy in addition to thermal and internal energy, Eq.(2.132c) can be defined by Eq.(2.133) across shock wave front.

$$\frac{\partial}{\partial t} \left(\frac{1}{2} \rho u^2 + \frac{p}{\gamma-1} + \frac{1}{2} \epsilon_0 E_r^2 + \frac{B^2}{2\mu_0} \right) + \frac{k}{r^k} \left(r^k u \left[\frac{1}{2} \rho u^2 + \frac{\gamma p}{\gamma-1} + \frac{1}{2} \epsilon_0 E_r^2 + \frac{B^2}{2\mu_0} \right] \right) = 0 \quad (2.133)$$

Let $x = r/R$ where, $R = R(t)$, distance is travelled by the shock fronts. Thus, $x = 1$ represents the locus of the shock wave front. For $x < 1$, represents the situation behind of shock fronts while for $x > 1$, the situation before the reachability of shock fronts. The solution of strong shock front in connection with exploding blast wave in self-similar form, the velocity of blast wave, sudden change in pressure and mass density through high conductivity plasma are expressed in terms of shock velocity.

$$v = \pm \frac{2}{\gamma+1} V \quad (2.134)$$

$$p = \pm \frac{2}{\gamma+1} \rho_0 V^2 \quad (2.135)$$

$$\rho = \rho_0 \frac{\gamma+1}{\gamma-1} \quad (2.136)$$

The negative sign in Eqs.(2.134) and (2.135) shows the streaming of local plasma is towards center of convergence. The stored total energy before explosion is denoted by E_0 . When the local region is exploded due to formation of secondary shock waves, the distance travelled by exploding shock in connection with the stored energy excluding viscosity, collision and electric potential energy is specified by Eq.(2.137) for neutral plasma fluid.

$$R(t) = \mathcal{H} \left[\frac{\gamma+3}{n+2} \right]^{\frac{2}{(\gamma+3)}} t^{\frac{(n+3)}{\gamma+3}} \quad (2.137)$$

Where, $\mathcal{H} = \left[\frac{E_0}{\rho_0} \frac{(\gamma+1)^2}{2^{\gamma+1} \pi^{1/2} \gamma^{(3-\gamma)}} \frac{1}{\left[\frac{1}{\gamma-1} + \gamma^2(\gamma-1) \right]} \right]^{\frac{1}{(\gamma+3)}}$, the blast wave propagates behind of the moving shock wave travels a distance given by Eq.(2.137) that describes the propagation of sonic shock waves through high conductivity pre-unmagnetized neutral plasma.

2.16.1. Energy of explosive (blast) wave

The sudden release of large amount of energy, E from the small locally compressed region that surrounded by high conductivity background plasma with density of ρ_0 creates a strong explosion. It is identified by infinitely trains of fast moving shock fronts followed by intense explosive or blast waves emanated from small compacted local region. This explosion is occurred due to formation of intense intrinsic explosive, VSP, in the same principle as detonation process of solid explosive materials. The expected source of explosion is the collapsed current sheet due to strong response of high negative dynamic pressure at the center of convergence region, see chapter 2 Eqs.(2.74a), (2.74b), (2.75a), (2.75b), (2.76a), (2.98) and (2.99).

The exploding shock wave propagates in spherical harmonic oscillation mode. However, in this model it is much difficult to solve the second order partial differential equation in spherical harmonic oscillation numerically due to complex nature of shock waves dynamics. Here, we focus that the exploding shock wave propagates in radial direction so as to minimize complexity. The exploding shock wave propagates a distance of $r(t)$ for $r(t) \gg r_c$ and the mass is swept out or ejected from the small local region by the generated strong explosive wave surfaces. The swept out plasma mass coupled with exploding shock surface is specified by Eq.(2.124).

$$M_e = \frac{4}{3}\pi m_e n_e r^3 \quad (2.138)$$

This ejected plasma mass pushes the background high conductivity plasma. Some of the background plasma particles are accelerated by the exploding shock fronts. The mass n_e denoted the number electron density that is ejected behind of infinitely strong shock wave passage. Velocity of the fast moving shock is given by $\vec{V} = \vec{R}/t$ followed by blast waves. Total kinetic energy and thermal energy of the ejected plasma elements behind shock fronts is calculated.

$$E_{kin} = \frac{2}{3}\pi\rho\frac{r^5}{t^2} \quad (2.139)$$

$$E_{th} = \frac{1}{2}kT \quad (2.140)$$

The quantities $P(r, t)$, $\rho(t)$ and $T(t)$ are specified behind the explosive shock fronts. Since electron, neutral and ion are accelerated by shock surface, radiation pressure from the accelerated electrons and ions of plasma jet may plays a crucial role even in non-radiative shock waves. The total energy behind of the shock surface across neutral plasma is mainly given by Eq.(2.141) for negligible shock wave induced electric field and magnetic field behind ejected plasma radiation.

$$E_2 = \left[\frac{2\pi\rho_2}{3} \frac{r^5}{t^2} \left(\frac{\gamma+1}{\gamma-1} + \frac{2}{\gamma+1} \right) \right] + \frac{16}{3c}\pi\sigma r^3 T_2^4 \quad (2.141)$$

The subscript 2 represents the state behind of moving shock while the subscript 1 represents the state before shock. These shock surface moves with a radial velocity of $\vec{V}(r, t)$ and engulfs plasma density of ρ_1 before the expected explosive shock fronts. The density of plasma ρ_2 behind the secondary shock surface has dynamic pressure of P_2 and plasma element flows with lower velocity $\vec{u}_2$ behind the secondary shock surface (i.e., $\vec{V} \gg \vec{u}_2$) is assumed. The dynamic pressure behind fast moving shock wave is related with the state before shock wave is given by Eq.(2.135), describes the dynamic pressure. Radiation energy and compressive pressure behind the shock surface are given by $E_{rad} = h\nu$ and $p_{rad} = \frac{4\sigma}{3c}T^4$ where h and ν are planks constant and electromagnetic frequency respectively.

We assumed that the radiation is thermal radiation behind of shock passage which affects the surrounding high conductivity collision-less plasma in the absence of electric field and

magnetic field. Most probably the non-thermal radiation is relativistic radiation. The intense radiation pressure is generated by shock wave [211]. From the explosive shock waves we can observe a secondary light while from the primary imploding and exploding shock waves we observe the primary light. If the shock wave is radiative shock, the shock front could be a source of radiation. However, in this model the primary light or first light is existed not only thermal radiation but from non-thermal radiation due to the induction of intense electric field and presence of surface induce magnetic field, and fast propagating shock waves. In both primary and secondary shock waves non-thermal acceleration due to infinitely intense shock wave is inevitable.

2.17. Summary

Before the development of SWIF-1SQR model, it is clearly defined that how the surface plasma dynamics is described with concomitant plausible plasma theory and kinetic theory integrated with evolution of electric field and magnetic field. From observational view point, the global nature of stellar surface is stated in steady state or hydrostatic situation with continuous emission of electromagnetic radiation and accelerated particles from its surface for ignorable effects of magnetic field. When the star has been treated in steady state situation, electrostatic potential is developed on its uniformly rotating surface. The agent of stellar surface electric field is the migrating electrons from interior to surface. The electron depletion on the stellar surface determines the age of the star. Migration of electrons from stellar interior to its surface in steady state situation provides radial steady surface current that is predicted using symmetry condition. The radial steady surface current generates most probably non-radial magnetic field. The non-radial magnetic field interacts with the pre-existed magnetic field, if there, and confines the stellar materials from dispersing to surrounding strong vacuum potential space.

However, from contemporary observational evidences, the solar surface is in small perturbation about the equilibrium condition. It is observed that plasma element is in highly dynamic motion at local region of stellar atmosphere. This dynamic motion is raised from surface convection, surface non-radial oscillation and turbulence motion of local surface plasma. The local surface electron plasma steep density gradient creates strong charge separation. Due to the steep density gradient associated with surface plasma turbulent, a local low density cavity

(PVR) is developed at stellar atmosphere. The formation of PVR is well known at high conductivity completely ionized plasma associated with shock surfaces. A small sized PVR is also created interior of the star, at convection zone, during local nuclear reaction, due to steep temperature gradient that brings convective bubble of hot plasma reaches at stellar surface. The adiabatic convection process and plasma quasi-neutrality process is violated at stellar surface.

Moreover, we are focused on PVR that is formed on the stellar surface and above. The non-radial oscillation of stellar surface may create local PVR at photosphere, mass deficiency region and nearby mass excess region coupled with surface plasma convection and turbulence. Due to extreme difference in dynamic pressure at convergence point and surrounding plasma, the VSP is created during sudden collapsing of PVR due to strong vacuum potential (VP) development at center of convergence. Here, we assumed that the collapsing or growing cavity (PVR) is in local spherical coordinate. The high conductivity plasma is instantly compacted at convergence region followed by sudden explosion. The fast moving imploding or exploding shock wave generated instant intense over-voltage electron current near the convergence region. The shock induced imploding or exploding current generated strong local magnetic field with its strength intensity is comparable to star-spots (sunspots) magnetic field strength. The shock induced secondary complex magnetic field brings a strong blown of clamps of magnetized plasma, CME from small local region. The SWIF-1SQR model manifests the delivery of stellar flares, CMEs and electromagnetic wave burst from stellar, solar, atmosphere.

CHAPTER 3

3. SHOCK WAVE INDUCED FLARE IN SOLAR ACTIVE REGION

3.1. Aim of SWIF-2SAR Model development

In this thesis chapter, our aim is to advance a physical model which predicts and explains energy of stellar explosive events in-connection with force free magnetic field. Solar atmosphere is characterized by inhomogeneous force free or non-potential magnetic field associated with its highly dynamical nature of rare dense hot plasma [212, 213]. Electron and ion move along the force free magnetic field line at strong magnetic flux region of solar atmosphere with small drift across magnetic field lines. However, where the thermal energy of super-hot plasma is dominant at the region where weak magnetic field fluxes, plasma particles may move in random direction, *see chapter 2, section 2.2 - 2.9.*

The dynamical nature of solar atmosphere plasma coupled with complex magnetic field is a main cause of solar explosive events such as solar flares and CMEs (i.e., that is theorized by SWIF-1SQR model as we have seen before in chapter 2). Many observations from LASCO, YOHKOH, SOHO, SDO and other observatory stations show that, more impulse solar flares are frequently existed and more populated at the solar active region than quite region. From observational view point, we can suggest that intense solar explosive events are frequently occurred at solar active region. The strong solar magnetic field intensifies the explosive events most probably occurred at solar atmosphere region between 15 degree and 65 degree latitude of both north and south [214, 215]. The shock wave induced flare in solar atmosphere, SWIF-2SAR model, is differed from the first model, SWIF-1SQR model because of the presence force free or non-potential complex and strong magnetic field. Flares which can be modeled by SWIF-2SAR model occurred everywhere on the solar atmosphere at a region where strong magnetic field while solar flares that can be modeled by the first model, SWIF-1SQR model, defines the region of weak magnetic field. The second SWIF-2SAR model of solar flares is developed based on the idea of shock wave acceleration in magnetized plasma associated with fast magnetic reconnection (FMR) theory model, *see chapter 4, section 4.7.*

The idea of Fermi like acceleration and shock wave acceleration associated with the concept of fast magnetic reconnection theory in high conductivity plasma fluids leads to the formation of extreme intense solar explosive events. The problem of slow magnetic diffusion which hinders the fast magnetic reconnection problem is solved by the effect of surface shock wave acceleration associated with high magnetic pressure and formation of PVR followed by strong implosion-explosion process. Thus, SWIF-2SAR model is the continual of SWIF-1SQR model most probably effective at upper layer of inhomogeneous magnetized stellar photosphere, chromosphere and corona.

3.2. Magnetized Plasma Flows at Solar Active Region

Several data from YOHKOH X-ray telescope show that solar active region temperature ranges from 3MK to 10MK at corona and during intense flares [216]. However, the temperature of solar active region at solar surface is at lower temperature relative to the solar quiet region [217]. This inhomogeneity in temperature on solar surface is due to existence of discrete bundle of closed and opened magnetic flux tubes. Foot points of strong magnetic flux tubes are anchored at deep solar photosphere having a magnitude from 10G to 3000G [218, 219]. Random motion of plasma at active region of solar atmosphere is prohibited from diffusing across magnetic flux tubes [220].

Let we assume that magnetic flux tubes are most probably radial at the thin layer solar photosphere. Horizontal flowing plasma outside magnetic flux tubes are in random motion at high collisional local system of solar surface is occurred. Due to plasma pressure perturbation, an alignment of flowing plasma is occurred inside and outside magnetic flux tubes. The aligned horizontally flowing photosphere plasma pushes the magnetic flux tubes wall and bounce back. Most of plasma particles do not cross the strong magnetic flux tubes. When the aligned plasma streaming exerts high pressure, the magnetic flux tube may be deformed. Collisions between magnetic flux tubes and head on fast flowing plasma create a shock and Fermi like acceleration, *see chapter 4, section 4.7*. Based on the first model (i.e., SWIF-1SQR model) when parcel of fast flowing hot plasma density is higher than the background density, electrons move in front of ions and they induces an intense surface electric field at the front surface boundary of plasma element. When ions and electrons are at the same temperature, and if inertial velocity of electrons and ions are greater than their thermal velocity, electrons and ions enter to electron

runaway, and ion runaway condition [135, 221, 222]. When the fast moving plasma elements collide with wall of magnetic flux tube, fast moving electrons push the wall of magnetic flux tubes faster than ions. And, bounce back with velocity is twice their incident velocity.

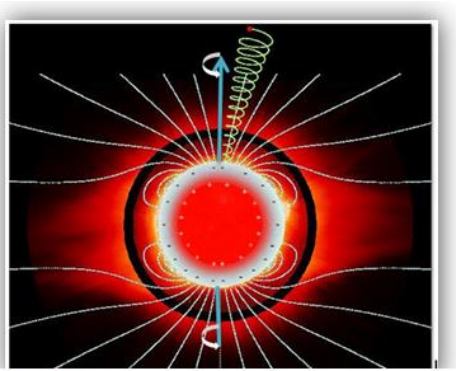


Fig.3.1 *rotating magnetized active star/sun*

Some of the fast moving electron and ion may be trapped by the strong magnetic surface flux tubes. These trapped particles drift towards the center of magnetic flux tubes due to high magnetic gradient. However due to instantaneous charge separation process, a strong shock is developed inside the magnetic flux tubes as well as around of the magnetic flux tubes. Electron and ion decrease their

velocity on the surface of magnetic flux tubes suddenly. The abrupt change of electron and ion velocity before bouncing is due to wave-particle interaction and overloading of phase velocity of gyrating electron and ion on surface of magnetic flux. So, the expected bouncing velocity of electron and ion must be greater than twice their incoming velocity. This shows that energetic particles are created on magnetic surface due to non-thermal effect. Before we develop our second model of strong solar flares, SWIF-2SAR model, let us explain the nature of stellar surface and atmosphere associated with its rotational, oscillation effects in the presence of complex magnetic flux, and arbitrary topology of magnetic fields, presence of strong electric currents at solar atmosphere briefly.

3.3. Effects of Magnetic Fields on Rotating Stellar Surface and Atmosphere

The star is made up of a self-gravitating giant ball of plasma cloud situated at low density space vacuum. Like most astronomical objects the sun rotates on its rotational axis at the center of solar system. However, based on differential rotation theory, different part of the star rotates at different rate. We can detect rotation of stellar surface by observing the motion of solar structures such as sunspots on the visible solar surfaces, prominences, magnetic flux tubes and coronal holes [94, 135, 223 - 225]. The local regions of the solar surface near its equator rotate once about every 25 days [226]. The Sun's surface rotation rate decreases with increasing

latitude, so that its surface rotation rate is slowest near its poles, *see* Fig.3.2. At its poles the Sun rotates once about every 35 days [69]. The interior of the Sun does not spin the same way as does its surface. Scientists believe that the inner region of the Sun, including the Sun's core and radiative zone, do rotate more like a solid body. The outer parts of the Sun, from the convective zone outward, rotate at different rates that vary with latitude [227]. The boundary between the inner parts of the Sun that spin together as a whole and the outer parts that spin at different rates is called the "tachocline" [69].

The behavior of the Sun's magnetic field is strongly influenced by the combination of convective currents, which bring the charged particles from deep within the Sun to the Sun's surface, and the differential rotation of the outer layers of the Sun. Differential rotation is apparently the main driver of the 11 year sunspot cycle and the associated 22 year solar cycle [228]. The notion that differential rotation and convective motion drive these cycles was first put forth in 1961 by the American astronomer Horace Babcock, and is now known as the Babcock Model [229, 230].

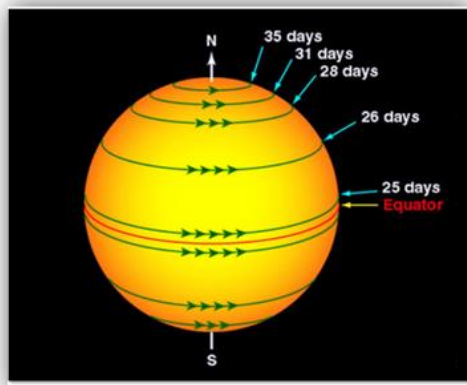


Fig.3.2 Surface rotation of active sun

Let us consider a parcel of plasma having a position vector field $\vec{r}$ fixed on the surface of the rotating star. The surface of the star rotates at a uniform angular velocity, $\vec{\Omega} = \vec{\Omega}(\theta)$, the velocity of the parcel of plasma relative to the rotating system of the solar surface has a velocity of $\vec{v} \neq 0$ while relative to the non-rotating system is $\vec{u} = \vec{\Omega} \times \vec{r}$, and considering the spherical layer of the solar photosphere which consists of a strong inhomogeneous magnetic flux tubes and partially

ionized plasma. The momentum equation describes the movement of plasma particles at the stellar surface. It is possible to predict the velocity of solar energetic particles coupled with force-free oscillating magnetic field lines. To model the solar atmosphere, using the spherical coordinate is more natural than other coordinates. The spherical coordinate divides the star into longitudinal (meridians), which are South-North lines extending from the South Pole to the North Pole and latitudes (parallels), which are West-East lines parallel to each other extending around the star.

Inertial acceleration of surface plasma elements, on solar surface is derived by considering that, to an observer fixed in space, the absolute velocity of the plasma element (ms^{-1}) of a parcel of plasma in motion near the surface of the lower part of solar photosphere is given by $\vec{v}_A = \vec{v} + \vec{\Omega} \times \vec{r}$, where $\vec{v}$ is the local velocity of plasma element, defined as local vector, $\vec{v} = v_r \hat{r} + v_\theta \hat{\theta} + v_\phi \hat{\phi}$ and the horizontal local velocity vector is given by $\vec{v}_h = v_\theta \hat{\theta} + v_\phi \hat{\phi}$ in spherical coordinate. The quantity represented by $\vec{\Omega} \times \vec{r}$ is rate of change in position of plasma element due to solar rotation. The solar angular velocity vector ($rad\ s^{-1}$) and radius vector (m) are defined as $\vec{\Omega} = \Omega \sin \theta \hat{r} + \Omega \cos \theta \hat{\phi}$ which is constant at stellar surface for the sake of simplicity. Local acceleration is the rate of change of velocity of plasma element fluid in motion of rotating magnetized stellar atmosphere relative to coordinate system fixed on star includes Coriolis acceleration and centrifugal acceleration. The Coriolis acceleration is the change of velocity of parcels of plasma due to rotation of spherical star underneath the partially ionized photosphere plasma.

The solar centrifugal acceleration field is the outward directed rate of change of velocity field of parcel of plasma due to its motion around the solar axis. As we have seen in chapter 2, the stratified surface plasma of rotation star at steady state or static equilibrium situation generates instantaneously static surface electric field. Stellar surface charged particle distribution at steady state or equilibrium situation of isothermal condition coupled with constant magnetic beta parameter is given by the following Eq.(3.1).

$$n_j = n_0 \exp \left\{ - \left[\frac{q_j \phi}{kT} + \frac{m_j \Phi_g}{kT} - \frac{1}{2} \frac{m_j \Omega^2}{kT} r^2 \sin^2 \theta \right] - \int (\vec{K}_1 \cdot d\vec{s}) + \int \frac{2\beta_j}{R_c} \hat{n} \cdot d\vec{s} + \frac{q}{kT} \int \vec{K} \cdot d\vec{s} - \frac{mv}{kT} (\vec{v} \cdot \vec{s}) + \frac{2m}{kT} (\vec{A} \cdot \vec{s}) + c \right\} \quad (3.1)$$

The functions $\frac{1}{p_j} \vec{\nabla}_\perp \left(\frac{B_0^2}{2\mu_0} \right) = \vec{K}_1$, $\vec{A} = \vec{\Omega} \times \vec{v}$, $(\vec{\Omega} \times \vec{r}) \times \vec{B}_0 = \vec{K}$ and $\vec{r} = \vec{r}_0 + \vec{s}$. The parameter β_j is magnetic beta which is constant at isothermal layer with constant magnetic field strength. The radius of magnetic curvature and its unit vector pointing to center of curvature is given by R_c and $\hat{n}$ respectively. The displacement $\vec{s}$ is considered as a fixed point above the critical stellar surface and measured from stellar critical surface. The integration constant c could be determined using the boundary condition in steady state situation. The constant parameter v is

particles collision frequency and $\vec{v}$ is velocity of plasma elements in steady state. At static equilibrium the particle collision effects and Coriolis effects are vanished as $\vec{v}$ is vanished. The integration is extended from solar radius of $\vec{r}_0$ to some height of $\vec{r}_0 + \vec{s}$ at isothermal layer of stellar atmosphere coupled with constant *magnetic beta*. The Eq.(3.1) is similar to Eq.(2.1) at static equilibrium situation except the last two magnetic terms inside the brace.

The additional magnetic terms in Eq.(3.1) indicates the effect of collisions of plasma particles and effect of magnetic fields. The effect of plasma viscosity in steady state introduced a non-linear effect that makes the system is so complex. In Eqs.(2.1) and (3.1), we use the assumption of that isothermal and convective stellar surface layer moves with constant angular rotational velocity $\vec{\Omega}(\theta)$ on solar surface. In steady state or static equilibrium it is a good assumption that the magnetized isothermal plasma is considered as incompressible high conductivity plasma.

3.4. Stellar Surface Pressure at Equilibrium Coupled with Magnetic Fields

The stellar surface is emitting electromagnetic radiation and particle radiation in steady state monotonously. This continuously production of electromagnetic radiation, particle radiation and relatively uncommon phenomena such as stellar explosive events accompanied with evolution of magnetic fields and stellar rotation are arisen from deviation about equilibrium state. From linearized momentum equation of constantly rotating in-homogeneously stellar surface at steady state, we obtained Eq.(3.2) that describes the propagation of small disturbance of surface plasma fluid. The propagating acoustic speed on the stellar magnetized surface is influenced by the surface electrostatic potential, surface magnetic field, and surface centrifugal force coupled with gravitational force is driven from equation of momentum described by Eq.(3.2) for spontaneous propagation of sound waves on surface or photosphere.

$$c_s^2 = -\gamma \left[\frac{q\phi}{m} + \Phi_g \right] - \frac{1}{2} \gamma v_A^2 \left[1 - \frac{2s}{R_c} \right] + \frac{\gamma q}{m} \int (\vec{K} \cdot d\vec{s}) - \gamma v (\vec{v} \cdot \vec{s}) + \gamma \Omega^2 r^2 \sin^2 \theta + 2\gamma \int (\vec{A} \cdot d\vec{s}) \quad (3.2)$$

Where, $\hat{n} \cdot \vec{s} = s$, for, $r_0 \ll s$, on stellar surface. Here we assumed that the surface plasma density is constant of position at minimum temperature surface layer of stratified magnetized plasma fluid. If elements of magnetized plasma on stellar surface flows with velocity greater than sound speed, $c_s < v$, formation of shock wave is inevitable. The plasma dynamic pressure on stellar surface is constant and negligible compared to dynamic pressure at stellar center. At steady state situation, the stellar surface produces non-radial magnetic field that confines the surface charged particles coupled with gravitational force and stellar centripetal force.

3.5. Effects of Magnetic Field on Solar Surface Plasma Convection

From observational evidences, the minimum temperature of stratified stellar (solar) surface is specified with in-homogeneously magnetized plasma [231, 232]. Beneath the stellar surface the convective plasma is expected in adiabatic process. However, the stellar surface is in steady state slow plasma motion below the critical surface. Strong magnetic flux influences plasma motion above the solar surfaces [147, 233, 234]. The non-radial components of complex magnetic field hinder ionized plasma from radially flow out. Neutral particles are not affected by the presence of magnetic field at stellar atmosphere. Only shock waves and plasma radiation can affect neutral particles in non-thermal sense. To show how shock waves can influence neutral particle, see chapter 2, and effects of radiation and pressure on neutral particles would be beyond of our scope.

To theorize the dynamics of magnetized stellar surface or atmosphere we use the concept of magneto-hydrodynamics and particle kinematics in connection with particle-field or particle-wave interaction. In this section we will see that how magnetic field can influence ionized plasma convection. Situations below the stellar critical surface are considered in steady state slow radial plasma motion. When the surface convective plasma is assumed to be in double adiabatic condition, using the assumption of spherical symmetry condition the adiabatic condition is described by Eqs.(3.3a) and (3.3b) at steady state analogous to Eqs.(2.11a) and (2.11b) neglecting viscosity and collision. However, on stellar critical layer the effect of particle collision and viscosity remains constant at thin layer of plasma cloud. The process is characterized by adiabatic heating through the thin surface layer that fulfills the symmetry condition coupled with magnetic field.

$$\left(\frac{dT}{dr}\right)_{ad} = \frac{(\gamma-1)T}{\gamma} \frac{dp}{p} \frac{dr}{dr} - \frac{T}{p} \frac{d}{dr} \left[\frac{1}{2} \rho v^2 + \rho \Phi_g - \frac{1}{2} \rho \Omega^2 r^2 \sin^2 \theta + \frac{B^2}{2\mu_0} \right] + \frac{T}{p} \left[\frac{B^2(\hat{n} \cdot \hat{r})}{\mu_0 R_c} - \rho v v_r + 2\rho A_r \right] \quad (3.3a)$$

Including linear terms of plasma viscosity and surface electrostatic potential at steady state, the adiabatic Eq.(3.3a) can be described by Eq.(3.3b) as linearized form that includes viscosity term.

$$\left(\frac{dT}{dr}\right)_{ad} = \frac{(\gamma-1)T}{\gamma} \frac{dp}{p} \frac{dr}{dr} - \frac{T}{p} \frac{d}{dr} \left[\frac{1}{2} \rho v^2 + \frac{q_j \phi}{m_j} + \rho \Phi_g - \frac{1}{2} \rho \Omega^2 r^2 \sin^2 \theta + \frac{B^2}{2\mu_0} \right] + \frac{T}{p} \left[\frac{B^2(\hat{n} \cdot \hat{r})}{\mu_0 R_c} - \rho v v_r + 2\rho A_r - \rho \frac{2\mu}{r^2} v_r \right] \quad (3.3b)$$

Here, we assumed that density of convective magnetized plasma is position independent at solar photosphere. Compare Eqs.(3.3b) and (2.11a) yields additional terms due to presence of magnetic field. The surface plasma collision, stellar surface rotation condition and additional local inertial forces associated with the generated shock waves on stellar surface, the situation becomes so complex. The non-radial components of magnetic field confines ionized surface plasma. On the stellar surface, the ionized plasma moves along magnetic flux tubes to a specified direction. The temperature gradient below the stellar surface is influenced by the strong magnetic fluxes. At the magnetized solar surface, the radiation process is dominant over convection. We assumed that effect of magnetic field on radiation at solar surface is neglected here. The temperature gradient at solar surface is described as in the sense of magneto-hydrostatic condition before surface perturbation. When the stellar convective stability condition is violated, the instability convective condition is described by Eq.(3.4) in comparison to Eq.(2.2a) of non-magnetized young star.

$$\left| \frac{3}{4ac} \frac{\rho c_s^2}{(\gamma-1) T^4} \frac{k}{4\pi r^2} \frac{F_{rad}}{dr} \right| < \left| \frac{(\gamma-1)T}{\gamma} \frac{d}{dr} (\ln p) - \frac{\gamma T}{c_s^2} \frac{d}{dr} \left[\frac{1}{2} v^2 + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta + \frac{1}{2} v_A^2 \right] + \frac{\gamma T}{c_s^2} \left[\frac{v_A^2}{R_c} (\hat{n} \cdot \hat{r}) + \frac{q}{m} K_r - v v_r + 2A_r - \frac{2\mu}{r^2} v_r \right] \right| \quad (3.4)$$

where v_A is Alfven velocity. Stellar plasma convection process begins if this Eq.(3.4) suffices. So, stellar surface is convective and convectively unstable plasma coupled with surface magnetic field. From Eq.(3.4) we understand that the Alfven velocity associated with small radius of magnetic curvature plays a crucial role for stellar surface instability. When the effects of collision and viscosity are negligible, the plasma becomes unstable on the stellar surface. Surface

plasma turbulence is developed. This turbulence may lead to formation of shock waves due to non-linear perturbing effects of physical quantities.

3.6. Convective Energy Transport of Magnetized Photosphere Plasma

Magnetic field influences the energy transportation by convection method at solar surface. The temperature gradient is influenced by the nature of magnetic gradient through the high conductivity plasma fluids in addition to collisional and viscosity effect. Steep magnetic gradient which arises from inhomogeneous distribution of magnetic flux leads to formation of electric current at place where comparable to characteristic scale length of local magnetic field.

Let we consider a parcel of plasma raises adiabatically through magnetized background plasma until it spreads out and mixes with the surrounding material at stellar surface, delivering its heat to solar surface. When the superhot ionized plasma element rises a distance dr more probably along magnetic flux tubes, the warm magnetized surrounding plasma changes its temperature. The radial sub-photosphere temperature distribution of convective magnetized plasma is obtained from momentum equation for constant ionized number density of convective photosphere plasma. Neglecting plasma collision and viscosity in steady state during convection process of magnetized plasma on solar surface the surface temperature distribution is described by Eq.(3.5).

$$T(r) = T_0 \exp \left\{ \frac{(\gamma-1)}{2\gamma} \ln \left(\frac{p}{p_0} \right) - \frac{\gamma}{2c_s^2} \left[\frac{1}{2} v^2 + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta + \frac{1}{2} v_A^2 \right] + \frac{\gamma}{2c_s^2} \int v_A^2 \frac{dr}{R_c} (\hat{n} \cdot \hat{r}) + \frac{q}{m} K_r \right\} \quad (3.5)$$

Where p_0 and p are the dynamic surface pressure at lower boundary layer and upper boundary layer of sub-photosphere plasma respectively, as we go from high surface pressure region to lower pressure region radially. Analogous to Eq.(2.5), radial acceleration of convective plasma can be specified at the convective stellar photosphere is given by Eq.(3.6), critical layer, CL, in unsteady convective plasma, for $\alpha h = r$ where α is constant parameter its value is near to unity.

$$\vec{a} = -\frac{2p}{\rho \alpha h} \hat{r} - \frac{2}{\alpha h} \left[\Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta + \frac{1}{2} v_A^2 \right] \hat{r} + \left[\frac{1}{R_c} v_A^2 (\hat{n} \cdot \hat{r}) + \frac{q}{m} K_r - \nu v_r + 2A_r - \frac{2\mu}{r^2} v_r \right] \hat{r} \quad (3.6)$$

The quantity $\vec{a}$ is acceleration of moving up plasma elements from below the photosphere. We assumed that motion of plasma elements is uniformly accelerated motion. The horizontal plasma motion under the stellar photosphere has negligible acceleration compared to radial plasma motion. The velocity of parcel of plasma at the terminal point, i.e., at the solar surface or lower part of convection zone is given by simple formula Eqs.(3.7a) and (3.7b) equivalent to Eq.(2.22) in the absence of magnetic flux for condition $(\hat{n} \cdot \hat{r}) = 1$ is sufficed.

$$\bar{v}_c = \left[v_{in}^2 - 4 \left[\frac{1}{\gamma} c_s^2 + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta + \frac{1}{2} v_A^2 \right] + 2\alpha h \left[\frac{1}{R_c} v_A^2 + \frac{q}{m} K_r + 2A_r \right] \right]^{1/2} \quad (3.7a)$$

We assumed here, the effects of viscosity and plasma collision is negligible when we take the average convective velocity. When the initial velocity of convective plasma is vanished, $\bar{v}_{in} \approx 0$, the convection is known as spontaneous convection of magnetized plasma and the Eq.(3.7a) also can be expressed by Eq.(3.7b)

$$\bar{v}_c = \left[2\alpha h \left[\frac{1}{R_c} v_A^2 + \frac{q}{m} K_r + 2A_r \right] - 4 \left[\frac{1}{\gamma} c_s^2 + \Phi_g - \frac{1}{2} \Omega^2 r^2 \sin^2 \theta + \frac{1}{2} v_A^2 \right] \right]^{1/2} \quad (3.7b)$$

The quantity $\bar{v}_c$ is terminal velocity of convective plasma fluid when flowing up. When the convective plasma elements reach upper layer of stellar surface, the adiabatic conditions of Eq.(3.3) is violated and solar explosive events may be formed when small plasma fluids are blown out from small local region. Based on theory of SWIF-1SQR model as we have seen in chapter 2, myriads of Nano flares and micro flares are created on solar surface that are located at top of convective cell. These phenomena may be taken as a precursor of extreme flares and CMEs. Several researches have been conducted on observations of solar explosive events such as locations of flares, prominences and CMEs [235 - 237]. The presence of magnetic field intensifies the stellar explosive events such as flares and CMEs by providing additional magnetic energy stored at small spherical volume is $2\pi(B^2/\mu_0)r^2 dr$ at local region of solar atmosphere for magnetic field is position independent. This is a good calculation in simple way to understand how plasma convection process is working in stellar (solar) convection zone which has a significant effect on the solar surface explosive events such as solar flares, solar winds and CMEs in connection with in-homogeneous bundles of force free magnetic fields.

Perturbation of solar plasma and magnetic fields under solar photosphere is the source of energy for solar explosive events at solar atmosphere and CMEs. Plasma flows horizontally as well as vertically on observable solar surface region [238, 239]. The motion of plasma at the photosphere is specified by two conditions. The first condition is motion of partially ionized plasma at weak magnetic field region of star (sun), properties of a local region is controlled by hydrodynamic system as a view of macro-system associated with particle kinematics and particle wave interaction. The second condition is that a local region of star (sun) is highly dominated by magnetic field; this local system is described by magneto-hydrodynamics and charged particle kinematics with wave interaction. When the quantity of change in temperature gradients $\delta(dT/dr)$ is extreme steeping at the local solar surface along magnetic fields, the surrounding plasma particles absorb heat energy and this local plasma is extremely heated and hot plasma can flow from photosphere to chromosphere is observed from SOHO, LASCO and SDO [240 - 242].

In reality the adiabatic process is violated at stellar (solar) surface due to dynamic nature of stellar plasma even in the presence of magnetic field. Due to the plasma convection motion associated with magnetic flux tubes, the stratified solar photosphere is expected as inhomogeneously plasma density. When the non-radial force free magnetic field and surface plasma density remains independent position and time, the scale height of rotating magnetized stellar surface or photosphere is approximated from equation of motion by Eq.(3.8) that describes the isothermal increment of vertical heat distribution.

$$h \approx \frac{1}{\gamma r_0 \Omega^2 \sin^2 \theta} [c_s^2 + \gamma \rho_0 \Phi_{g0} + q n_0 \phi_0 + v_A^2] \quad (3.8)$$

The convective amplitude of moving up plasma is controlled by gravitational force, surface dynamic pressure, surface electrostatic potential and surface centrifugal force. However, inhomogeneity of stellar surface magnetic field influences the scale height of stratified magnetized photosphere plasma at equilibrium. When the magnetized plasma of stellar surface is in steady state situation, the surface dynamic pressure is determined by local gravitational potential, surface electric potential, binary collision of surface plasma and surface force free magnetic field. The quantity plasma velocity, surface plasma density and non-radial magnetic field is assumed to be position independent in steady state condition. The stellar surface dynamic pressure of rotating star can be influenced by force free magnetic field.

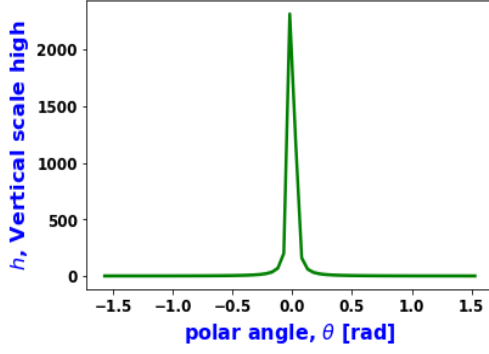


Fig.3.3a Scale height length depends on polar angle on stellar atmosphere between $-\pi/2 \leq \theta \leq \pi/2$

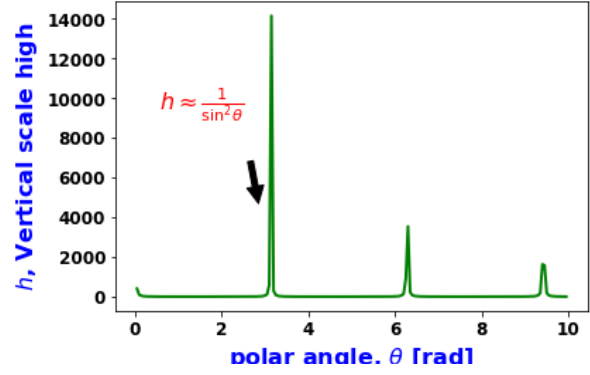


Fig.3.3b Scale height length depends on polar angle on stellar atmosphere between $0 \leq \theta \leq 20\pi/2$

The Fig.3.3a and Fig.3.3b show that the vertical or radial scale height length of stellar atmosphere in steady state situation or in hydrostatic condition of rotating active star depends on polar angle. The maximum value of scale height is obtained at equator region while its minimum value is also obtained at polar region. The surface dynamic pressure is described by Eq.(3.9) at minimum surface temperature of magnetized active star.

$$p_0 = -\rho_0 \Phi_{g0} - q n_0 \phi_0 + \frac{1}{2} \left[\rho_0 \Omega^2 \sin^2 \theta + \frac{1}{2} q n_0 \Omega \sin \theta B_{0\phi} \right] r^2 - 2\rho_0 \Omega v_\theta \sin \theta r - \rho_0 v v_r r - \frac{1}{\mu_0} (B_{\theta 0}^2 + B_{\phi 0}^2) \ln r + i \int f^{1/2} dr + c \quad (3.9)$$

$$\text{Where, } f = \left[2\rho_0 \Omega (v_\phi \cos \theta - v_r \sin \theta) + \rho_0 v v_\theta - \rho_0 \Omega^2 r \sin \theta \cos \theta - \frac{1}{\mu_0 r} (B_{\theta 0} B_{r0} - B_{\phi 0}^2 \cot \theta) \right]^2 + \left[q n_0 \Omega r B_{0r} \sin \theta - 2\rho_0 \Omega v_\theta \cos \theta + \rho_0 v v_\phi - \frac{B_{\phi 0}}{\mu_0 r} (B_{r0} + B_{\theta 0} \cot \theta) \right]^2$$

The integration constant c is determined using the boundary condition at steady state. We assumed that a thin electron cloud layer characterized by minimum effective temperature of rotating surface with constant surface rotational velocity at fixed latitude. We can evaluate the acoustic blast waves which is responsible for shock wave formation at the thin electron cloud layer when the violation of adiabatic condition of Eq.(3.4) suffices. As the star was so aged, the instantaneous volume charge separation leads to supernovae explosion [228]. The complex term of Eq.(3.9) tells us that the system is at equilibrium and also isolated or in steady state surrounding by interplanetary space of high VP. There is no strong interaction with its surrounding *vacuum space* due to formation of surface induced magnetic fields, *see* chapter 2, and complex magnetic field emanated from stellar interior [243]. The surface induced magnetic

field may interact with the stellar potential magnetic fields and charged particles, *see* Eqs.(2.24), (2.25a) and (2.25b). If there were strong interaction between the star and the surrounding low density space, the surrounding vacuum would suck the stellar material and the isolated system would burst suddenly.

However, due to small perturbing of self-gravitating star, very small amount of mass relative to total mass of star is emanated monotonously to surrounding low density space coupled by electromagnetic fields radiation and particle radiation from the stellar surface to surrounding low density space. Alfvén wave is a fundamental physical phenomenon in all kinds of magnetized plasma that regulates the stellar atmosphere. Scientists believed that Alfvén waves contribute to variety of physical processes at solar atmosphere. These processes are such as heating of solar chromosphere and corona, wave-particle interaction, generation of force free magnetic perturbation, turbulence of high conductivity magnetized plasma and solar wind acceleration of electrons and ions. Kinetic Alfvén waves are the extension of magneto-hydrodynamic Alfvén waves to the range of short (kinetic) cross-field scales comparable to the ion gyro-radius and to the electrons inertial length. Kinetic Alfvén waves interact with plasma particles and their energy can be converted in to the energy of electrons and ions (heating and acceleration). Kinetic Alfvén waves interact non-linearly with each other and form a power-law turbulent spectrum at low density plasma of stellar atmosphere coupled with force free magnetic field [39, 244].

3.7. Brunt-Vaisala like Frequency of Magnetized Plasma of Stellar Surface

The Brunt-Vaisala like frequency of stellar surface tells us that how much plasma elements can rise from stellar surface against the gravitational force and magnetic force of inhomogeneous force free surface magnetic field. The surface induced electric field, stellar surface rotation, surface plasma collision and plasma viscosity influences the Brunt-Vaisala like frequency due to introduction of nonlinear plasma effects. Here we have driven the Brunt-Vaisala like frequency of magnetized plasma from vertical component of momentum equation and using the first order term of Taylor series expansion. The Brunt-Vaisala like frequency is arisen from first order approximation of stellar perturbation in case of collision-less and non-viscous plasma. The inertial radial convective acceleration of magnetized surface plasma elements most probably occurred at active region of stellar surface is described by Eq.(3.10).

$$a = \left[\frac{H}{\rho} + \frac{v_A^2}{R_c} \right] \left(\frac{d\rho}{dr} - \frac{1}{c_s^2} \frac{dp}{dr} \right) (r - r_0) + \frac{\partial}{\partial r} \left(\frac{B^2}{2\mu_0} \right) \quad (3.10)$$

The effective surface gravitational acceleration in case of $(\hat{n} \cdot \hat{r}) = 1$ is denoted by $H = -\left(\frac{\partial}{\partial r} \left[\frac{1}{2} v_r^2 + \frac{q\phi}{m} + \Phi_g + \frac{1}{2} |\Omega r \sin \theta|^2 \right] + 2A_r \right)$ and $\vec{\Omega} \times \vec{v} = \vec{A}_r$ represents the Coriolis force effect term. For vanishing magnetic pressure, the Brunt-Vaisala like frequency is obtained from Eq.(3.10) that yields Eq.(3.11). The oscillation frequency N of parcel of magnetized plasma fluid is displaced around its equilibrium position in a medium of effective gravity, H , see Eq.(3.10).

$$N^2 = \left[\frac{H}{\rho} + \frac{v_A^2}{R_c} \right] \left(\frac{d\rho}{dr} - \frac{1}{c_s^2} \frac{dp}{dr} \right) \quad (3.11a)$$

where N is Brunt Vaisala like frequency and this oscillation is known as gravity wave like oscillation. At equilibrium condition, the density inside the plasma elements and surrounding is the same. To determine the nature of Brunt Vaisala like frequency, N , we use two kinds of assumption as we have seen in chapter 2, see Eqs.(2.12) and (2.13). For non-vanished gradients of plasma pressure, perturbed stellar radial displacement which is measured from stratified magnetized surface is solved from Eq.(3.10) that yield Eq.(3.11b).

$$\xi_r = A \exp \left\{ \frac{i}{2} N \left[1 \pm \left[1 + \frac{2}{N^4} \frac{\partial p_m}{\partial r} \right]^{1/2} \right]^{1/2} t \right\} \quad (3.11b)$$

The physical quantity A is normalization constant and p_m also magnetic pressure. If the value of Brunt-Vaisala like frequency is imaginary, some plasma elements rise with radial amplitude distance that is given by Eq.(3.11b). The instability of Brunt-Vaisala like frequency indicates the radial motion of surface plasma associated extreme amplitude of surface oscillation. When magnetic field is position independent at small thickness of stellar surface Eq.(3.11b) can be expressed as follow.

$$\xi_r = A \exp \left\{ \frac{1}{2} i N t \right\} \quad (3.11c)$$

The perturbing plasma column of stellar surface due to convection effect is oscillatory. When the stellar surface plasma is stable for N is real. While the perturbing stellar surface is decaying or growing exponentially if system is not stable for N is complex. Plasma elements may sink or blown out at local region of stellar surface due to instability surface convective effect.

3.8. Stellar Surface Oscillation Associated with Global Magnetic Fields

We consider the non-radial oscillating inhomogeneous stellar photosphere is situated in magneto-hydrodynamic situation and distribution of magnetic flux is inhomogeneous. The surface temperature distribution is influenced by magnetic flux distribution. Small non-radial perturbation of solar surface is observed from space born and ground based solar observatory [170, 245]. The small amplitude solar surface perturbation triggers solar explosive events; the presence of magnetic field at local region also intensifies solar explosive events. The source of steady state inhomogeneous blowing of solar winds of our active star depends on small perturbation of stellar surface and nature of complex magnetic field. The stellar surface non-radial oscillation is assumed to be occurred due to small perturbation in dynamic quantities such as pressures and magnetic fields ...etc. The first order of continuity and momentum equations are given by Eq.(3.12) and Eq.(3.13).

$$\frac{d\rho_1}{dt} + \vec{\nabla}(\rho_0 \vec{v}) = 0 \quad (3.12)$$

$$\begin{aligned} \rho_0 \frac{\partial^2 \vec{\xi}}{\partial t^2} = & -\vec{\nabla} p_1 - q n_1 \vec{\nabla} \phi_0 - q n_0 \vec{\nabla} \phi_1 - \rho_0 \vec{\nabla} \Phi_{g1} - \rho_1 \vec{\nabla} \Phi_{g0} + \frac{1}{\mu_0} [-2\vec{\nabla}(\vec{B}_0 \cdot \vec{B}_1) + \\ & (\vec{B}_0 \cdot \vec{\nabla}) \vec{B}_1 + (\vec{B}_1 \cdot \vec{\nabla}) \vec{B}_0] + q n_1 \Omega r_0 \sin \theta [B_{0\phi} \hat{r} - B_{0r} \hat{\phi}] + q n_0 \Omega r_0 \sin \theta [B_{1\phi} \hat{r} - B_{1r} \hat{\phi}] + \\ & q n_0 \Omega \xi \sin \theta [B_{0\phi} \hat{r} - B_{0r} \hat{\phi}] - \rho_0 v \vec{v}_1 + \rho_0 \Omega^2 \vec{\nabla} [r_0 \xi_r \sin^2 \theta] + \frac{1}{2} \rho_1 \Omega^2 \vec{\nabla} (r_0 \sin \theta)^2 + 2\rho_0 \vec{A}_1 \end{aligned} \quad (3.13)$$

The function $\vec{\Omega} \times \vec{v}_1 = \vec{A}_1$ denotes the Coriolis term and the quantity $\vec{\xi}$ represents complex instantaneous displacement of oscillating surface plasma. If the small perturbation in surface mass density, $\rho_1 \rightarrow 0$, the perturbation in dynamic pressure is coupled with temperature perturbation at constant mass density, the surface acoustic propagating speed is determined by temperature perturbation associated with Alfvén wave, surface electrostatic potential and surface rotational effects see Eq.(3.2). The non-radial surface oscillation amplitude is calculated from continuity and momentum equations by decomposing in to radial and non-radial components. The perturbed non-radial distance of solar surface given by Eq.(2.11) is modified as Eq.(3.14) including effects plasma collision, viscosity and magnetic fields on stellar oscillation.

$$\vec{\xi} = \sqrt{4\pi} \left[\xi_r \hat{r} + \xi_h(r) \left[\hat{\theta} \frac{\partial}{\partial \theta} + \hat{\phi} \frac{1}{\sin \theta} \frac{\partial}{\partial \phi} \right] \right] Y_{lm}(\theta, \phi) e^{-i\omega t} \quad (3.14)$$

where,

$$\xi_r(r) = \frac{1}{\rho_0 \omega^2} \left[\frac{\partial \tilde{p}_1}{\partial r} + q n_0 \frac{\partial \tilde{\phi}_{g1}}{\partial r} + \rho_0 \frac{\partial \tilde{\phi}_{g1}}{\partial r} + \frac{1}{\mu_0} \tilde{F}_r - \tilde{Q}_r - 2\rho_0 \tilde{A}_{1r} \right] \left[1 + \frac{iv}{\omega} + \frac{\Omega^2}{\omega^2} i k_r r_0 \sin^2 \theta \right]^{-1},$$

$$\xi_h(r) = \frac{1}{\omega^2 r} \left[\frac{\tilde{p}_1}{\rho_0} + \frac{q}{m} \tilde{\phi}_1 + \tilde{\phi}_{g1} - \frac{r \tilde{F}_h}{\rho_0 \mu_0} - \frac{r \tilde{Q}_h}{\rho_0} - 2r \tilde{A}_{1h} \right] \left[1 + \frac{iv}{\omega} + i k_h r_0 \frac{\Omega^2}{\omega^2} \sin^2 \theta \right]^{-1},$$

$$\tilde{Q}_r = q \tilde{n}_1 \Omega \tilde{B}_0 r_0 \sin \theta, \quad \tilde{Q}_h = -q \tilde{n}_1 \Omega r_0 \tilde{B}_{0r} \sin \theta$$

$$\tilde{F}_r = [-2ik_r \tilde{B}_1 \tilde{B}_0 + ik \tilde{B}_1 \tilde{B}_{0r} + ik \tilde{B}_0 \tilde{B}_{1r}] \quad , \quad \tilde{F}_h = [-2ik_h \tilde{B}_1 \tilde{B}_0 + ik \tilde{B}_1 \tilde{B}_{0h} + ik \tilde{B}_0 \tilde{B}_{1h}]$$

The quantity $\xi_r, \xi_h, \tilde{p}_1, \tilde{\phi}_1, \tilde{\phi}_{g1}$, are the normalized quantities of radial perturbing displacement field, perturbing non-radial displacement field, perturbed dynamic pressure, electrostatic potential and gravitational potential respectively. The functions of $\tilde{Q}_r, \tilde{A}_{1r}, \tilde{Q}_h$ and $\tilde{A}_{1h}$, represent the normalized terms that express the radial and non-radial components of field particle interaction and effects of Coriolis forces respectively at stellar surface of perturbing plasma. Generally the surface instantaneous electrostatic potential and magnetic field coupled with constantly rotating surface and non-radially oscillating stellar surface influences the nature of stellar atmosphere. The instantaneous velocity of oscillating magnetized plasma can be calculated from Eq.(3.14) is equivalent to Eq.(2.42) obtained by Eq.(3.15),

$$\vec{v} = -i\omega \vec{\xi} \quad (3.15)$$

This shows that the surface oscillating velocity depends on instantaneous oscillating displacement amplitude and oscillation frequency. The oscillating surface acceleration also obtained from momentum Eq.(3.15).

$$\vec{a}_{\xi} = -\omega^2 \sqrt{4\pi} \left[\xi_r \hat{r} + \xi_h(r) \left[\hat{\theta} \frac{\partial}{\partial \theta} + \hat{\phi} \frac{1}{\sin \theta} \frac{\partial}{\partial \phi} \right] \right] Y_{lm}(\theta, \phi) e^{-i\omega t} \quad (3.16)$$

The Eq.(3.16) tells us that plasma particles are accelerating uniformly at solar surface. The blowing out plasma particles gain additional heat energy from rare density of solar atmosphere and their velocity is increasing uniformly. The surface oscillation acceleration is influenced by the emergence of bundles of magnetic flux tubes, surface centrifugal force, Coriolis forces,

particle collision and local gravitational forces as we have seen from Eq.(3.16) clearly. This kinds of acceleration is oscillatory acceleration if the oscillation frequency, ω is purely real. When the oscillation frequency is complex or imaginary, the blowing accelerating particles may increase their velocity exponentially or decay their velocity exponentially. The instability in stellar surface plasma leads to formation of local cavity and shock surfaces.

The surface perturbation acceleration contributes on radiation of energetic particles and radiations of electromagnetic fields in connection with the non-thermal particle accelerations and electromagnetic bursts at stellar atmosphere. For the sake of simplicity we assumed that the plasma collision is effective as we go from stellar interior radially out ward. By substitution of the non-radial displacement field, Eq.(3.13) in to Eq.(3.12), we obtain the perturbing surface dynamic pressure given by Eq.(3.17) at magnetized stellar surface near its equilibrium condition.

$$p_1 = \frac{\omega^2}{k_h^2} [\rho_1 + i k_r \rho_0 \xi_r] + \left[-q n_0 \phi_1 - \frac{q}{i k_h} \Omega \sin \theta [n_1 r_0 B_{0r} + n_0 r_0 B_{1r} + n_0 \xi B_{0r}] - \frac{\rho_0}{i k_h} v v_{1h} \right] + \frac{1}{k_h \mu_0} [-2 k_h (B_{1r} B_{0r} + B_{1h} B_{0h}) + k B_1 B_{0h} + k B_0 B_{1h}] + \Omega^2 \rho_0 r_0 \xi_r \sin^2 \theta + \frac{1}{2} \rho_1 \Omega^2 r_0^2 \sin^2 \theta - \frac{2}{k_h} i \rho_0 A_{1h} \quad (3.17)$$

The perturbing dynamic surface oscillating pressure includes the electron pressure, ion pressure, neutral pressure and radiation pressure. Substitution of Eq.(3.17) in to the perturbing radial displacement field that is obtained from Eq.(3.13) yields Eq.(3.18). The initial unperturbed condition is determined using the quasi-neutrality of stellar surface plasma, $q n_0$ is vanished.

$$\omega^2 \rho_0 \left[1 + \frac{k_r^2}{k_h^2} + \frac{i v}{\omega} \right] \xi_r = -\rho_1 \vec{g} + \frac{\omega^2}{k_h^2} i \vec{k}_r \rho_1 + i \vec{k}_r \rho_0 \Phi_{g1} + i \vec{k}_r q n_1 \phi_0 - \frac{\vec{k}_r}{k_h} q \Omega r_0 \sin \theta [n_1 B_{0r} + n_1 B_{0\phi}] + \frac{i \vec{k}_r}{\mu_0} \left[\frac{k}{k_h} (B_1 B_{0h} + B_0 B_{1h}) - \frac{k}{k_r} (B_1 B_{0r} + B_0 B_{1r}) \right] + 2 \rho_0 \left(\frac{\vec{k}_r}{k_h} A_{1h} - \vec{A}_{1r} \right) \quad (3.18)$$

The radial vector function $i \vec{k}_r \rho_1 \Phi_{g0} = -\vec{g}$ indicates local gravitational acceleration at stellar surface. From Eq.(3.18) clearly, we see that, the third term on left hand side shows collisional effect, the fourth term on right hand side is effects of electrostatic potential, and the fifth term on right hand side indicates the interaction of charged particles with magnetic field couples on the rotating stellar surface. The last term of Eq.(3.18) on the right hand side shows the effects of Coriolis force on the perturbing stellar surface. The stellar surface potential dynamics can be

expressed using Poisson's like Eq.(3.19). Using the spherical harmonic expansion, the Poisson's like equation of first order is expressed as

$$\frac{1}{r^2} \frac{\partial}{\partial r} \left[r^2 \frac{\partial \Psi}{\partial r} \right] + \frac{l(l+1)}{r^2} \Psi = 4\pi G \rho_1 - \frac{q n_1}{\epsilon_0} + \mu_0 \vec{J} \quad (3.19)$$

Where $\vec{\nabla}_h^2 = l(l+1)/r^2$ and $\Psi = \Phi_{g1} + \phi_1 + \vec{A}_1$ stellar dynamic potential field and $\vec{J}$ surface current density, $\vec{A}_1$ is surface vector magnetic potential.

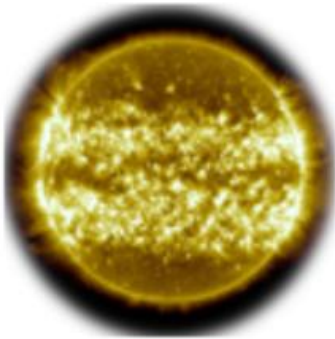


Fig.3.4 Solar active region,
Credited: NASA

From Eq.(3.19) we understand that stellar surface is characterized by force free magnetic field and intense electric current coupled with stellar gravity. From observational evidences of stellar surface, plasma flows in random direction at solar quite region while at solar active region parcels of plasma moves in aligned motion [246]. The velocity potential difference is occurred because of difference in pressure between two regions. The diagram of Fig.3.4 indicates the stellar active region is located at the region between equator

and poles in both hemispheres. Intense flares are occurred at this active region of rotating star (sun). Most of the flares are followed by CMEs associated with topological change in structure of magnetic flux tubes.

3.9. Evolution of Dynamics Cavity on Stellar Surface (SWIF-model-2SAR)

Solar surface plasma is highly magnetized plasma at the site of strong magnetic field region [247, 248]. The solar active region is the place where strong in-homogenously bundles of magnetic fluxes are situated. The presence of magnetic flux tubes at the solar photosphere affects *local* solar surface oscillation amplitudes. Formation of PVR or flowing of dense plasma through lower density background plasma at high velocity is observed on solar surface [249, 250]. Due to an extreme local pressure perturbation of solar interior region associated with the local plasma convection theory, a layer of plasma cloud lift up from solar surface if the buoyancy frequency is imaginary, see Eqs.(3.15) and (3.16). Thus, stream of plasma may be blown out from local stellar surface to its surrounding atmosphere and plasma cloud is created above solar surface. This stream of plasma is controlled by strong magnetic flux tubes, see chapter 4. The blowing

out plasma creates inhomogeneous distributions of plasma elements at stellar atmosphere coupled with inhomogeneous distributions of magnetic flux tubes. The dynamics of stellar atmosphere increases its complexity. The field-field interaction and particle-field interaction at rare plasma density makes the solar atmosphere is so sophisticated.

When floating cloud of plasma cools and falls down, the fast electron diffuse from all directions to convergence point faster than ions at the region outside of magnetic flux tubes or inside magnetic flux. Here, we assumed that at high temperature of strong magnetic flux tube, electrons are moving faster than ions parallel to magnetic field lines. When dense enough plasma flows through magnetic flux tubes, electron runaway condition is fulfilled faster than ion runaway condition through magnetic flux tubes for negligible collision and viscosity processes, *see* Eqs.(2.126a) and (2.126b). A strong shock wave is developed through magnetic flux tubes. Outside magnetic flux tubes, flowing electrons induce instant electric field on the front surface of flowing plasma fluid, *see* chapter 2, Fig.2.7. Let us consider a PVR of spherical shape with radius of $\vec{r}$ is measured from its center of convergence inside high conductivity magnetized plasma at solar photosphere associated with surface convection and non-radial surface oscillation mode. To determine the topology of solar magnetic field associated with PVR is very difficult.

However, the force-free magnetic field inside the cavity can be expressed in local spherical coordinate obtains an arbitrary topological orientation. The magnetized plasma inside PVR may have an incompressible behavior at equilibrium. When the high conductivity plasma is in non-uniform directional flow, its compressibility depends on applied inertial force. The orientation of magnetic field may be determined by topological orientation of magnetic field lines.

Due to formation of PVR, a strong imploding primary shock wave and exploding primary shock surfaces are developed and propagate through magnetized cavity. We can evaluate the separated equation of motion for electron fluid plasma at inner side dynamic boundary surface of collapsing PVR similarly as we have modeled in *chapter 2* in the absence of pre-existed magnetic field. Let $\vec{r}(t)$ is the instant radius of the local coordinate of collapsing PVR inside uniform high conductivity plasma fluid. The motion of plasma is determined by the presence of complex magnetic field. The complex magnetic field is denoted by $\vec{B}$ has the same strength inside PVR as well as outside for the sake of simplicity at equilibrium. This magnetic field may

be average value of induced local magnetic field and original solar potential field which is force free magnetic field.

When high conductivity plasma fluid flows along magnetic field lines, a parallel electric current is created along magnetic field lines. When this longitudinal plasma current induces strong enough magnetic field, the external magnetic field created a bundle of magnetic flux tubes. Due to new induction of temporary micro magnetic field, the system becomes so complex. If the solar magnetic field is strong enough to trap electron, the shock wave which is generated by fast flowing electron is most probably propagating along magnetic field line. The shock wave generated by ion interacts with shock wave generated by electron inside the magnetic flux. Here, we assumed that the size of PVR is smaller than the thickness of magnetic flux tube so as to minimize the complexity. Since PVR has been created, the magnetized plasma is collapsing due to strong local VP. The inflowing plasma during collapsing of magnetized PVR may not be necessary radial. The magnetic fluxes inside the PVR hinder plasma from flowing across magnetic field lines. A flux of collapsing electrons collides to magnetic flux wall when electrons try to cross magnetic field lines.

However, formation of imploding and exploding shock fronts is inevitable even in the presence of magnetic field. When VP is strong enough at convergence point, the wall of magnetic flux is highly deformed. We consider the local system which produces shock waves and explosive waves in spherical coordinate as we have seen in *chapter 2*. The plasma continuity, momentum and energy equation respectively in non-relativistic magnetized plasma fluid is given Eqs.(3.20), (3.21) and (3.22) at small local region.

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (\rho r^2 v_r) + \frac{1}{r \sin \theta} \frac{\partial}{\partial r} (\rho v_\theta \sin \theta) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \varphi} (\rho v_\varphi) = 0 \quad (3.20)$$

$$\frac{d\vec{v}}{dt} = \frac{1}{\rho} \vec{\nabla} p + nq \vec{\nabla} \phi - \vec{\nabla} \left(\frac{B^2}{2\mu_0} \right) + \frac{1}{\mu_0} (\vec{B} \cdot \vec{\nabla}) \vec{B} + \mu \left[\vec{\nabla}^2 \vec{u} + \frac{1}{3} \vec{\nabla} (\vec{\nabla} \cdot \vec{u}) \right] - \rho v \vec{v} \quad (3.21)$$

$$\frac{\partial}{\partial t} \left(\frac{1}{2} \rho v^2 + \frac{p}{\gamma-1} + \frac{B^2}{2\mu_0} + \frac{1}{2} \epsilon_0 E^2 \right) = -\vec{\nabla} \cdot \left[\left(\frac{1}{2} \rho v^2 + \frac{p}{\gamma-1} + \frac{B^2}{2\mu_0} + \frac{1}{2} \epsilon_0 E^2 \right) \vec{v} - \frac{\vec{v} \cdot \vec{B}}{\mu_0} \vec{B} + \frac{\eta}{\mu_0} \vec{j} \times \vec{B} \right] \quad (3.22)$$

So, the equations of continuity, momentum and energy are described by Eqs.(3.20), (3.21) and (3.22) are specified at local cavity inside magnetic flux tube. Where $\vec{\nabla} = \hat{r} \frac{\partial}{\partial r} +$

$\hat{\theta} \frac{1}{r} \frac{\partial}{\partial \theta} + \frac{1}{r \sin \theta} \frac{\partial}{\partial \varphi}$ and $\vec{B}$, is the force free magnetic field inside PVR during collapsing or growing. We consider here the geometry of PVR is nearly spherical at local region of solar atmosphere (i.e., photosphere) for the sake of simplicity. However, the real geometrical shape of PVR may be spherical, cylindrical, plane like or line like shaped. The imploding electron plasma of spherical shell induces predominantly radial component of intense electron shell induced electric field, see chapter 2.

However, the imploding plasma momentum depends on angular parameters due to the presence of complex magnetic field. Initial plasma speed v_0 is equivalent to the thermal speed of background plasma in the absence of external inertial force. Utilizing conservation of momentum, it is possible to evaluate how electron plasma fluid behaves at the dynamic boundary surface of PVR associated with strong magnetic fluxes. Due to the intense electric field inside PVR, the convergence point, line or plane of PVR reflects imploding waves and plasma fluids. Electrons and ions are accelerated non-thermally from the PVR because of intense instantaneous electric field coupled with *synchrotrons* and *cyclotron radiation*, see chapter 4, section 4.1. The accelerating particles are highly oscillating around the strong magnetic field lines at the PVR and finally move across the magnetic field lines after they have gain enough kinetic energy which enables them to escape from confinement by magnetic field. The accelerated electrons and ions would have gain kinetic energy from shock wave much greater than magnetic energy of the PVR in case of weak magnetic field. The non-thermal acceleration may be cyclotron acceleration, synchrotron acceleration due to force free complex magnetic field and particle acceleration due to fast moving shock wave fronts propagating through rare density plasma.

During shock passage exterior PVR throughout magnetized plasma, the PVR is strongly compressed by the dynamic electron boundary followed by ambient plasma. The rate of acceleration of charged particles at the dynamic boundary is determined by the surface energy density of magnetic PVR dynamic boundary. Most probably the plasma electrical resistivity η may be effective at the convergence region in connection with the reflection of moving shock fronts at that point. Another new plasma resistivity may be arisen due to non-linear phase wave interaction. This kind of plasma resistivity is known as *anomalous resistivity* of high conductivity plasma. This anomalous resistivity is arisen from overloading of mechanical waves annihilation and creation of electromagnetic waves and particle-wave interaction principles. The

body (volume) current of collapsing PVR in steady state situation for collision-less, non-viscous and for negligible anomalous resistivity, $\eta \approx 0$ of plasma in adiabatic collapsing process is given by Eq.(3.23) inside collapsing magnetic PVR.

$$\vec{J} = \frac{\rho_c}{\sqrt{\rho}} \left[p - \frac{B^2}{2\mu_0} + \rho_c \phi + \frac{1}{3\mu_0} \int \vec{H} \cdot d\vec{X} \right]^{1/2} \hat{X} \quad (3.23)$$

The quantities ρ_c net charge density inside magnetized PVR, $\vec{H}$ represents magnetic tension force, $d\vec{X}$ is infinitesimal displacement and $\hat{X}$ unit position vector in local spherical coordinates. In unsteady state situation inside magnetized PVR, charged particles are accelerated due to surface induced electrostatic potential, strong oscillations of magnetic field lines and inertial force exerted by VP. The acceleration of charged particles at magnetized PVR has been derived from Eq.(3.21) and effects of collision are negligible to suffice adiabatic condition behind shock passage. This kind of collapsing acceleration is known as *adiabatic acceleration* or *non-thermal acceleration* of charged particles.

$$\vec{a}(r, t) = \vec{\nabla} \left[\frac{1}{\gamma} c_s^2 + \frac{\rho_c}{\rho} \phi - \frac{1}{2} v^2 \right] - \vec{\nabla}_\perp \left(\frac{v_A^2}{2} \right) \cdot \hat{X} + \frac{v_A^2}{R_c} (\hat{n} \cdot \hat{X}) \quad (3.24)$$

From Eq.(3.24) we can understand that radiation inside magnetized PVR is occurred due to thermal and non-thermal effect such as velocity gradient, electric field gradient, and magnetic field gradient and strong deformation of magnetic field line is occurred. As the radius of magnetic curvature is so smaller for $\hat{n} \cdot \hat{X} = 1$, the non-thermal acceleration may be dominated by *cyclotron* and *synchrotron radiation*. In collision-less motion, instantaneous strong charge separation process generates instantaneous electrostatic potential field most probably along magnetic field lines.

When the flowing plasma moves with velocity much greater than sound speed of background magnetized plasma, shock wave is produced in front of the moving plasma element coupled with the fast oscillating electron of dynamic surface inside the magnetic flux. Since we have chosen the local coordinate is a spherical coordinate, the shock wave fronts are produced at collapsing dynamic boundary of electron shell, see chapter 2, section 2.14. In reality the shape of PVR may not be necessarily spherical and it depends on topology of magnetic flux. The induced electrostatic potential due to strong inertial forces that separate electrons and ions sufficiently

could be greater than Dirac electrostatic potential yields Dirac electric field $\vec{E}_D$. When the PVR is highly magnetized, the electrons and ions distribution is no more Maxwellian distribution at equilibrium. The PVR is continuously perturbed due to unstable high VP which creates a local inertial compressive force. When the VP inside PVR is so much higher than the magnetic potential inside PVR, the magnetic flux surface is highly deformed and compressed at small local region. Plasma particles and magnetic fields are compacted and heated continuously at stagnation region or convergence region controlled by magnetic pressure. The compacted and shocked charged particles interact with the magnetic field and shock waves.

If the collapsing ambient plasma density is very high, collisional effects play a crucial role in dissipation of electric current. During collapsing process electrons bounce several times between the convergence point and dynamic surface boundary current layer of PVR in addition to surface magnetic flux. These kinds of electrons motion inside the PVR with velocity much higher than electron velocity of collapsing dynamic boundary across magnetic field lines. Fermi acceleration plays a crucial role inside magnetized PVR before collapsing. Generally, most of electrons are expected as to create electron radiation at PVR while most ion may create ion radiation at high density region behind of collapsing dynamic boundary region in case of unsteady collapse of PVR, see Eq.(3.24). This indicates that ions require large enough energy from shock wave fronts so as to radiate intensely and to carry large momentum. The radial particle distribution of magnetized PVR in this situation is given by Eq.(3.25).

$$n(r, t) = n_0 \exp \left\{ -\ln \left(\frac{T}{T_0} \right) + \frac{m}{k_B} \int \frac{1}{T} \frac{\partial}{\partial r} \left(\frac{1}{2} v_r^2 \right) dr - \frac{q}{k_B} \int \frac{1}{T} \frac{\partial \phi}{\partial r} dr - \frac{m}{k_B} \int \frac{1}{T} [Q + i h^{1/2}] dr + c \right\} \quad (3.25)$$

Let p and ϕ are only radial position dependent and we have,

$$h = \left[\frac{1}{r\rho} \frac{\partial}{\partial \theta} \left(\frac{B_r^2}{2\mu_0} + \frac{B_\theta^2}{2\mu_0} + \frac{B_\phi^2}{2\mu_0} \right) - \frac{B_r}{\rho\mu_0} \frac{\partial B_\theta}{\partial r} - \frac{B_\theta}{r\rho\mu_0} \frac{\partial B_\theta}{\partial \theta} - \frac{B_\phi}{r\rho\mu_0 \sin \theta} \frac{\partial B_\theta}{\partial \phi} - \frac{B_r B_\theta}{r\rho\mu_0} + \frac{B_\phi^2 \cot \theta}{r\rho\mu_0} \right]^2 + \left[\frac{1}{\rho} \frac{1}{r \sin \theta} \frac{\partial}{\partial \phi} \left(\frac{B_r^2}{2\mu_0} + \frac{B_\theta^2}{2\mu_0} + \frac{B_\phi^2}{2\mu_0} \right) - \frac{B_r}{\rho\mu_0} \frac{\partial B_\phi}{\partial r} - \frac{B_\theta}{r\rho\mu_0} \frac{\partial B_\phi}{\partial \theta} - \frac{B_\phi}{r\rho\mu_0 \sin \theta} \frac{\partial B_\phi}{\partial \phi} - \frac{B_r B_\phi}{r\rho\mu_0} - \frac{B_\theta B_\phi \cot \theta}{r\rho\mu_0} \right]^2$$

$$Q = -\frac{1}{\rho} \frac{\partial}{\partial r} \left(\frac{B_\theta^2}{2\mu_0} + \frac{B_\phi^2}{2\mu_0} \right) + \frac{\partial}{\partial r} \left(\frac{B_r^2}{2\mu_0} \right) + \frac{B_\theta}{r\rho\mu_0} \frac{\partial B_r}{\partial \theta} + \frac{B_\phi}{\rho\mu_0 r \sin \theta} \frac{\partial B_r}{\partial \phi} - \frac{1}{\rho\mu_0 r} (B_\theta^2 + B_\phi^2)$$

From Eq.(3.25), it is clearly shown that the plasma number density distribution has complexity due to its exponential non-linear function coupled with the integrand function. The imaginary part of Eq.(3.25) comes from the orthogonally properties of vector force quantities.

When plasma particles are accelerating out from inside PVR, they should have a frequency higher than frequency of magnetic field inside PVR and the dynamic boundary layer. The plasma particle acceleration inside the local isolated cavity is approximated by Eq.(3.24). The dynamic pressure of PVR in steady state is obtained from Eq.(3.21) in the absence of plasma particles collision and viscosity behind and after shock wave passage inside PVR surrounded by high density plasma is,

$$p = -\rho_c \phi + \frac{B^2}{2\mu_0} - \frac{1}{3} \int \left[\frac{\vec{H}}{\mu_0} - \rho \vec{U} \right] \cdot d\vec{x} + \frac{1}{3} \rho v \int \vec{v} \cdot d\vec{x} \quad (3.26)$$

where, $\vec{U} = (\vec{v} \cdot \vec{\nabla})\vec{v} = U_r \hat{r} + U_\theta \hat{\theta} + U_\phi \hat{\phi}$ and $\vec{H} = H_r \hat{r} + H_\theta \hat{\theta} + H_\phi \hat{\phi}$, the term $\rho_c \phi$ in Eq.(3.26) represents the radiation pressure loss inside PVR at steady state. As we have seen in our first model (i.e., SWIF-1QSR model) an intense electric surface current sheet of nearly spherical shell is created during cavity collapsing or growing. At the small local region when the intense plasma current is collapsing, magnetic field is highly compressed. An anomalous plasma resistivity is created due the complexity of collapsing high conductivity plasma. The non-linear effect of negative dynamic pressure, magnetic pressure and inertial velocity inside PVR results particle radiation. Using symmetry assumption of polar and azimuthal coordinates over all types of forces inside PVR, Poisson's equation for constant plasma density in steady results Eq.(3.27) during implosion or explosion of PVR.

$$\left[\frac{\partial^2}{\partial r^2} + \frac{2}{r} \frac{\partial}{\partial r} \right] \left[p \pm \frac{B^2}{2\mu_0} \right] + \left[\frac{\partial}{\partial r} + \frac{2}{r} \right] \left[\frac{H_r}{\mu_0} \pm \rho U_r \right] = \frac{\rho_c^2}{\epsilon_0} \quad (3.27)$$

The function $p_r = -\rho_c^2/2 \epsilon_0$ is radiation pressure exerted by accelerated charged particles corresponding to $\rho_c \phi$ term in Eq.(3.26) due to electrostatic effect of plasma. As we have obtained from Eq.(3.27), the strong radial position variation of dynamic and magnetic pressure creates a radiation pressure inside collapsing cavity. From the solution of Eq.(3.27) for incompressible plasma fluid and negligible magnetic tension force, the temperature distribution collapsing dynamic PVR is obtained.

$$T = \frac{1}{k_B} \frac{1}{2} m v_A^2 + \frac{1}{3 k_B} m \omega_p^2 r^2 + \frac{1}{n k_B} \left[\frac{G_0}{r} + c \right] \quad (3.28)$$

The quantity G_0 would be determined using initial condition and boundary value of dynamic pressure and magnetic pressure. The integration constant c in Eq.(3.28) would be determined

using initial value of inertial velocity and corresponding boundary value. The Alfvén kinetic energy and plasma oscillation kinetic energy associated with strong negative dynamic pressure generates or controls the plasma temperature inside PVR during collapsing or growing. In case of unsteady collapsing or growing PVR, the radial temperature distribution given by

$$T = \frac{1}{k_B} \frac{1}{2} m v_A^2 + \frac{1}{k_B} m a r + \frac{1}{3 k_B} m \omega_p^2 r^2 + \frac{1}{n k_B} \left[c + \frac{c_1}{r} - \frac{G_0}{r} \right] \quad (3.29)$$

The second phase integration constant c_1 also determined using initial condition and boundary value of PVR as before. The inertial acceleration, $\vec{a}$, is constant radial acceleration of imploding or exploding PVR and $\omega_p^2 = q^2 n / m \epsilon_0$ is plasma frequency. At this situation, when the plasma density is so small and magnetic field strong enough for infrequent particle collision, the local plasma inside PVR can be described by plasma orbit theory. At solar atmosphere we do not ignore radiative effects on solar prominences, CMEs, magnetic flux tubes and magnetic field produced by fast ejecting plasma elements.

3.10. Spherical Dynamics PVR Coupled with Magnetic field

Let we considered that the initial condition of static magnetized PVR on perturbing stellar surface or atmosphere of high conductivity plasma medium. We now proceed to identify the subsequent dynamics of PVR growth and collapse process through high conductivity magnetized plasma results solar explosive events at stellar or solar atmosphere. The behavior of PVR is defined in an infinite domain of high conductivity magnetized plasma relatively at rest far away from the developing PVR and with uniform temperature of surrounding plasma. The spherically symmetric situation provides a simple case that is amenable to analysis and reveals a number of important phenomena of PVR dynamics.

Consider the spherical PVR of radius $R(t)$ where t is time, in an infinite domain of high conductivity magnetized plasma with temperature and pressure far from convergence point of PVR are T_∞ and $p_\infty(t)$ respectively. The temperature, T_∞ , is assumed to be a simple constant since temperature gradients were eliminated *a priori* and uniform shock heating of the plasma due to internal heat sources or generation of shock waves. Radiation will not be considered before and after shock wave propagation in non-relativistic case. The surrounding dynamic pressure, $p_\infty(t)$, is assumed to be a known input which regulates the formation and collapse of the

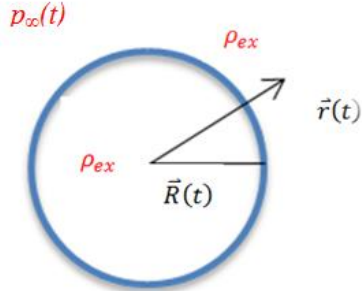


Fig.3.5 Spherical cavity (PVR) model

PVR results explosive waves, out flowing plasma jets and radiation to surrounding ambient plasma. Though compressibility of the plasma, it can be important in the context of PVR collapse, it will, for the present, be assumed that the exterior plasma density, ρ_{ex} , is a constant. Furthermore, the dynamical viscosity, μ , is assumed constant and uniform if plasma density of collapsing cavity is

high enough. It will also be assumed that the contents of the PVR are homogeneous and that the temperature, $T_{in}(t)$ and pressure, $p_{in}(t)$, within the PVR are assumed uniform before shock wave passage. These assumptions may not be justified across the moving normal shock fronts. The radial position within the surrounding plasma or inside PVR will be denoted by the distance, $\vec{r}$, from the center of the convergence region; the dynamic boundary pressure, $p(r,t)$, radial inward velocity during collapse or growing with outward velocity during growth, $\vec{u}(r,t)$, and temperature, $T(r,t)$, within the PVR or surrounding plasma will be so designated.

Conservation of mass, momentum and energy are expressed by Eqs.(3.20), (3.21) and (3.22) inside PVR with no mass flux is passing across the dynamic boundary. Here we assumed that $\rho_{in} \ll \rho_{ex}$ and $\vec{E}_{in} \gg \vec{E}_{ex}$ of collapsing or growing PVR at local surface. Let us study the interaction between PVR and its surrounding higher density plasma through the dynamic boundary surface. To study the dynamics of PVR in simple way, we assumed that the symmetry of polar and azimuthal coordinates. The collapsing or growing velocity of dynamic surface electron beam is approximated by $u(R,t) = dR/dt$. Using Eq.(3.20) for vanishing non-radial components collapsing or growing velocity field is obtained as follow.

$$\vec{u}(r,t) = \frac{1}{r^2} G(r,t) \hat{r} \quad (3.30)$$

Here, the function $G(r,t)$ is imagined as gradient of velocity shock potential function. We have to consider two cases during collapsing process of dynamic PVR which has a velocity field of $\vec{u}(r,t)$ given by Eq.(3.30). These are: (1) Collapsing of PVR with no particles passing through dynamic boundary. (2) Collapsing of PVR, with accelerated particles passing through dynamic boundary. From Eq.(3.21), using Eq.(3.30), and assuming $G(t)$ only time dependent

dynamic pressure difference between the convergence point and dynamic electron surface of PVR near boundary is given by Eq.(3.31) describes spontaneous velocity shock potential.

$$p_c - p = \rho \left[\frac{1}{r} \frac{\partial G(t)}{\partial t} - \frac{1}{2} \frac{G(t)^2}{r^4} \right] + \frac{q\phi}{m} - \frac{1}{2} \int (\vec{\nabla}_\perp v_A^2 \cdot \hat{r}) dr + \int \frac{v_A^2}{R_c} dr + \frac{\nu G(t)}{r} \quad (3.31)$$

We use the assumption $p \rightarrow p_c$ as $r \rightarrow 0$, p and p_c are dynamic pressure near boundary of dynamic electron surface of PVR and at convergence center respectively. The integration constant, c would be determined using the boundary value of PVR during collapsing or expansion in steady state situation, but we chose its value is zero in case of spontaneous process. To determine the dynamic pressure difference between convergence region and dynamic boundary of PVR, it is mandatory to consider the energy density at dynamic electron surface boundary of PVR. The dynamic boundary of PVR is assumed to be as thin enough that stored energy density of ϵ_α in addition to surface pressure and viscosity term. Considering the dynamic surface pressure, surface energy density and plasma viscosity of collision-less plasma, using Eq.(3.31) for position is time independent $\partial r / \partial t = 0$ near dynamic boundary electron surface.

$$p_c - p_B = \frac{4\mu}{R} \frac{dR}{dt} + \frac{2\epsilon_\alpha}{R} + \rho R \frac{\partial^2 R}{\partial t^2} + \frac{3}{2} \rho \left(\frac{dR}{dt} \right)^2 + \frac{q\phi}{m} - \frac{1}{2} \int (\vec{\nabla}_\perp v_A^2 \cdot \hat{r}) dr + (\hat{n} \cdot \hat{r}) \int \frac{v_A^2}{R_c} dr + \nu R \frac{dR}{dt} \quad (3.32)$$

The plasma pressure at dynamic boundary is denoted by p_B in Eq.(3.32). The Eq.(3.32) shows that the difference in dynamic pressure between the center of convergence point and the dynamic boundary. The surrounding exterior plasma density is connected to interior dynamic pressure through the dynamic surface boundary. Let $\rho_{in} = \rho$ mass density inside the PVR and $n_{in} = n$ plasma number density inside PVR during collapsing or exploding. Assuming $p_B(t)$ is balanced by exterior dynamic pressure at instant boundary position of collapsing or growing PVR far away from dynamic boundary and p_{ex} dynamic pressure at dynamic boundary surface of collapsing PVR for $r \geq R$ from outside. We can approximate p_{ex} is the current surface dynamic pressure equals to the boundary pressure. By using the surface energy density, ϵ_α of dynamic PVR boundary surface, we can verify the dynamic pressure difference between surface boundary and surrounding far region of high conductivity plasma medium.

$$p_B(t) - p_{ex} = -\frac{4\mu}{R} \frac{dR}{dt} - \frac{2\epsilon_\alpha}{R} + \rho_{ex} \left[R \frac{\partial^2 R}{\partial t^2} + \frac{3}{2} \left(\frac{dR}{dt} \right)^2 \right] - \frac{1}{2} \int (\vec{\nabla}_\perp v_{Ae}^2 \cdot \hat{r}) dr + (\hat{n} \cdot \hat{r}) \int \frac{v_{Ae}^2}{R_c} dr + \nu R \frac{dR}{dt} \quad (3.33a)$$

When the system is characterized by collision-less and non-viscous condition, Eq.(3.33a) is reduced to Eq.(3.33b) and the collapsing or growing cavity becomes unstable.

$$p_B(t) - p_{ex} = -\frac{2\epsilon_\alpha}{R} + \rho_{ex} \left[R \frac{\partial^2 R}{\partial t^2} + \frac{3}{2} \left(\frac{dR}{dt} \right)^2 \right] - \frac{1}{2} \int (\vec{\nabla}_\perp v_{Ae}^2 \cdot \hat{r}) dr + \int \frac{v_{Ae}^2}{R_c} dr \quad (3.33b)$$

In steady state situation for $p_{ex} - p_B \neq 0$ the energy density of dynamic boundary layer could be determined by dynamic pressure difference between the dynamic surface boundary and surrounding dynamic pressure and nature of magnetic fields. If the magnetic field is non-deformable and non-radial associated with collision-less plasma, the surface boundary energy density is approximated by Eq.(3.33c) in steady state situation.

$$\epsilon_\alpha = -R \left[\frac{1}{2} (p_B - p_{ex}) + v_{Ae}^2 \right] \quad (3.33c)$$

When the difference in dynamic pressure between surface boundary and far region of high conductivity plasma medium is vanished, the boundary surface energy density is verified from Eq.(3.33a) in unsteady state condition that is described by Eq.(3.33d).

$$\epsilon_\alpha = -\frac{1}{2} \rho_{ex} R \left[R \frac{\partial^2 R}{\partial t^2} + \frac{3}{2} \left(\frac{dR}{dt} \right)^2 \right] + \frac{1}{4} R \int (\vec{\nabla}_\perp v_{Ae}^2 \cdot \hat{r}) dr - \frac{1}{2} R \int \frac{v_{Ae}^2}{R_c} dr \quad (3.33d)$$

Verifying Eq.(3.33d) at steady state situation, the dynamic boundary surface energy density of PVR is determined by magnetic intensity in case of $\hat{n} \cdot \hat{r}$ is unity and the ratio of magnitude of Alfvén velocity square to magnetic curvature radius as constant of position, results Eq.(3.33e).

$$\epsilon_\alpha = \frac{1}{2} R v_{Ae}^2 \left[\frac{1}{2} - \frac{1}{R_c} \right] \quad (3.33e)$$

The Eq.(3.33e) indicates that the dynamic surface energy density stores magnetic energy density that prevents charged particles from passing through it but neutral particles may pass. For viscous less high conductivity plasma fluid, the first term on right hand side of Eq.(3.33a) is vanishing. When PVR is collapsing or growing by $4\pi R^2 \frac{dR}{dt}$ rate also mass rate PVR must be increase by $\rho_{in} 4\pi R^2 \frac{dR}{dt}$ during expanding or collapsing with mass rate $\rho_{ex} 4\pi R^2 \frac{dR}{dt}$ of PVR. If some mass is passing across the dynamic surface boundary, then in turn mass must be equal to

the mass flow of plasma inward relative to the interface, and hence the inward velocity of plasma relative to the interface is given by

$$\vec{v} = \left[1 \pm \frac{\rho}{\rho_{ex}}\right] \frac{1}{r^2} G(r, t) \hat{r} \quad (3.34b)$$

The quantity $\rho/\rho_{ex} \ll 1$ mass density ratio and the direction of flowing velocity are radially inward during collapsing and radially outward during growing. The flowing radial velocity exterior, $\vec{v}_{ex}$ of PVR may be radial outward or inward and also the same is true inside PVR for $\vec{v}_{in}$ may be radially inward or outward. When the dynamic pressure difference between center of convergence point and surrounding high conductivity plasma is tends to infinitely large, the PVR is collapsed suddenly, see Eq.(3.31), (3.32), (3.33a) and (3.33b) of collapsing or growing PVR. During sudden collapsing of PVR, the collapsing velocity that is given by Eq.(3.30) or (3.34b) is equal to velocity of shock wave.

3.11. Formation and Propagation of Shock Waves in Magnetized Plasma

In chapter 2, we have developed the SWIF-1SQR model that describes the solar hydrodynamic explosive events on stellar (solar) atmosphere of weak magnetic field region. Based on SWIF-1SQR model solar explosive events are arisen because of supersonic flows of local ionized hydrogen plasma coupled with strong surface charge separation process of fast moving electrons at weak magnetic field region (i.e., Quiet region). The model of SWIF-1SQR model well describes the nature of micro flares and Nano flares at stellar surface associated with surface plasma convection and non-radial stellar oscillation modes. However, the presence of strong magnetic field associated with SWIF-1SQR model nicely describes the most intense explosive events on stellar (solar) atmosphere (i.e., photosphere, chromosphere and corona) that enables us to develop the further second model of SWIF-2SAR model. Formation of PVR at strong magnetic field region of high conductivity medium leads to sudden release of huge amounts of energy. Electrons and other charged particles are discharged from the complex surface current at maximum limit of electron surface current. The surface of magnetic flux tube is characterized by strong wave-particle interaction and field-particles interaction. The induced instantaneous surface net electric field accelerates the nearby electrons and ions. The second model of SWIF-2SAR model is more effective at upper layers of solar atmosphere than the first

model of SWIF-1SQR model which is preferable on weak magnetic field region. By reducing the model of SWIF-2SAR model for small magnetic beta, we get the first model of SWIF-1SQR model.

When discrete magnetic fluxes tubes are approaching to each other through high conductivity plasma, no matter their topological structure, the density of un-magnetized plasma between the approaching magnetic flux tubes continuously decrease behinds of the approaching fluxes, see chapter 4. The attracting magnetic fluxes may be ranging up to several current carrying fluxes. At head on magnetic surfaces, magnetic pressure becomes dominant over the dynamic pressure for strongly attracting fluxes. Normal shock surface is generated on the magnetic surface and propagates through the low density un-magnetized plasma in front of approaching fluxes. The magnetic field surface propagates behind of normal shock surface against plasma dynamic pressure. The attracting magnetic fluxes are meeting quickly at convergence plane or region or line. Electrons and ions are drift or moved from contacting magnetic surfaces quickly. The reconnection process becomes so fast and magnetic energy is stored quickly at small convergence region inside high conductivity gaseous medium. The oscillating contacting magnetic surface continuously generated moving shock fronts.

As we have observed from Eq.(3.32), the fifth, sixth and seventh terms on the right hand side indicate that surface electrostatic potential and force free complex magnetic field makes the dynamic pressure difference between convergence point and dynamic surface boundary is so high. Inside the PVR, if the non-radial magnetic field lines are deformed with very small radius of curvature, the restoring magnetic pressure becomes so high. The restoring magnetic pressure generates fast moving shock surfaces propagating through magnetized plasma. The complexity of collapsing local region of high conductivity medium creates anomalous plasma resistivity.. Those charged particles choose their path along local magnetic field lines. However, due to propagating fast moving shock surface, instantaneous surface electrostatic potential and high negative dynamic pressure of convergence point, line or plane, the charged particles gain high inertial force and moves across the magnetic field lines to wards of convergence point, line or plane. Ions and electrons are repeatedly reflected between successive shock fronts and finally accelerated. This acceleration is known as shock wave acceleration. Non-radial flow of ambient plasma during collapsing may be created because of non-radial strong magnetic field lines

alignment and vorticity effects of imploding plasma fluids. The continuous oscillation of electron and ion lead to cyclotron acceleration, synchrotron acceleration of electrons and ions in addition to Fermi like acceleration and shock wave acceleration.

When magnetic field inside PVR is highly deformable, the imploding electrons and ions create local plasma current along the deforming magnetic field surface. If the highly deforming magnetic field is strong enough, electrons and ions are oscillating several times and they form non-thermal in addition to non-thermal shock acceleration. However, when the magnetic flux is strong enough inside PVR, it prohibits plasma from fast reaching of the convergence point, line or plane across magnetic field line. Electromagnetic radiation and particle radiation may be emanating from dynamic boundary of PVR. From observational evidences, the solar surface is expected as partially ionized hydrogen plasma [251, 252]. The evolutional life time of PVR is controlled by ionization process in partially ionized plasma fluid. Initially, it is assumed that the PVR plasma satisfies quasi-neutral condition. The radial electron density distribution has been obtained from radial momentum distribution of spherical uniform plasma. Consider the PVR is in isothermal condition of collision-less and non-viscous plasma and also magnetic curvature is position independent and $(\hat{n} \cdot \hat{r}) = 1$. The radial electron distribution inside isothermal PVR is obtained from Eq.(3.25) in steady state if shock wave is not yet developed.

$$n_e(r) = n_0 \exp \left\{ - \left[\frac{1}{2} m v_e^2 - e\phi + \frac{1}{2} m v_A^2 \left[1 - \frac{2r}{R_c} \right] - mc \right] / k_B T_e \right\} \quad (3.35)$$

The integration constant c in Eq.(3.35) would be determined using boundary condition in steady state. The electron number density distribution depends on the orientation of deforming magnetic field lines. Thus, we neglect the neutral particles during collapsing of PVR or growing of PVR inside dense high conductivity plasma fluid so as to minimize complexity. Across a single moving shock surface electrons become much hotter than ions. The hot electrons are remaining in thermodynamic like equilibrium at electron temperature $T_e(r)$ is much higher than ion temperature coupled with low-frequency plasma waves. Before collapsing of PVR, the radial electron density distribution is described by Eq.(3.35) at thermal equilibrium.

The quantity $\phi(r)$ is surface electrostatic potential associated with moving dynamic boundary and shock surface in steady state. The quantity n_0 defines the number density of

electron or ion of static PVR at initial state before production of shock surface and electrostatic potential begins at upstream region. Thus, the electron number density given by Eq.(3.35) includes initial number density denoted by n_0 before shock passage. The imploding normal shock surface from dynamic boundary belongs to shock velocity $\vec{V}(r)$ surrounded by ambient shocked plasma. The imploding shock surface produces radial imploding instant and static electron surface current density given by $\vec{J} = -en_e\vec{V}$ followed by imploding dense ambient plasma.

Across the moving shock frame, the electrostatic potential remains constant of time in steady state situation. As an observer is set at the collapsing or exploding shock surfaces, he/she sees a stream of ion that is engulfed by shock surface from PVR or a stream of plasma is engulfed by shock surfaces from ambient plasma behind of it. The moving observer also observed electron cloud that is created at dynamic boundary layer. Since we assumed that $T_i \ll T_e$ before shock surface, all ions are incident with the same velocity $\vec{u}_1 = \vec{V}_0$ to shock surface. The electron distribution is bi-Maxwellian for the magnetized plasma inside PVR, if the shock surface is moving with velocity intermediate between ion sound speed and electron sound speed. We assumed that the imploding shock surface moves with ions acoustic velocity. However, the shock surface generated by fast moving electron beam never move with velocity slower than electron acoustic velocity.

So, the shock surface that is moving with velocity slower than electron thermal velocity is known as *ion-acoustic shock surface* while shock surface moves with velocity greater than ion acoustic velocity is known as *electron acoustic shock surface*. The velocity of electron or ion at the outlet shock surface from dynamic boundary in steady state situation is calculated from momentum equation using Eq.(3.35) at collapsing time of PVR is given by Eq.(3.37) and neglecting plasma viscosity and collision at isothermal electron layer or isothermal ions layer for the sake of simplicity. The graph of Fig.3.6a -3.6d shows the electron distribution of collapsing or growing magnetized PVR is described by Eq.(3.35) when the magnetic tension force is dominant over other forces. The graph of Fig.3.6a describes the electron distribution of PVR when the magnetic curvature radius is smaller than the characteristic scale of length PVR while the graph of Fig.3.6b describes the electron distribution of PVR in case of non-deformable

magnetic field. In general case, the electron distribution at fixed position inside PVR as magnetic field is deforming described by the graph of Fig.3.6c and Fig.3.6d describes non-linear electron distribution inside PVR for $R_c \leq r$ and $R_c \geq r$ respectively in case of dominant magnetic tension force region.

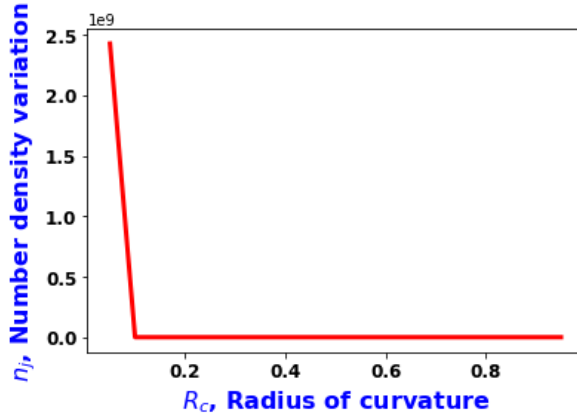


Fig.3.6a Number density variation for small radius of magnetic curvature

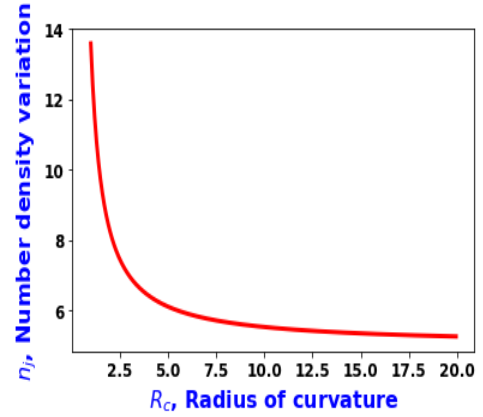


Fig.3.6b Number density variation for large radius of magnetic curvature

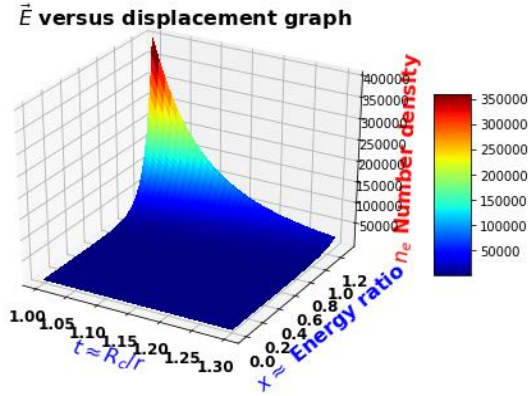


Fig.3.6c Number density as functions of magnetic curvature and energy ratio, $R_c \leq r$

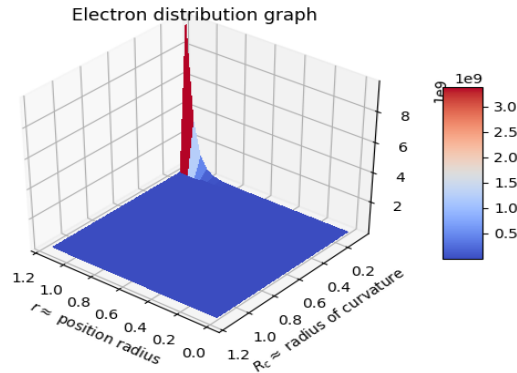


Fig.3.6d For non-linear variation of electron density for $R_c \geq r$

3.12. Imploding Shock Wave in Magnetized Plasma (Electrostatic shock surface)

Initially, electron, ion and neutral are imping in to imploding shock surface from dynamic boundary of PVR inside high conductivity plasma medium. As long as PVR is developed inside high conductivity plasma medium, intense electrostatic potential is created before generation of imploding shock surfaces at dynamic boundary layer. Electrons and ions from upstream region may not freely move in to shock surface if magnetic field is strong enough to trap electrons and

ions. Most probably, accelerating charged particles are entered quickly to shock surface before entrance of normal flowing particles across or parallel to magnetic field lines. Due to strong electrostatic potential and steep gradient of magnetic field and dynamic pressure inside PVR, electrons and ions are accelerating before arrival of imploding shock surface. The imploding velocity of dynamic boundary is approximated by velocity of imploding shock surface.

Here, the moving shock surface is considered as electrostatic shock surface coupled with current carrying double layer. For the sake of simplicity we assumed that electrons, ions and neutrals are at the same temperature inside the magnetized PVR before shock surface arrival. However, the temperature distribution of magnetized plasma before shock wave and behind shock wave is determined as parallel and perpendicular temperature distribution relative to orientation direction of magnetic field lines. Neutral particles are ionized across shock surface if the electrostatic shock surface is strong enough. The strength of single shock surface could not be determined simply. Its strength may depend on the nature of shock generation for non-relativistic and non-radiative shock wave.

When the dynamic boundary surface associated with continuous production imploding shock surface and exploding shock wave moves to center of convergence point, we use two assumptions. These are, when the electrostatic potential remains so strong during collapsing of PVR, electrons are pushed toward center of convergence region while ions are pulled toward imploding dynamic surface across or parallel to magnetic field lines. The tendency motion of neutral particles inside PVR depends on the strength of VP at convergence point. The second assumption is that, when the electrostatic potential of dynamic boundary remains constant of position, it does not exert electric force on charged particles inside PVR. However, the orientation of magnetic field inside PVR makes the system is complex. To minimize complexity, using the idea of polar and azimuthal symmetry condition in steady state situation that suffice adiabatic process before shock wave and behind shock wave, the radial particle distribution of upstream or downstream region is obtained from momentum equation. When the plasma number density is position independent in steady state of high conductivity magnetized plasma fluid under definite inertial force we get the radial charged particle distribution that is expressed by Eq.(3.36) indicates that the plasma density depends on gradients of magnetic pressure, electrostatic potential energy, plasma kinetic energy and thermal energy.

$$n = \left[\frac{\partial}{\partial r} \left(\frac{B^2}{2\mu_0} \right) - \frac{B^2}{\mu_0 R_c} \right] \left(\frac{\partial}{\partial r} \left[q\phi - \frac{1}{2}mv^2 + k_B T \right] \right)^{-1} \quad (3.36)$$

Here, we assumed $\hat{n} \cdot \hat{r} = 1$, the particle number density n is constant of position. The particle velocity inside PVR is triggered by gradient of magnetic field, electrostatic potential, temperature and other unknown potential. Where $\vec{v}$ is inertial velocity in steady state, and ϕ is electrostatic potential associated with imploding dynamic boundary which generates imploding and exploding shock waves. Let we consider the imploding collision-less shock surface is generated from a large amplitude ion wave and electron wave. The minimum velocity of imploding shock surface is approximated by collapsing velocity of dynamic boundary. If velocity of imploding shock surface is slower than velocity of imploding dynamic boundary surface, the imploding shock surface enters to region behind dynamic surface boundary. At the imploding shock surface frame, the intense electrostatic potential remains constant of time coordinate, it is position dependent. As the observer is set at the imploding shock front or dynamic surface boundary, he sees a stream of plasma impinging in to shock surface.

Since motion of electrons and ions have been controlled by strong magnetic field and intense electrostatic potential, we have assumed that ions are engulfed by imploding shock surface with velocity of $\vec{u}_i + \vec{V}$ while electrons are engulfed with velocity of $\vec{u}_e + \vec{V}$ even behind of instant dynamic surface boundary. The imploding velocity of shock surface is given by $\vec{V}$ and the approaching ions velocity to shock surface and receding electron velocity from shock surface is given by $\vec{u}_i$ and $\vec{u}_e$ respectively. The radial particle distribution of magnetized plasma before shock wave and behind shock wave is no longer Maxwellian. When we modeled PVR, the intense electrostatic potential is more effective inside PVR than far exterior. Generally, the electrostatic potential that is drop inside the PVR is greater than exterior region. Thus, $\phi > \phi_2$ and $\rho_{in} \ll \rho_{ex}$, where ϕ and ρ_{in} are electrostatic potential and plasma density inside PVR, and ϕ_2 and ρ_{ex} are electrostatic potential and plasma density exterior of PVR respectively.

Ions enter in to imploding shock surface with relative velocity approximated by velocity of dynamic shock waves $\vec{V}$ while electrons with velocity slightly different that of ions velocity. The shocked plasma is emanated from electrostatic shock surface with velocity of $\vec{u}_{2i}$ left behind of shock surface. Since $M_{s2i} = V/c_{s2i}$ and $M_{A2i} = V/v_{A2i}$, sonic shock Mach number, and

Alfven shock Mach number for ions respectively. The initial velocity could not be thermal velocity for spontaneous process; it is initial inertial velocity of impinging ion approximated by velocity of shock surface $\vec{v}_0 = \vec{V}$, and the emanating velocity of ions from shock surface is given by $\vec{v} = \vec{u}_{2i}$. Thus, by choosing across the jump condition, $c_1 = 0$, spontaneous change across the moving shock surface. From momentum equation that suffice adiabatic process behind of shock surface the magnitude of ions' velocity behind of electrostatic shock surface is given by Eq.(3.37) when plasma number density is position independent.

$$u_{2i} = V \left[1 + \frac{2}{M_{s2i}^2} (\mathcal{X}_i - 1) - \frac{1}{M_{2Ai}^2} \left(1 - \frac{2r}{R_c} \right) \right]^{1/2} \quad (3.37)$$

Where, $\mathcal{X}_i = ze\phi/k_B T_i$, is dimension-less parameter. The parameter M_{A2i} remains constant of position behind shock surface of non-variable shock wave and we take v_{A2i}/R_c or $v_{A2i}k_c$ are position independent at fixed point behind imploding shock surface. The symbol k_c is magnitude of magnetic curvature at local region. Here, we choose that v_{A2i}/R_c is position independent at local region behind of imploding shock surface at steady state situation. However, in reality the electrostatic shock surface process could be time dependent shock wave process.

Here, we assumed that $V \gg u_{1i}$ and $V \gg u_{1e}$, thus the relative velocity is approximated by shock velocity during impinging of ions to shock surface. The engulfed plasma fluid by shock surface with velocity of $\vec{V}$ and the emanated plasma from shock surface has velocity of $\vec{u}_{2i} \neq \vec{V}$ for imploding shock surface. We have used the continuity equation in steady state across the moving shock surface so as to evaluate mass conservation law. We assumed that no sink or source of mass, momentum and energy inside shock surface. By equating the impinging ions flux in to imploding shock surface with the emanating ions flux from moving shock or stationary shock on moving coordinate, the emanating ion number density in steady state situation can be expressed in terms of $\mathcal{X}_i$, M_{A2i} and M_{2Ai} behind of imploding shock surface.

$$n_i = n_0 \left[1 + \frac{2}{M_{s2i}^2} (\mathcal{X} - 1) - \frac{1}{M_{2Ai}^2} \left(1 - \frac{2\xi}{\alpha_i} \right) \right]^{-1/2} \quad (3.38)$$

Where, $\alpha_i \lambda_D = R_c$, $\xi \lambda_{Di} = r$ and n_0 is ion number density that enters to shock surface instantly. The value of dimensionless parameter α_i is a real number, $0 < \alpha_i < \infty$ for ion beam

inside fast moving electron plasma layer. However, the interaction between ions and electrons makes the system is complex. If the radius of magnetic curvature is so small for very intense magnetic field of rare dense plasma, huge amount of magnetic energy will be stored at small local region, see chapter 4, *section 4.7*. Let we consider that ions and electrons are at the same temperature behind of imploding shock surface in steady state. Since electrons are moving faster than ions, during electrons are impinging in to imploding shock surface as well as emanating from shock surface, it is a good assumption that they are spontaneous flowing particles and the electron number density emanating from moving shock surface is given by Eq.(3.39) that describes behavior of shocked electron fluid.

$$n_{2e} = \frac{1}{m_e} \left[\frac{B^2}{\mu_0 \alpha} - \frac{\partial}{\partial \xi} \left(\frac{B^2}{2\mu_0} \right) \right] \left[[1 + \mathcal{X}] \frac{\partial c_{2e}^2}{\partial \xi} + c_{2e}^2 \frac{\partial \mathcal{X}}{\partial \xi} \right]^{-1} \quad (3.39)$$

Where $\mathcal{X}_{e2} = e\phi/k_B T_{2e}$ and $c_{2e}^2 = k_B T_{2e}/m_e$ behind shock surface. When ions and electrons are at the same temperature behind shock surface, $\mathcal{X} = \mathcal{X}_{i2} = \mathcal{X}_{e2}$, the plasma fulfills adiabatic condition. Here we evaluate effects of electrostatic shock surface near region behind of imploding dynamic surface boundary. It is also necessary to evaluate the radial electron distribution behind of shock surface coupled with the dynamic shock surface boundary region with the assumption of polar and azimuthal symmetry in steady state. The electron radial distribution and ion radial distribution of number density behind shock surface given by Eqs.(3.38) and (3.39) is uniform charged particle distribution. Using Poisson's equation, manipulating Eqs.(3.38) and (3.39) behind the imploding shock surface results the following equation that describes pseudo-potential that suffices Poisson's equation is Eq.(3.40).

$$\frac{d^2 \chi}{d\xi^2} = \left[\left[\frac{v_{Ae}^2}{\alpha} - \frac{1}{2} \frac{\partial}{\partial \xi} (v_{Ae}^2) \right] \left[[1 + \mathcal{X}] \frac{\partial c_{2e}^2}{\partial \xi} + c_{2e}^2 \frac{\partial \mathcal{X}}{\partial \xi} \right]^{-1} - \left[1 + \frac{2(\mathcal{X}-1)}{M_{s2i}^2} - \frac{1}{M_{2Ai}^2} \left(1 - \frac{2\xi}{\alpha_i} \right) \right]^{-1/2} \right] \quad (3.40)$$

When the electrostatic shock surface manifests as non-relativistic current layer or charge layer, the function $\chi \ll 1$ is considerable for thermal plasma. Let us choose $\xi_e \approx \xi_i = \xi$ so as to minimize complexity. Since small disturbance of electron sound speed remains very small, that gradient of c_{2e} remains constant, zero at fixed point for small of magnetic curvature, $\alpha_i > 2\xi$ and if v_{Ae}^2/α is independent of ξ and M_{A2i} also independent of $\mathcal{X}$ at fixed point before imploding

shock surface simplifies the complexity. Using the assumption of $\xi/\alpha_i \ll 2$ and $\xi \ll \alpha$ integrating Eq.(3.40) over variable $\mathcal{X}$ results the Eqs.(3.41a) and (3.41b) that describe the steep gradient of effective electrostatic potential across the electrostatic shock wave.

$$\mathcal{V}(\mathcal{X}) \equiv \mathcal{X} \left(1 + \frac{1}{M_{s2i}^2} \right) + \frac{1}{2} \frac{M_{s2e}^2}{M_{A2e}^2} - \frac{\xi}{\alpha} \frac{M_{s2e}^2}{M_{A2e}^2} + \frac{\mathcal{X}}{2M_{2Ai}^2} \left(1 - \frac{2\xi}{\alpha_i} \right) \quad (3.41a)$$

Where, $\mathcal{V}(\mathcal{X})$, is effective electric field across imploding shock surface. If $\xi/\alpha_i \ll 2$ and $\xi \ll \alpha$ the effective electric field behind shock surface produced by non-relativistic electric current layer or charge layer is given by the following Eq.(3.41b).

$$\mathcal{V}(\mathcal{X}) \equiv \mathcal{X} \left(1 + \frac{1}{M_{s2i}^2} + \frac{1}{2M_{2Ai}^2} \right) + \frac{1}{2} \frac{M_{s2e}^2}{M_{A2e}^2} \quad (3.41b)$$

When the imploding shock surface, imploding dynamic boundary surface, provides very strong current layer, $\mathcal{X} \gg 1$, the effective electric potential behind of dynamic boundary surface is approximated by Eq.(3.42) that is obtained from solutions of Eq.(3.40), Poison's equation.

$$\mathcal{V}(\mathcal{X}) = \left(\frac{1}{2} - \frac{\xi}{\alpha} \right) \frac{M_{s2e}^2}{M_{A2e}^2} + \int \left[1 + \frac{2\mathcal{X}}{M_{s2i}^2} - \frac{1}{M_{2Ai}^2} \left(1 - \frac{2\xi}{\alpha_i} \right) \right]^{-1/2} d\mathcal{X} \quad (3.42)$$

However, if $\mathcal{X} < M_{s2i}$, and $\left| \frac{1}{M_{2Ai}^2} \left(1 - \frac{2\xi}{\alpha_i} \right) \right| < 1$, for very strong current layer or charge layer of outer side of imploding shock surface dominated by strong VSP. The strong current layer or charge layer may be double layer or single layer. In reality, the outer ions layer of imploding dynamic boundary surface is expected as temporary layer because the shocked ions are quickly replaced by injecting electrons [253]. Thus, Eq.(3.42) yields Eqs.(3.43a), (3.43b) and (3.43c) that are described below.

$$\mathcal{V}(\mathcal{X}) = \mathcal{X} \left[1 + \frac{1}{2M_{2Ai}^2} \left(1 - \frac{2\xi}{\alpha_i} \right) \right] - \frac{\mathcal{X}^2}{2M_{s2i}^2} + \left(\frac{1}{2} - \frac{\xi}{\alpha} \right) \frac{M_{s2e}^2}{M_{A2e}^2} \quad (3.43a)$$

If $\xi/\alpha_i \ll 2$ and $\xi/\alpha \ll 1/2$ Eq.(3.43a) yields

$$\mathcal{V}(\mathcal{X}) = \mathcal{X} \left[1 + \frac{1}{2M_{2Ai}^2} \right] - \frac{\mathcal{X}^2}{2M_{s2i}^2} + \frac{1}{2} \frac{M_{s2e}^2}{M_{A2e}^2} \quad (3.43b)$$

If $\xi/\alpha_i \gg 2$ and $\xi/\alpha \gg 1/2$ Eq.(3.43a) yields

$$\nu(\mathcal{X}) = \mathcal{X} \left[1 - \frac{1}{2M_{2Ai}^2} \frac{2\xi}{\alpha_i} \right] - \frac{\chi^2}{2M_{s2i}^2} - \frac{\xi}{\alpha} \frac{M_{s2e}^2}{M_{A2e}^2} \quad (3.43c)$$

This condition suffices criteria for non-relativistic moving shock surface or dynamic boundary layer. The local magnetic curvature plays a crucial role on production of effective electrostatic potential across the moving shock surface. When the temperature T_i is constant of position behind of shock surface and ions are in isothermal adiabatic plasma behind shock wave. The emanating of velocity ion from the imploding shock surface in to the shocked region of collision-less plasma is obtained as follow.

$$u_{2i} = V \left[1 + \frac{2}{M_{s2i}^2} (\mathcal{X} - \ln n_i) + \frac{2}{M_{A2i}^2} \frac{\xi}{\alpha_i} \right]^{1/2} \quad (3.44)$$

Applying Eq.(3.44) on the continuity equation across the moving electrostatic shock surface, the ion number density distribution behind of shock surface in isothermal condition of steady state situation is obtained as follow.

$$n_i = n_0 \left[1 + \frac{2}{M_{s2i}^2} (\mathcal{X} - \ln n_i) + \frac{2}{M_{A2i}^2} \frac{\xi}{\alpha_i} \right]^{-1/2} \quad (3.45)$$

The Eq.(3.45) tells us that the radial distribution of ions is non-uniform behind of imploding shock waves. The corresponding radial distribution of spontaneous diffusing electrons behind of electrostatic imploding shock surface coupled with dynamic surface of PVR is approximated from electron momentum equation as follow.

$$n_e(\xi) = n_0 \exp\{M^2 \xi/\alpha - \mathcal{X}\} \quad (3.46)$$

The dimensionless parameter $M = M_{s2e}/M_{A2e}$ denotes the ratio of sonic Mach number to Alfven Mach number. The ion and electron distribution behind electrostatic shock surface is given by Eqs.(3.45) and (3.46) are not more Maxwellian. In Eq.(3.45) using the assumption of $\mathcal{X} > \ln n_i$ approximation and substituting Eq.(3.45) and (3.46) in to Poisson's equation when strong VSP is dominant over coulomb forces we get that

$$v(\mathcal{X}) \equiv e^{\left\{ \frac{M_{s2e}^2 \xi}{M_{A2e}^2 \alpha} - \mathcal{X} \right\}} - M_{s2i}^2 \left[1 + \frac{2\mathcal{X}}{M_{s2i}^2} + \frac{2}{M_{A2i}^2 \alpha_i} \xi \right]^{1/2} - \frac{M_{s2i}^2}{\alpha_i M_{A2i}^2} \int \left[1 + \frac{2\mathcal{X}}{M_{s2i}^2} + \frac{2}{M_{A2i}^2 \alpha_i} \xi \right]^{-1/2} d\xi \quad (3.47a)$$

if $\mathcal{X}/M_{s2i}^2 < 2$ and $\xi/\alpha_i < 1$ the above equation becomes

$$v(\mathcal{X}) \equiv e^{\{M_{s2e}^2 \xi / \alpha - \mathcal{X}\}} - M_{s2i}^2 \left[1 + \frac{2\mathcal{X}}{M_{s2i}^2} + \frac{2}{M_{A2i}^2 \alpha_i} \xi \right]^{1/2} - M_{s2i}^2 \xi / \alpha_i \left[1 - \frac{1}{M_{A2i}^2 \alpha_i} \xi \right] + \frac{1}{M_{A2i}^2} \int \frac{\mathcal{X}}{\alpha_i} d\xi \quad (3.47b)$$

The function $M_i = M_{s2i}/M_{A2i}$ is ratio of ion sonic Mach to Alfvén Mach number and here we assumed that $M_{s2e}^2 \xi / M_{A2e}^2 \alpha$ is constant of $\mathcal{X}$ but the variable $\mathcal{X}$ is dependent of ξ in the expression Eqs.(3.47a) and (3.47b). This condition is existed due to anisotropic nature of magnetized plasma. The electron distribution before fast moving shock surface is influenced by presence of magnetic field and electrostatic potential. When the average magnetic field is vanished behind of the imploding shock surface, ions distribution behind of shock surface is still under the control of electrostatic surface potential.

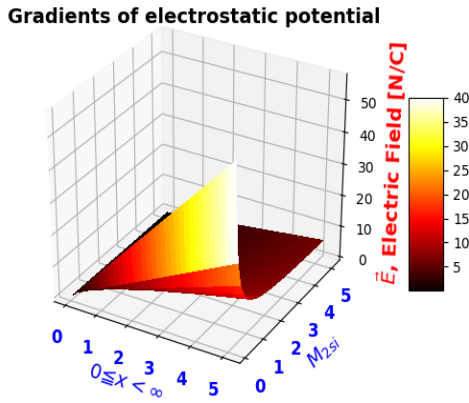


Fig.3.7a Electric field generated by ions across shock

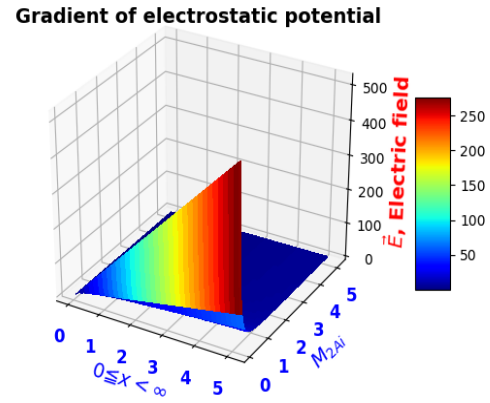


Fig.3.7b Electric field generated by magnetized ions

The graphs of Fig.3.7a and Fig.3.7b describe the steep gradients of electrostatic potential across the moving shock fronts in steady state situation associated with sonic Mach number and Alfvén Mach number respectively. The presence of magnetic field in high conductivity plasma makes the gradient of electrostatic potential is so steep, see Fig.3.7a and Fig.3.7b. The radial ion distribution behind shock surface is obtained as follow. When n_i is position independent behind of imploding shock surface in steady state, using the polar and azimuthal spherical symmetry

condition we can approximate the emanating velocity of ion behind shock surface for negligible effects of magnetic field.

$$u_{2i} = V \left[1 + \frac{2\mathcal{X}_i}{M_{s2i}^2} - \frac{2}{M_{s2i}^2} \right]^{1/2} \quad (3.48a)$$

The ion number density distribution is uniform behind shock surface we get that

$$n_i = n_0 \left[1 + \frac{2\mathcal{X}_i}{M_{s2i}^2} - \frac{2}{M_{s2i}^2} \right]^{-1/2} \quad (3.48b)$$

The electron distribution behind of imploding shock surface can be evaluated in the absence of magnetic field at equilibrium situation yields $\phi = -k_B T_e / e$ of the surface of moving shock waves. This electrostatic potential remains constant of position coupled with the moving shock frame. This shows that the production of electrostatic potential is arisen by sudden change in electron temperature behind shock surface. The electron distribution is spontaneous distribution and uniform on back surface of electrostatic shock surface. The electron radial distribution is independent of physical quantities behind of moving shock surface given by Eq.(3.48b). The effective electric field produced by the pseudo-potential across shock surface in the absence of magnetic field effect is obtained as follow.

$$\nu(\mathcal{X}) \equiv \mathcal{X} \left(1 - \frac{n_e}{n_0} \right) - \frac{1}{M_{s2}^2} \left(\frac{1}{2} \mathcal{X}^2 - \mathcal{X} \right) \quad (3.49a)$$

If electron number density before shock wave and behind shock wave remains constant, only ions generate electric field behind shock. In this sense Eq.(3.49a) can be written as follow.

$$\nu(\mathcal{X}) \equiv \frac{1}{M_{s2}^2} \left(\mathcal{X} - \frac{1}{2} \mathcal{X}^2 \right) \quad (3.49b)$$

When isothermal condition behind shock surface is sufficed, and temperature T_i is position independent behind of imploding shock surface, the impinging ions distribution to imploding shock surface is related to non-linear ion distribution behind of shock surface.

$$n_0 = n_i \left[1 + \frac{2\mathcal{X}}{M_{s2i}^2} - \frac{2}{M_{s2i}^2} \ln n_i \right]^{1/2} \quad (3.50)$$

If $\mathcal{X}_i/M_{s2i}^2 < 1/2$ and $\ln n_i/M_{s2i}^2 < 1/2$ Eq.(3.50) can be expressed as

$$n_0 = n_i \left[1 + \frac{\mathcal{X}}{M_{s2i}^2} - \frac{1}{M_{s2i}^2} \ln n_i \right] \quad (3.51)$$

However, for relativistic current layer or strong charge layer $\mathcal{X}_i \gg \ln n_i$, thus Eq.(3.50) is reduced to the following Eq.(3.52) described below.

$$n_0 = n_i \left[1 + \frac{2\mathcal{X}}{M_{s2i}^2} \right]^{1/2} \quad (3.52)$$

In this condition the electron distribution behind of shock surface remains Maxwellian. The non-linear ion distribution across the fast moving shock wave is well described in graphs of Fig.3.8a and Fig.3.8b. The Fig.3.8b describes the absolute value of under square root value in Eq.(3.51) by normalizing the inverse of shock Mach number so as to minimize computational errors. The Fig.3.8c describes non-linear distribution of ions behind fast propagating shock waves and the when medium is characterized by thermal condition. In this case the ratio of electric energy to thermal energy is vanished. Form graph of Fig.3.8a the non-linear distribution of ion density ratio across the fast moving shock wave is determined at interval between $1 - \ln n_i$ that yields real value. While the graph of Fig.3.8b describes non-linearity ion's density distribution ratio including the interval of $\ln n_i \geq 1$.

The graphs of Fig.3.8c, Fig.3.8d and Fig.3.8e describe ion density across shock fronts for dominant thermal energy distribution; the non-linear distribution of ions across the moving shock wave front is clearly shown. The graphs of Fig.3.8f and Fig.3.8g describe the non-linear relation of ions distribution across fast moving shock waves. Fig.3.8h describes ion density distribution across fast moving shock waves when the effect of electrostatic potential is significant. The ion number distribution across fast moving shock wave front for negligible effects of magnetic field is described by Fig.3.8j below. The steep gradient of electrostatic potential across the fast moving shock wave is described by figures of Fig.3.8k and Fig.3.8L. The graph of Fig.3.8m describes steep gradient electrostatic potential when velocity of shock is equals to plasma acoustic speed. Here, we assumed that electron and ion are at the same temperature. The effective electric field near region behind of imploding shock surface is approximated as follow.

$$v(\mathcal{X}) \equiv e^{-\mathcal{X}} - M_{s2i}^2 \left[1 + \frac{2\mathcal{X}}{M_{s2i}^2} \right]^{1/2} \quad (3.53)$$

The electrostatic potential field coupled with the moving shock surface is evaluated from Poisson's equation, see chapter 4, fast magnetic reconnection process. From Eqs.(3.41a) - (3.53), we understand that shock waves have a characteristic of sharp electric field in the pressure transition region. The electric field is oriented in the direction of propagation and it enables to reflect charged particles under certain condition with a maximum of twice incident velocity.

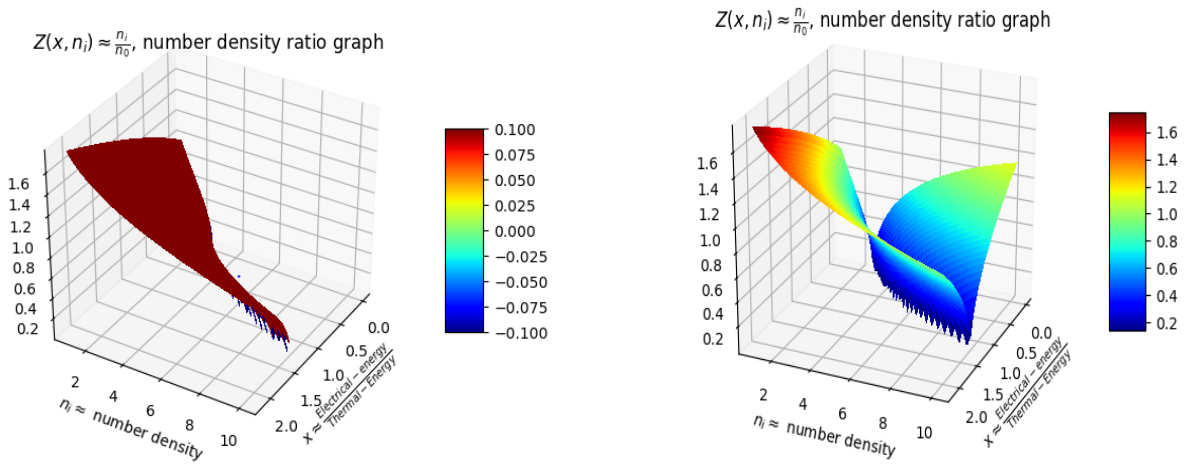


Fig.3.8a Non-linear ion distribution enter to shock

Fig.3.8b Non-linear ion distribution centers to and emanated from shock

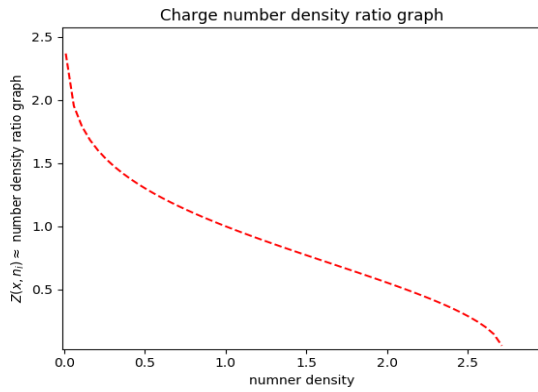


Fig.3.8c Charged particles are compressed inside shock

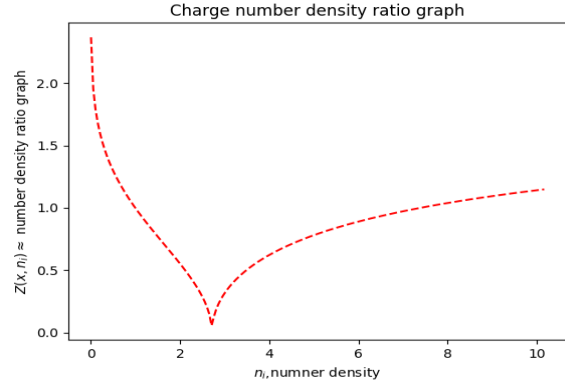


Fig.3.8d Shock compressed charged particles release exploding energy

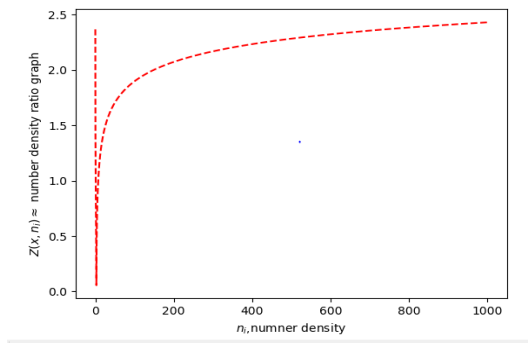


Fig.3.8e Steep density gradient across shock surface

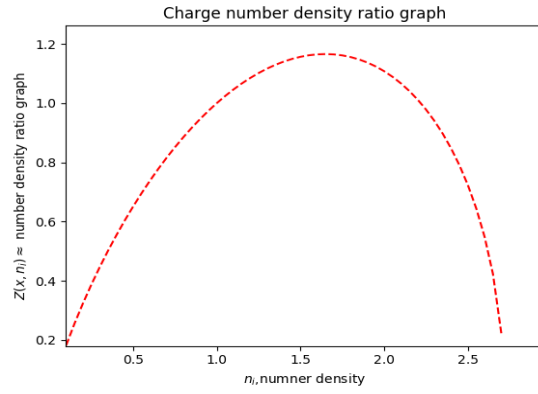


Fig.3.8f Ion depletion inside instant shock

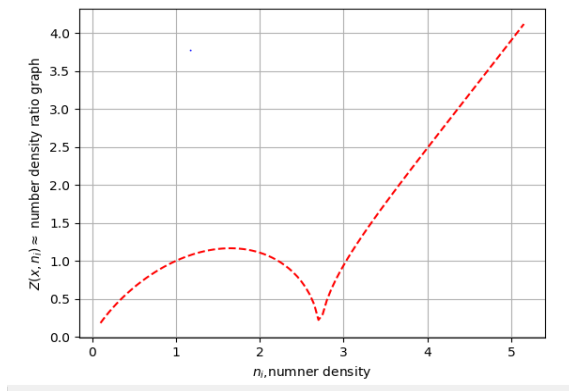


Fig.3.8g Cold ion depletion across instant shock

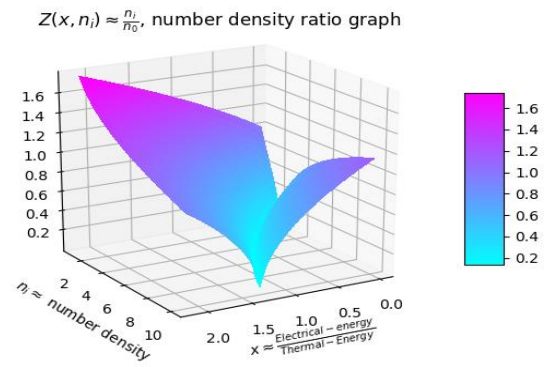


Fig.3.8h Cold ion depletion across electrostatic shock

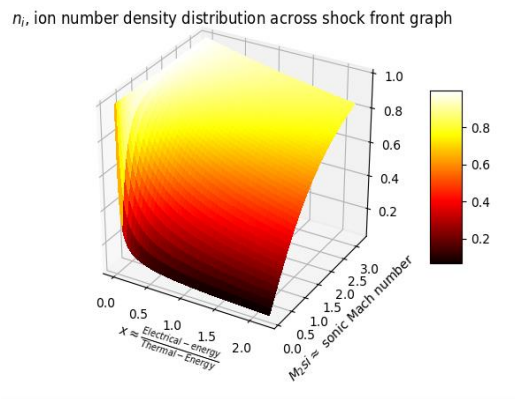


Fig.3.8j Ion distribution across electrostatic shock

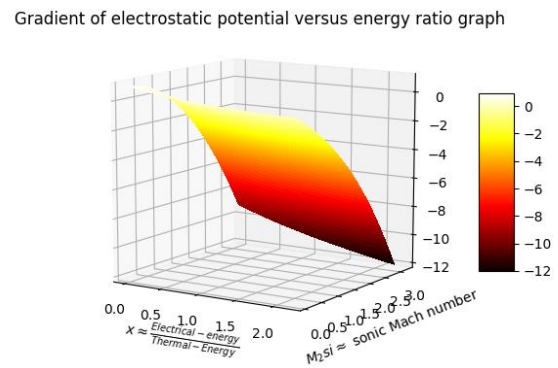


Fig.3.8k Gradient electrostatic potential across shock

Gradient of electrostatic potential versus energy ratio graph

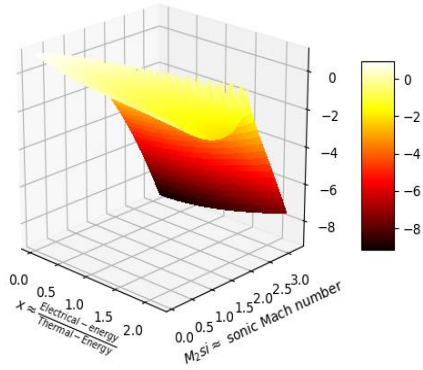


Fig.3.8L Induced electric field across shock

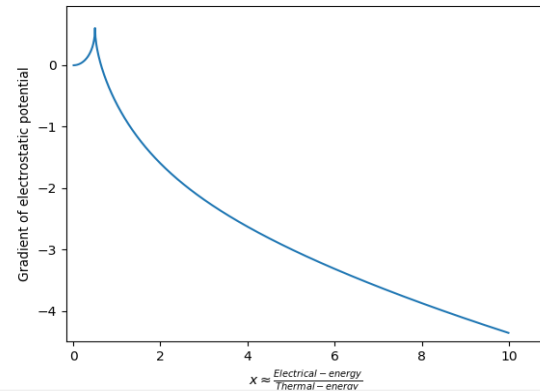


Fig.3.8m Induced electric field across sonic shock

The Fig.3.8a - Fig.3.8m illustrated the nature of electrons and ions across fast propagating shock surfaces. For instance, Shock wave formed in solar atmosphere in front of a plasma jet flying at supersonic speeds produced normal electric field on its surface. On Langmuir moving shock surface or turbulent shock surface intense instant electrostatic field is generated, see Eqs.(3.41a), (3.42), (3.47a), (3.49) and (3.53).

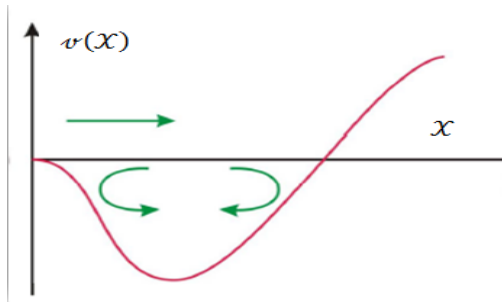


Fig.3.9 Static electric field versus energy ratio

The ions, which flow from upstream (i.e., most probably inside PVR before collapse) to downstream (most probably surrounding PVR), may be slowed down by the surface electrostatic shock potential, and reflected back into the upstream for strong imploding shock waves. Fig.3.9 is obtained from Eq.(3.53) for sonic shock.

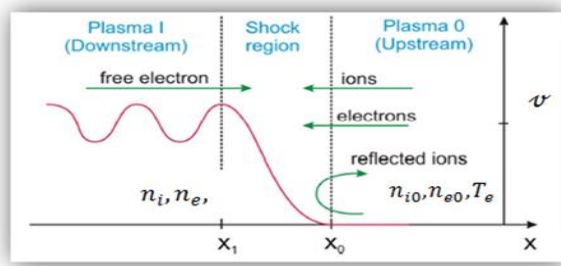


Fig.3.10 Electrostatic potential across shock surface

Let we consider non-magnetized plasma; ions from the upstream region enter to shock surface more freely, while electrons from the downstream region can be either free or trapped. When incident ions from ambient surrounding plasma may be reflected at shock surface with their velocity is twice shock velocity, the shock

accelerated ions in steady state obtain the shock kinetic energy is given by $2m_i V^2$ for $\vec{u}_{1i} \ll \vec{V}$, and indicates that the evaluation of changes in kinetic energy of ions during their interaction with the shock surface.

$$E_k = 2m_i V^2 \quad (3.54)$$

Generally, ion at upstream region far away from the shock surface moves with velocity $\vec{u}_{1i} \pm \vec{V}$ towards shock surface. When the inflowing charged particles are reflected at shock surface with velocity $2(\vec{u}_{1i} \pm \vec{V})$ belong to kinetic energy of proportional to $4(\vec{u}_{1i} \pm \vec{V})^2$ after reflection at the upstream region. When ions passed through shock surface, they are propagating through the downstream plasma with velocity of $\vec{u}_{2i} \pm \vec{V}$ relative to the inertial frame.

3.13. Normal Moving Shock Waves through Magnetized Plasma

Shock wave occurs both in steady and unsteady flow of high conductivity fluid. The existed shock waves associated with physical phenomena of local system makes a change on physical quantities. For instance, the gravitational collapse creates a shock that triggers nuclear reaction interior of stars, and chemical reaction changes the shock in to explosive waves. Shock waves in low density region responsible for acceleration of particles and electromagnetic wave burst. This kind of shock may be collisional shock or collision-less shock which is observed from space and astronomical objects like solar explosive events, supernovae explosions, Earth's bow shock and inter-Galactic shocks [27, 254, 255].

Let us imagine that a fast moving normal shock wave is propagating through high conductivity magnetized neutral plasma. Since we have assumed a system, through which fast moving shock wave field is propagating, electrons, ions and neutrals are accelerated due to non-linear effects of wave function and also neutrals are ionized. The propagating shock wave field is constructed from continuous trains of shock wave surfaces. To minimize complexity, the average value of shock surface induced electrostatic field is assumed to be zero except at outer dynamic boundary surface of the isolated system. The moving shock field may be collisional shock or collision-less shock field. The thickness of collisional shock may be approximated by mean free path of plasma particles. Collisional shock field is characterized by energy dissipation across the moving shock field. However, we do not know the thickness of collision-less shock field. The

thickness of collision-less shock field is much less than the plasma particle mean free path. In collision dominated shock field the wave profile results from a balance between *convective* and *dissipative* effects while in collision-less shock field the wave profile is arisen from a balance between *convective* and *dispersive* effects.

We evaluate the physical quantities passing through the propagating normal shock field excluding the surface of local system. We imagine that the topology of complex magnetic field has an arbitrary geometrical coordinate. The considered complex magnetic field is assumed to be the average value of plasma induced micro magnetic field and external magnetic field located at the interesting region. The moving shock field can be unsteady moving shock field and steady moving shock field in space and time coordinates. As we see in chapter 2 and 5, SWIF-1SQR model, when the PVR reaches its minimum low density limit during its evolution, the electrostatic potential field becomes independent of position in steady state situation.

Consider a radial moving one dimensional normal shock field. The term shock field defines continuous trains of same families of shock wave fronts. In magneto-hydrodynamics (MHD) there are three fundamental small amplitude shock waves. These are fast, intermediate (Alfven) and slow mode waves. So as to define the physical system in terms of different characteristic speed, there could be different Mach numbers before shock field as well as behind shock field. These are Alfven Mach number (M_A), shock Mach number or sonic Mach number (M_c), slow Mach number (M_s) and fast Mach number (M_f) which are the flow speed divided by Alfven, sound, slow and fast speed respectively. Because of the formation of three different small amplitude wave modes, it could be difficult to determine the nature of moving shock field in high conductivity magnetized plasma medium. The complexity in moving shock wave is arisen from non-linearity of small amplitude waves and particle-wave interaction principle. The behavior of magnetized plasma before shock wave and behind shock wave is in double adiabatic process if the magnetic field is strong enough.

Intermediate waves are purely transverse and do not steepen to form shock waves through high conducting plasma. The fast and slow modes in general contain both transverse and longitudinal components and these modes give rise to shock waves through high conductivity medium. For collision dominated shock wave, the dissipation mechanism is expected as

viscosity, heat conductivity, and electrical conductivity (Joule heating) coupled with non-linear effects of wave phases. The mass conservation, momentum conservation and energy conservation equations across normal moving shock surface in steady state situation independent of shock structure is described Eqs.(3.55), (3.56) and (3.57) that relates the behavior of neutral magnetized plasma upstream to downstream, see Eqs.(2.81), (2.82) and (2.83) in chapter 2.

Charged particles inside PVR before shock wave passage are trapped if magnetic field is strong enough. The imploding plasma element may be in parallel motion or perpendicular motion to the strong local magnetic field. Ions and electrons that are passing through continuous trains of shock wave fronts may absorb wave energy and gain enough kinetic energy which enables them to escape from trapping by magnetic force. They may form electromagnetic and particle radiation behind shock passage. When the propagation direction of shock fronts is at an angle of, θ_B , with magnetic field $\vec{B}$, the magnetic field is influenced by propagating local shock wave fronts at the local system. Magnetic energy may be changed in to kinetic energy, heat energy and radiation energy.

The primary imploding shock wave moves, as we have seen in chapter 2 that $u_1 + V$ is the relative shock speed, and $u_1 + c_1$ is the propagation speed of small disturbances of plasma elements before the shock wave. The relative speed $u_2 + c_2$ denotes the propagation speed of small disturbances behind of the shock wave passage. Propagation speed of Alfven wave before shock wave front as well as behind shock wave front is given by $u_1 + c_1 + v_{A1}$ and $u_2 + c_2 + v_{A2}$ respectively. The shock velocity may be time and position dependent, $\vec{V}(X, t)$ where $X(r, \theta, \varphi)$ in spherical coordinate. Thus, the Mach number before shock wave is $M_{x1} \gg 1$ for supersonic flow of high conductivity plasma. So that, $V > c_1$ and $V > v_A$, the shock wave travels faster than speed of sound and Alfven speed respectively. The condition of $V + u_2 + v_{A2} < u_2 + c_2 + v_{2A}$ show that the shock travels slower than small pressure wave in magnetized plasma behind the shock wave, while the equation, $V + u_1 + v_{1A} > u_1 + v_{1A} + c_1$ show that the shock wave travels faster than small pressure waves and Alfven wave in the magnetized plasma. Using assumption of azimuthal and polar symmetry of space coordinate, the set of resistive MHD equations in steady state across moving shock wave can be obtained as

$$\rho_1 V = \rho_2 [V \pm (u_{1n} - u_{2n})] \quad (3.55)$$

$$\rho_1 \vec{V} \vec{V} + \left(p_1 + \frac{B_1^2}{2\mu_0}\right) \mathbf{I} - \frac{1}{\mu_0} \vec{B}_1 \vec{B}_1 = \rho_2 [\vec{V} \pm (\vec{u}_1 - \vec{u}_2)] [\vec{V} \pm (\vec{u}_1 - \vec{u}_2)] + \left(p_2 + \frac{B_2^2}{2\mu_0}\right) \mathbf{I} - \frac{1}{\mu_0} \vec{B}_2 \vec{B}_2 \quad (3.56)$$

$$\begin{aligned} & \left(\frac{1}{2}\rho_1 V^2 + \frac{\gamma p_1}{\gamma-1} + \frac{B_1^2}{2\mu_0}\right) V - \frac{1}{\mu_0} V B_{1n}^2 + \frac{\eta_1}{\mu_0} \vec{\nabla}_\perp \left(\frac{B_1^2}{2\mu_0}\right) \cdot \hat{n} - \frac{B_1^2}{\mu_0^2 R_c} (\hat{b} \cdot \hat{n}) = \left(\frac{1}{2}\rho_1 V[V \pm (u_{1n} - u_{2n})] + \frac{\gamma p_2}{\gamma-1} + \right. \\ & \left. \frac{B_2^2}{2\mu_0}\right) [V \pm (u_1 - u_2)] - \frac{1}{\mu_0} B_{2n}^2 [V \pm (u_{1n} - u_{2n})] + \frac{\eta_2}{\mu_0} \vec{\nabla}_\perp \left(\frac{B_2^2}{2\mu_0}\right) \cdot \hat{n} - \frac{B_2^2}{\mu_0^2 R_c} (\hat{b} \cdot \hat{n}) \end{aligned} \quad (3.57)$$

The symbol $\mathbf{I}$ represents the dyadic tensor and $\hat{b}$ and $\hat{n}$ are the unit vectors of magnetic field and direction motion of normal moving shock surfaces respectively. The symbols η_1 and η_2 represent the electrical resistivity before shock wave and behind shock wave respectively. The subscript 1 and 2 denotes the condition before and behind the moving shock surface. For normal moving shock surface, the tangential shock velocity remains the same before shock surface and behind shock surface. From Eq.(3.55), we have found that tangential flowing velocity before shock surface and behind shock surface is continuous, $u_{1t} = u_{2t}$ for neutral plasma elements. The velocity of normal moving shock surface is much smaller than speed of light but faster than acoustic plasma speed in radial direction.

The Eqs.(3.55), (3.56) and (3.57) represent the conservation of mass, momentum, and energy, respectively. The mass flux, momentum flux and energy flux across the normal moving shock surface can be split in to *tangential* plane component and *normal* component. The represented normal and tangential components of physical quantities are relative to normal unit vector of moving shock surface. Based on this condition, the high conductivity plasma fluid in magnetic field can support two further modes of wave propagation. These are the *tangential* (one *longitudinal*) and *normal* (two *transverse*) that have three degrees of freedom in high conductivity plasma relative to direction of magnetic field line. However, we have used here the orientation of directional flow and direction of magnetic field relative to direction of normal unit vector of shock surface. For simplicity, we restrict our discussion to plane shocks moving in a radial direction normal in spherical coordinate of the shock surface.

Let this be the $\vec{r}$ local radial position vector; then all variables are functions of $\vec{r}$ only inside the shock wave field and are constant outside the shock field in steady state situation. From $\vec{\nabla} \cdot \vec{B} = 0$ we have obtained that

$$\vec{B}_1 \cdot \hat{n} = \vec{B}_2 \cdot \hat{n} \quad (3.58a)$$

$$\vec{B}_1 \cdot \hat{t} = \vec{B}_2 \cdot \hat{t} \quad (3.58b)$$

The unit vector $\hat{t}$ is a unit vector tangential to direction motion of normal shock surface. The Eqs.(3.58a) and (3.58b) indicate that normal component of magnetic field is continuous across shock surface. This is only true if and only if there are no particles inside the non-relativistic shock wave. However, if the thickness of shock wave is large enough comparing with ion and electron gyro-radius and plasma frequency wave length, interaction of particles and fields inside the shock region is inevitable. Magnetic energy can be converted in to heat energy, kinetic energy, and radiation energy and vice versa. From Ampere's law, the tangential and normal continuity of electric field is described by Eq.(3.59a) and (3.59b).

$$[\vec{V} \times \vec{B}_1] \times \hat{n} - \eta_1 \vec{j}_1 \times \hat{n} = ([\vec{V} \pm (\vec{u}_1 - \vec{u}_2)] \times \vec{B}_2) \times \hat{n} - \eta_2 \vec{j}_2 \times \hat{n} \quad (3.59a)$$

$$[\vec{V} \times \vec{B}_1] \times \hat{t} - \eta_1 \vec{j}_1 \times \hat{t} = ([\vec{V} \pm (\vec{u}_1 - \vec{u}_2)] \times \vec{B}_2) \times \hat{t} - \eta_2 \vec{j}_2 \times \hat{t} \quad (3.59b)$$

The Eq.(3.59a) describes continuity of tangential electric field while Eq.(3.59b) describes continuity of normal electric field across fast moving shock waves. The quantity η_1 and η_2 denotes plasma resistivity before shock surface and after shock surface tends to zero for high conductivity plasma corresponds to $\vec{j}_1$ and $\vec{j}_2$ respectively. The Eq.(3.58a) and (3.59a) give the jump conditions for the magnetic field expressing the continuity of the normal component of $\vec{B}$ and the tangential component of electric field $\vec{E}_1 = -\vec{V} \times \vec{B}_1$ before shock wave and $\vec{E}_2 = -[\vec{V} \pm (\vec{u}_1 - \vec{u}_2)] \times \vec{B}_2$ behind of the moving shock surface. The pressure is anisotropic upstream and downstream region. Across the normal moving shock, necessary condition to fulfill shock condition is $\vec{V} \cdot \hat{n} \neq 0$ which shows that the propagation of normal shock surface through high conductivity plasma fluid. The tangential velocity of plasma element is continuous across moving normal shock wave, $u_{1t} = u_{2t}$ which shows that tangential flowing of high conductivity plasma fluid is not influenced by the presence of normal moving shock surface in high conductivity plasma.

Evaluating the tangential energy flux which satisfies discontinuity in tangential component of energy flux and equating with Eq.(3.55) in steady state situation yields the relation between normal flowing speed of high conductivity plasma and magnetic field across normal

shock wave that is described by Eq.(3.60) in terms of shock wave speed and components of magnetic field.

$$u_{2n} - u_{1n} = \pm V \left[1 - \frac{B_{1n}B_{1t}}{B_{2n}B_{2t}} \right] \quad (3.60)$$

The Eq.(3.60) indicates that change in plasma velocity across normal moving shock wave is controlled by velocity of moving normal shock waves and magnitudes of normal and tangential magnetic field components. As magnetic field behind shock surface decreases, the change in normal flow of plasma along shock wave propagation may increase or decrease by V times the factor of $(1 - B_{1n}B_{1t}/B_{2n}B_{2t})$ tends to negative infinite. If tangential component of magnetic field across normal shock wave is continuous, $B_{1t} = B_{2t}$ we get that

$$u_{2n} - u_{1n} = \pm V \left[1 - \frac{B_{1n}}{B_{2n}} \right] \quad (3.61a)$$

While the normal component of magnetic field across normal shock surface is continuous, $B_{1n} = B_{2n}$ the tangential components of magnetic field changes abruptly we get that

$$u_{2n} - u_{1n} = \pm V \left[1 - \frac{B_{1t}}{B_{2t}} \right] \quad (3.61b)$$

If $B_{1t} \ll B_{2t}$ in Eq.(3.61b), the change in normal flow of plasma is controlled by switch-off normal shock surface while for $B_{1t} \gg B_{2t}$ the shock switch-on condition controls the change in radial flow of high conductivity plasma across normal moving shock surface. In case of shock switch-on condition, for constant magnitude of normal magnetic field, the shock wave converts flow energy to magnetic energy while the magnetic energy is converted to shock kinetic energy $\sim \rho_1 V^2$ through shock field during shock switch-off condition. Particle radiation is created coupled with shock surface. In this special case we assumed that total mass flux including the normal and tangential mass density distribution before and behind normal moving shock surface remains constant of position in steady state situation. Using Eq.(3.55) the change velocity of normal flow across normal moving shock wave is described by Eq.(3.62).

$$u_{2n} - u_{1n} = \pm \frac{1}{\rho_1 V} (P_2 - P_1) \pm \frac{1}{\rho_1 V} \left(\frac{B_1^2}{2\mu_0} - \frac{B_2^2}{2\mu_0} \right) \quad (3.62)$$

If $u_{1n} = 0$, $P_2 \gg P_1$ and $B_2 \ll B_1$ the system supports spontaneous explosion or implosion and strong magnetic field is produced behind of moving shock surfaces or vice versa. Anisotropy plasma pressure, $p_1 \mathbf{I} = p_{1t} + p_{1n} = P_1$ across the normal moving shock fronts is assumed small. Let us define the dynamic pressure of flowing magnetized plasma across moving normal shock surface, namely, p_t , is the corresponding pressure tangential to moving shock normal vector, and p_n , also the corresponding pressure parallel to moving shock normal. When collision-less flowing magnetized plasma passes through normal moving shock wave, and if the temperature develops an anisotropy such that $p_t \neq p_n$, the anisotropy persists for long time. From tangential component of momentum flux, a discontinuity in tangential component in dynamic pressure and magnetic pressure can be described by Eq.(3.63).

$$p_{2t} - p_{1t} = \frac{B_{2t}^2}{2\mu_0} - \frac{B_{1t}^2}{2\mu_0} \quad (3.63)$$

Here, also there is no shock wave formed and the discontinuity is a *contact discontinuity*. The Eq.(3.63) shows that total tangential pressure is conserved in the system. If tangential magnetic field remains constant across the normal moving shock surface, tangential dynamic pressure continuous across the moving shock surface. Thus, the normal dynamic pressure, magnetic pressure and velocity are continuous. Only the temperature and mass are changed along tangential direction of the normal moving shock surface. Substituting Eq.(3.60) in to Eq.(3.62) results the change in dynamic pressure across normal moving shock surface in terms of shock velocity and magnetic field components that is described by Eq.(3.64).

$$P_2 - P_1 = \rho_1 V^2 \left(1 - \frac{B_{1n}B_{1t}}{B_{2n}B_{2t}} \right) - \left(\frac{B_{1t}^2}{2\mu_0} - \frac{B_{2t}^2}{2\mu_0} \right) \quad (3.64)$$

Using anisotropy properties of high conductivity magnetized plasma medium through which normal shock surface propagates, the general expressions of Eqs.(3.62) and (3.64) is defined by Eqs.(3.65) and (3.66).

$$u_{2n} - u_{1n} = \pm \frac{1}{\rho_1 V_n} (p_{2n} - p_{1n}) \pm \frac{1}{\rho_1 V} \left(\frac{B_{1n}^2}{2\mu_0} - \frac{B_{2n}^2}{2\mu_0} \right) \pm \frac{i}{\rho_1 V} \left[p_{2t} - p_{1t} + \left(\frac{B_{1t}^2}{2\mu_0} - \frac{B_{2t}^2}{2\mu_0} \right) \right] \quad (3.65)$$

$$p_{2n} - p_{1n} = \rho_1 V^2 \left[1 - \frac{B_{1n}B_{1t}}{B_{2n}B_{2t}} \right] + \left(\frac{B_{2n}^2}{2\mu_0} - \frac{B_{1n}^2}{2\mu_0} \right) - 2i \left[p_{2t} - p_{1t} + \left(\frac{B_{1t}^2}{4\mu_0} - \frac{B_{2t}^2}{4\mu_0} \right) \right] \quad (3.66)$$

The complex terms in Eqs.(3.65) and (3.66) indicate the orthogonally properties of vector physical quantity of momentum conservation. The physical quantities in the complex term do not participate in shock wave process when the local system does not interact with its environment. Only the real part of Eq.(3.65) and (3.66) take part in shock wave process and are unstable terms. Here, we approximate the tangential dynamic pressure as $p_t = 2p$ is exerted on plane and normal dynamic pressure as $p_n = p$ respectively. The entropy corresponds to the tangential discontinuity remains constant both at upstream and downstream region. To determine the quasi-parallel and quasi-perpendicular normal moving shock surface, we take angles between the shock normal unit vectors and flowing plasma element before and after the shock surface is given by θ_1 and θ_2 respectively. The normal and tangential velocity components of flowing plasma are denoted by $u_{1n} = u_1 \cos \theta_1$, $u_{1t} = u_1 \sin \theta_1$ and $u_{2n} = u_2 \cos \theta_2$, $u_{2t} = u_2 \sin \theta_2$ at adiabatic process of steady state situation after shock surfaces and behind shock surfaces. The angles between shock normal unit vector and magnetic field also given as by θ_{B1} and θ_{B2} before and behind shock surface respectively. Since the tangential flow remains the same in upstream and downstream region, the flowing angle of downstream relative to direction normal shock motion is evaluated from Eq.(3.55) in high conductivity magnetized plasma medium.

$$\theta_{n2} = \tan^{-1}(\tan \theta_{n1}) \quad (3.67)$$

The flowing angles θ_{n1} and θ_{n2} is angle between shock normal and magnetized plasma flow before shock wave and behind normal shock wave respectively in steady state. However, the presence of magnetic field make the situation is difficult so as to determine direction of flow. The Eq.(3.67) is valued when normal shock wave is propagating through high conductivity magnetized plasma medium. From Eq.(3.59a) of the tangential change of static electric field across the moving shock surface which interacts with downstream plasma particles is defined by the following equations for high conductivity plasma across electrostatic shock waves.

$$\vec{E}_{1st} - \vec{E}_{2st} = \pm(\vec{u}_{1n} - \vec{u}_{2n}) \times \vec{B}_{2t} \quad (3.68)$$

This shows that tangential electric field is continuous across the moving normal shock fronts. The shock wave generated electric field lies on tangential plane to normal shock fronts. The static electric fields of $\vec{E}_{1st} = \vec{V} \times \vec{B}_{1t}$ and $\vec{E}_{2st} = \vec{V} \times \vec{B}_{2t}$ are laid on tangential plasma of front

side and back side of electrostatic normal shock surface. The quantity $\vec{u}_1 \times \vec{B}_2 = 0$ because $\vec{u}_1$ and $\vec{B}_2$ are in two different regions which are separated by shock boundary layer. There is no space and time connection at the two different regions at the same time across the moving shock surface. For single passage of shock surface through high conductivity plasma $\vec{V} \times \vec{B}_2 = 0$ because the shock wave, velocity, $\vec{V}$ and magnetic field, $\vec{B}_2$ behind shock wave are not connected by time coordinates. Thus, $\vec{E}_{2st} = 0$ for resistive plasma fluid we get that

$$\vec{E}_2 = \pm(\vec{E}_{2st} - \vec{E}_{1st}) \pm (\eta_2 \vec{j}_2 - \eta_1 \vec{j}_1) \quad (3.69a)$$

$$\vec{E}_2 = \pm(\vec{E}_{2st} - \vec{E}_{1st}) \pm \frac{1}{\mu_0} (\eta_2 \vec{V} \times \vec{B}_2 - \eta_1 \vec{V} \times \vec{B}_1) \quad (3.69b)$$

The quantity $\vec{E}_2$ is given by $\vec{u}_{2n} \times \vec{B}_{2t}$ plasma induced electric field behind shock surface of neutral plasma. From Eqs.(3.69a) and (3.69b) we understand that the change in tangential electric field across shock surface may influence the plasma behind shock passage. When a shock fronts are moving in magnetized plasma, static electric field is created at the back side of shock fronts. Where $\vec{E}_{1st}$ and $\vec{E}_{2st}$ are tangential static electric field induced due to moving normal shock surfaces in the front side and back side of moving shock surface boundary. The fast moving shock surfaces separates electrons from ions in high conductivity plasma medium, see Eqs.(3.68) and (3.69b). The electric field produced across the normal moving shock wave in perpendicular to the plane containing normal shock wave velocity component. It is expressed in terms of pressure, density and magnetic field that relate the upstream region with downstream region obtained from normal momentum flux components. This is evaluated from cross product of Eq.(3.68) coupling with jump condition in magnetic field yields Eq.(3.70).

$$V = \sqrt{\frac{B_{2t}}{\rho_1(B_{1t} - B_{2t})}} \left[p_{1n} - p_{2n} + \frac{B_{2n}^2}{2\mu_0} - \frac{B_{1n}^2}{2\mu_0} \right]^{1/2} \quad (3.70)$$

Here, we assumed that the direction of magnetic field before and behind shock surfaces are in same direction and also direction of plasma flowing before shock surface and behind shock surface is also the same but their magnitude may not be the same. As we have investigated Eq.(3.70), when $B_{1t} = -B_{2t}$ the shock surface moves with velocity is the same as normal velocity component of plasma flow before shock surface as long as direction of magnetic field

remains the same aftershock surface. When the shock velocity is much greater than change in normal flow velocity behind shock surface and before shock surface, $|u_{1n} - u_{2n}| < V_n$, substituting Eq.(3.60) in to Eq.(3.55) and manipulation with tangential discontinuity of Eq.(3.55), we verify the tangential dynamic pressure ratio behind shock surface to before shock surface in steady state situation results Eq.(3.71).

$$\frac{p_{2t}}{p_{1t}} = 1 + \frac{\gamma v_{A2t}^2}{2c_1^2} \left[2 - \frac{B_{1n}}{B_{2n}} B_{1t} \right] - \frac{\gamma}{2} M_{A1t}^2 \quad (3.71)$$

The parameter $v_{A1t}^2/c_1^2 = M_{A1t}^2$ is tangential Alfven Mach number before shock wave surface. From Eq.(3.71) we understand that the tangential discontinuity is arisen from effects of normal shock wave surface through high conductivity plasma. Across the normal moving shock surface, it may be happened that some of the flow energy is converted into magnetic energy so that $|\vec{B}_2| > |\vec{B}_1|$. Since the normal component of $\vec{B}$ has conserved, the passage of the shock surface creates a tangential component and it is said to be a *switch-on shock*, see Eq.(3.61b). The tangential dynamic pressure ratio is influenced by complex magnetic pressure across the moving shock surface. When the shock velocity is less than change in normal flow velocity behind shock and before shock, $|u_{1n} - u_{2n}| > V$, the tangential dynamic pressure ratio is verified by Eq.(3.72) as normal magnetic field remains constant before and behind shock $B_{2n} = B_{1n}$ and $B_{2t} = -B_{1t}$ in case of collision-less shock wave process.

$$\frac{p_{2t}}{p_{1t}} = 1 + \frac{\gamma}{2} \left[\frac{v_{A2t}^2}{2c_1^2} - M_{A1t}^2 \right] \quad (3.72)$$

When the shock switch-off and shock switch-on condition is sufficed, from Eq.(3.71) we have obtained Eq.(3.73a) and (3.73b).

$$\frac{p_{2t}}{p_{1t}} \approx 1 - \frac{1}{2} \gamma M_{A1t}^2 \quad (3.73a)$$

$$\frac{p_{2t}}{p_{1t}} = 1 - \frac{1}{2} \frac{\gamma v_{A2t}^2}{c_1^2} \quad (3.73b)$$

When the velocity of moving shock surface is balanced by change in normal flowing velocity of plasma fluid behind shock surface and before shock surfaces, the tangential dynamic pressure

ratio given by Eq.(3.71) is approximated as shown in Eq.(3.73c) that is described in terms of Alfven Mach number.

$$\frac{p_{2t}}{p_{1t}} \approx 1 - \frac{\gamma}{4} M_{A1t}^2 \quad (3.73c)$$

In this case the density ratio across normal shock surface is approximated by $\rho_2/\rho_1 = 1/2$ indicates tangential density distribution decrease by half across normal moving shock surface. The tangential dynamic pressure behind shock wave depends on Alfven Mach number before shock wave passage. For the condition of $M_{A1t} \ll 1$ the tangential dynamic pressure remains constant. Considering the anisotropic pressure behind and before shock surface for vanishing off-diagonal components of pressure tensor, the change in normal velocity component across shock surface depends on change magnetic pressure across moving shock wave and also change in sound speed across shock surfaces associated with mass flux enter to shock surface. Considering the conservation of momentum flux across the moving normal shock surface for continuous tangential flowing velocity, the change of normal flowing velocity in anisotropic plasma pressure behind and before normal moving shock is obtained as following.

$$u_{2n} - u_{1n} = \pm \frac{3}{\gamma} \left[c_2^2 - \frac{c_1^2}{\gamma} \right] \pm \left(\frac{p_{m1}}{\Gamma_1} - \frac{p_{m2}}{\Gamma_1} \right) \quad (3.74a)$$

The quantity $\rho_1 V_n = \Gamma_1$ is defined as the mass flux enters to shock surface or mass flux engulfed by shock surface against to or supported by magnetic pressure $p_{m1} = B_1^2/2\mu_0$ across the normal moving shock surface. Magnetic pressure behind normal moving shock surface is defined by $p_{m2} = B_2^2/2\mu_0$ in high conductivity plasma medium. When $u_{1n} \approx 0$ and $u_{2n} \gg 0$ a spontaneous exploding plasma jet is observed behind the moving normal shock wave. When $u_{2n} > c_2$, a spontaneous supersonic plasma flow is created behind shock surface. The spontaneous velocity behind normal moving shock surface is given by Eq. (3.74b). The agent of shock wave is the flowing plasma jets and its velocity behind of propagating shock wave is given by.

$$u_{2n} = \pm \frac{3}{\gamma} \left[c_2^2 - \frac{c_1^2}{\gamma} \right] \pm \left(\frac{p_{m1}}{\Gamma_1} - \frac{p_{m2}}{\Gamma_1} \right) \quad (3.74b)$$

The fast flowing high conductivity plasma is cooling behind shock surface when $u_{2n} \ll u_{1n}$ instantly. The upstream flowing velocity of plasma element is given by Eq.(3.74a) for $u_{2n} = 0$,

condensation and cooling process behind shock surface. If the tangential flowing velocity creates a discontinuity across the normal moving shock due to non-linear wave properties, the complex plasma density behind shock surface can be obtained from mass conservation law for non-continuous tangential flowing velocity is verified from Eq.(3.55) by spitting the mass flux in to tangential and normal components relative to direction of shock wave motion is given by Eq.(3.75).

$$\rho_2 = \frac{\rho_1 V}{(V \pm (u_{1n} - u_{2n}))} \left[1 + \left(\frac{u_{1t} - u_{2t}}{V \pm (u_{1n} - u_{2n})} \right)^2 \right]^{-1/2} \quad (3.75)$$

However, in this work we assumed that tangential velocity of flowing plasma element is continuous across the normal moving shock surface and the second term on right hand side under the square root of Eq.(3.75) in bracket is vanished and yields Eq.(2.81). The magnetized plasma behind shock wave and before shock wave is considered as in adiabatic condition. The dynamic pressure before shock wave and behind shock wave is defined by $P_1 = c_1^2 \rho_1 / \gamma$ and $P_2 = c_2^2 \rho_2 / \gamma$ respectively in adiabatic condition. From energy flux of Eq.(3.57) and momentum flux of Eq.(3.56) we have obtained Eqs.(3.76) and (3.77) which describe the corresponding sound speed behind shock surface respectively.

$$c_2^2 = c_1^2 + \frac{\gamma-1}{\rho_1} \left[\frac{B_{1t}^2}{2\mu_0} - \frac{B_{2t}^2}{2\mu_0} + \frac{B_{2n}^2}{2\mu_0} - \frac{B_{1n}^2}{2\mu_0} + \frac{1}{\mu_0} B_{2n} B_{2t} - \frac{1}{\mu_0} B_{1n} B_{1t} \right] - \frac{(\gamma-1)}{2} (u_{1n} - u_{2n})^2 \pm \frac{1-\gamma}{\rho_1 V} \left[\rho_1 V^2 + \frac{B_{2t}^2}{2\mu_0} - \frac{B_{2n}^2}{2\mu_0} - \frac{B_{2n}}{\mu_0} B_{2t} \right] (u_{1n} - u_{2n}) \quad (3.76)$$

$$c_2^2 = c_1^2 + \frac{\gamma}{\rho_1} \left(\frac{B_{2t}^2}{2\mu_0} - \frac{B_{1t}^2}{2\mu_0} \right) \pm \left[\frac{c_1^2}{V} - \gamma V + \frac{\gamma}{\rho_1 V} \left(\frac{B_{2t}^2}{2\mu_0} - \frac{B_{1t}^2}{2\mu_0} \right) \right] (u_{1n} - u_{2n}) - \gamma (u_{1n} - u_{2n})^2 \quad (3.77)$$

Equating Eqs.(3.76) and (3.77) for sound speed behind shock passage in adiabatic condition, we found quadratic equation of Eq.(3.78) in terms of change in radial flow velocity of magnetized plasma before shock and behind shock passage.

$$\left[\frac{B_{2t}^2}{2\mu_0 \rho_1} - \frac{B_{1t}^2}{2\mu_0 \rho_1} + \frac{B_{2n}^2}{2\mu_0 \rho_1} - \frac{B_{1n}^2}{2\mu_0 \rho_1} - \frac{B_{2n} B_{2t}}{\mu_0 \rho_1} + \frac{B_{1n} B_{1t}}{\mu_0 \rho_1} \right] + \frac{\gamma}{\rho_1} \left[\frac{B_{1t}^2}{\mu_0} - \frac{B_{2t}^2}{\mu_0} + \frac{B_{2n} B_{2t}}{\mu_0} - \frac{B_{1n} B_{1t}}{\mu_0} \right] \pm \left[V - \frac{c_1^2}{V} + \frac{\gamma}{\rho_1 V} \left(\frac{B_{1n}^2}{2\mu_0} + \frac{B_{1t}^2}{2\mu_0} - \frac{B_{2t}^2}{\mu_0} + \frac{B_{2n}}{\mu_0} B_{2t} \right) + \frac{1}{\rho_1 V} \left(\frac{B_{2t}^2}{2\mu_0} - \frac{B_{2n}^2}{2\mu_0} - \frac{B_{2n}}{\mu_0} B_{2t} \right) \right] (u_{1n} - u_{2n}) + \frac{(\gamma+1)}{2} (u_{1n} - u_{2n})^2 = 0 \quad (3.78)$$

So as to evaluate the solutions of Eq.(3.78), let us specify the functions of $G(V, B)$ and $F(V, B)$ are independent of variable u_{1n} and u_{2n} but functions F and G are shock velocity and magnetic field dependent. Thus, solution of Eq.(3.78) is given by Eq.(3.79) in terms of F and G .

$$u_{1n} - u_{2n} = \pm \frac{V}{(\gamma+1)} (F + G) \quad (3.79)$$

$$\text{Where, } F = - \left[1 - \frac{c_1^2}{V^2} + \frac{\gamma}{\rho_1 V^2} \left(\frac{B_{1t}^2}{2\mu_0} - \frac{B_{2t}^2}{\mu_0} + \frac{B_{2n}B_{2t}}{\mu_0} \right) + \frac{1}{\rho_1 V^2} \left(\frac{B_{2t}^2}{2\mu_0} - \frac{B_{2n}^2}{2\mu_0} - \frac{B_{2n}B_{2t}}{\mu_0} \right) \right]$$

$$G = \left[\left[1 - \frac{c_1^2}{V^2} + \frac{\gamma}{\rho_1 V^2} \left(\frac{B_{1n}^2}{2\mu_0} + \frac{B_{1t}^2}{2\mu_0} - \frac{B_{2t}^2}{\mu_0} + \frac{B_{2n}B_{2t}}{\mu_0} \right) + \frac{1}{\rho_1 V^2} \left(\frac{B_{2t}^2}{2\mu_0} - \frac{B_{2n}^2}{2\mu_0} - \frac{B_{2n}B_{2t}}{\mu_0} \right) \right]^2 - \frac{2(\gamma^2+1)}{\rho_1 V^2} \left[\frac{B_{2t}^2}{2\mu_0} + \frac{B_{1n}B_{1t}}{\mu_0 \rho_1} - \frac{B_{1t}^2}{\mu_0} - \frac{B_{2n}B_{2t}}{\mu_0} \right] + \frac{2(\gamma^2+1)}{\rho_1 V^2} \left(\frac{B_{1n}^2}{2\mu_0} - \frac{B_{2n}^2}{2\mu_0} \right) \right]^{1/2}$$

The density ratio across normal moving shock wave is obtained using Eqs.(3.55) and (3.79) as normal shock wave propagates through high conductivity plasma and given by Eq.(3.80a).

$$\frac{\rho_2}{\rho_1} = \left[1 + \frac{(F+G)}{(\gamma+1)} \right]^{-1} \quad (3.80a)$$

When magnitude of the function $(F + G)/(\gamma + 1) \ll 1$, is small the mass density ratio across moving normal shock wave is described by Eq.(3.81b) for weak magnetized plasma.

$$\frac{\rho_2}{\rho_1} = 1 - \frac{F+G}{\gamma+1} \quad (3.81b)$$

While $(F + G)/(\gamma + 1) \gg 1$, density ratio across shock wave is described by Eq. (3.81c),

$$\frac{\rho_2}{\rho_1} = \frac{\gamma+1}{F+G} \quad (3.81c)$$

Using Eqs.(3.62) and (3.79) we verify the dynamic plasma pressure across moving normal shock in case of $\rho_2/\rho_1 = 1 - (F + G)/(\gamma + 1)$ is found as Eq.(3.82a).

$$\frac{P_2}{P_1} = 1 - \frac{\gamma}{(\gamma+1)} M_s^2 (F + G) + \frac{1}{2} \gamma M_{A1}^2 \left(\left[1 - \frac{F+G}{\gamma+1} \right] \frac{v_{A2}^2}{v_{A1}^2} - 1 \right) \quad (3.82a)$$

Where, $V^2/c_1^2 = M_s^2$ the shock Mach number $|(F + G)/(\gamma + 1)| \ll 1$ we get that

$$\frac{P_2}{P_1} = 1 - \frac{\gamma}{2} M_{A1}^2 - \frac{\gamma}{(\gamma+1)} M_s^2 (F + G) + \frac{\gamma}{2} \frac{v_{A2}^2}{c_1^2} \quad (3.82b)$$

For $\rho_2/\rho_1 = (\gamma + 1)/(F + G)$ we get that

$$\frac{P_2}{P_1} = 1 - \frac{\gamma}{2} M_{A1}^2 - \frac{\gamma}{(\gamma+1)} M_s^2 (F + G) + \frac{\gamma(\gamma+1)}{F+G} \frac{v_{A2}^2}{2c_1^2} \quad (3.82c)$$

The parameter $M_{A1}^2 = v_{A1}^2/c_1^2$ is Alfven much number before shock wave propagation through high conductivity magnetized plasma. For non-magnetized plasma through which normal shock wave is propagating, the change in velocity flow behind and before shock surface approximated from Eq.(3.79) results Eq.(3.83) that relates the change in normal velocity of flowing plasma behind shock wave and before shock wave in terms of velocity of moving shock wave fronts.

$$u_{2n} - u_{1n} = \pm \frac{2V}{(\gamma+1)} \left[1 - \frac{1}{M_s^2} \right] \quad (3.83)$$

For strong shock wave (i.e., imploding shock surface), the Eq.(3.83) is approximated by Eq.(3.84a) for very large value of shock Mach number, equivalent to Eq.(2.134) for vanishing u_{1n} in case of spontaneous explosion.

$$u_{2n} - u_{1n} = \pm \frac{2V}{(\gamma+1)} \quad (3.84a)$$

For weak shock wave (i.e., exploding shock surface) Eq.(3.83) is approximated to Eq.(3.84b).

$$u_{1n} - u_{2n} \approx \pm \frac{2}{(\gamma+1)} \frac{V}{M_s^2} \quad (3.84b)$$

From Eqs.(3.83), (3.84a) and (3.84b) we suggest that the change in normal velocity of flowing plasma across the normal moving shock wave is determined by velocity of normal shock wave in un-magnetized plasma.

3.14. Summary

From observational evidences, magnetic field on stellar (solar) atmosphere is in-homogeneously distributed. Charged particles are fast flowing through staller magnetic flux tube. The stellar active region is characterized by strong magnetic field region where charged particles are under the control of magnetic field. The most impulsive or explosive events are observed from solar active region. As we have seen in

chapter 2, non-radial surface induced magnetic field is created on stellar surface even for magnetized star. The surface induced magnetic field interacts with pre-existed force free magnetic field and surface charged particles. This makes the stellar atmosphere to have a sophisticated dynamic nature and the surface particle distribution is no more Maxwellian. The presence of complex magnetic field on the solar atmosphere makes the solar explosive events are more intense. Highly energetic flares and huge CMEs are frequently observed from solar active region and highly populated during solar maximum activity.

The enhancement of magnetic field in to SWIF-1SQR model leads us to develop the second phase SWIF-2SAR model. When we have developed the SWIF-2SAR model, pre-existed magnetic field has been considered with the collapsing or growing PVR. The PVR is formed due to local plasma turbulence coupled with instantaneous local charge separation process as magnetic field lines are twisted and deformed through high conductivity gaseous medium. The fast propagating shock surface converts the magnetic energy in to radiation, heat and kinetic energy. Based on the theorization of SWIF-2SAR model, The VSP is intensified by the enhancement of magnetic energy. Basically, the SWIF-2SAR model is well effective with the integration of fast magnetic reconnection (FMR) theory before complete collapse of PVR. At solar active region, applying the SWIF-2SAR model, as shock induced magnetic field is highly stronger than the pre-existed force free magnetic field, CMEs is released behind of flares from solar corona. The oscillation frequency of magnetic field coupled with CMEs accelerates electrons and ions non-thermally and emits electromagnetic radiation. Thus, the receding CMEs penetrates the solar force free magnetic field envelop. The fast propagating shock wave through high conductivity plasma fluid is the crucial mechanism for stellar (solar) flare formation.

All kinds of electromagnetic spectrum are released from small local region of stellar (solar) atmosphere. The SWIF-2SAR model well explains how to form the electromagnetic burst at small local region spontaneously. The formation of electromagnetic wave from local region is specified by magnetized plasma pressure compression ratio, density compression ratio across shock wave fronts and magnitude of shock velocity. The fast propagating shock wave fronts through high conductivity plasma leaves a blast wave that blow out the plasma materials, explosion is created. Using the magnetic field measurement with the help of SWIF-2SAR model, we can predict the energy released during solar flaring time, the amount of ejected mass from solar surface, the intensity of electromagnetic burst on solar atmosphere in successful way. The SWIF-2SAR model like physical model is applied on the Earth laboratory, tokamak, stellator so as to simulate effective nuclear reaction, tested by Russian scientist and they invent magnetic bomb in 1950s.

CHAPTER 4

4. FAST MAGNETIC RECONNECTION ASSOCIATED WITH SWIF MODEL

The fast magnetic reconnection (FMR) theory is a central field on SWIF-2SAR model development. The force free stellar magnetic field interacts with the shock wave triggered complex magnetic field during evolution of stellar flaring process. Annihilation and formation of complex magnetic field associated with the non-linear behavior of particle and field interaction brings weak and strong stellar (solar) explosive events within fraction of seconds. The SWIF model which includes its first phase SWIF-1SQR and second phase of SWIF-2SAR supports by the observational flare data.

4.1. Current Carrying Magnetic Flux Tubes on Stellar Atmosphere

When magnetic field exerts a pressure on high conductivity plasma fluids, the charged particles may gain enough energy from the magnetic field due to wave and particle interaction principle. Charged particles are trapped by surface magnetic field lines if the magnetic field is strong enough. Since charged particles have been trapped by magnetic field, they are accelerated due to steep magnetic field gradients across magnetic field lines or along magnetic field lines. As free charged particles have been trapped by magnetic surface from surrounding, the trapped particle may be accelerated non-thermally on the surface wall of magnetic flux tubes. Charged particles are accelerated at magnetic surface of stellar (solar) magnetic flux tubes. The expected acceleration of charged particles at stellar magnetic flux surface may be acceleration due electron runaway or ion runaway condition, shock wave induced acceleration, Fermi acceleration and other kinds of non-thermal acceleration.

The hot magnetic flux tube is characterized by intense electron current. The intense electron currents has parallel (longitudinal) and perpendicular (traverse) components. The electron current of magnetic flux tube induces complex micro magnetic field. The induced micro magnetic field interacts with the originally potential magnetic field. Consequently, the magnetic field of stellar atmosphere is complex and assumed as force free oscillating magnetic field. The oscillation of magnetic field lines coupled with charged particles leads to formation of Alfven

waves [256]. When the magnetic pressure of flux tube is balanced by the plasma dynamic pressure, particle acceleration at magnetic surface or magnetic flux region is determined by steep gradient magnetic field and gradient of plasma density in isothermal condition. However, when magnetic pressure is higher than plasma dynamic pressure, trapped charged particles are freezing while some of them are diffusing across magnetic field line. As gradient of magnetic field is so steep and the magnetic field is strong enough, more charged particles drift towards region where strong magnetic field lines (i.e., center of magnetic flux tube) and plasma density gradient is developed soon. The dense plasma starts diffusing across inhomogeneous magnetic field lines. The diffusing plasma could not pass the boundary surface of magnetic flux tubes unless the charged particles are accelerated. Only accelerated charged particles are passing the magnetic surface.

Now, let us assume that the plasma density exterior of magnetic flux tube is much lower than interior. When the magnetic flux sucks the surrounding charged particles and it is filled, the oscillation of plasma inside magnetic flux creates a shock wave at its magnetic surface. Let us consider that the magnetic flux tube interacts with non-magnetized surrounding plasma at magnetic boundary surface. The property of un-magnetized plasma is altered at the boundary of magnetic surface. So, the magnetic surface separates the magnetized plasma region from its surrounding of un-magnetized plasma region. The un-magnetized plasma of solar atmosphere is most probably characterized by thermal radiation if and only if charged particles are in thermal equilibrium or electrons and ions are Maxwellian.

However, the magnetized plasma region (i.e., inside magnetic flux tube) is characterized both by thermal radiation as well as non-thermal radiation process, see Eqs.(4.1) and(4.59), at magnetic surface. At solar atmosphere, magnetic field accelerates charged particles due to appearance of Lorentz force through neutral background plasma. The non-thermal acceleration through magnetized neutral plasma is cyclotron acceleration in case of non-relativistic sense or synchrotron acceleration in relativistic case is given by Eq.(4.1) that describes *Synchrotron Radiation*.

$$\frac{d}{d\tau}(\gamma_v m \vec{v}) = \frac{q}{c}(\vec{v} \times \vec{B}) \quad (4.1)$$

Where $\gamma_v = (1 - v^2/c^2)^{-1/2}$ the Lorentz factor and, m , is mass of particle with charge, q and t time coordinate. The trajectory of the particle is helical with a gyration frequency $\omega_B = q\vec{B}/\gamma_v mc$ and the pitch angle $\theta = 90^\circ$ for circular gyration motion and $\theta = 0^\circ$ for parallel motion of particles to magnetic field lines. The radiated power from the accelerating charge is given (in *cgs* units) by Eq.(4.2) below for electron in particular.

$$\begin{aligned} -\frac{dE}{dt} &= \frac{2}{3} \frac{q^4}{m^2 c^5} (\gamma v)^2 (B \sin \theta)^2 \\ &= 2.37 \times 10^{-15} \left(\frac{E}{\text{erg}} \right)^2 \left(\frac{B \sin \theta}{\mu G} \right)^2 \end{aligned} \quad (4.2)$$

The final equality is given for electrons in particular, since the dependence on the mass-to-charge ratio means that electrons are by several orders of magnitude dominant over protons or ions in generating synchrotron radiation. The synchrotron power peaks at the characteristic frequency (in Hz) is described by Eq.(4.3).

$$\begin{aligned} \nu_c &= \frac{3}{4\pi} \frac{q}{mc} \gamma_v^2 \\ &= 6.26 \times 10^3 \left(\frac{E}{\text{erg}} \right)^2 \left(\frac{B \sin \theta}{\mu G} \right) \end{aligned} \quad (4.3)$$

The Eq.(4.3) tells us that for radio observations (frequencies at or above tens of *MHz*) and with typical magnetic field strengths of order μG , the observed population of electrons have $\gamma \gg 1$. The population of electrons has a power-law energy distribution given by Eq.(4.4).

$$n_e(\gamma) d\gamma = n_0 \gamma^{-p} d\gamma \quad (4.4)$$

Where a typical value for the power law index is $p = 2.5$ and the resulting synchrotron luminosity is thus also a power law, described by Eq. (4.5) is applicable at stellar atmosphere.

$$L_\nu \propto \nu^{-(p-1)/2} \equiv \nu^{-\alpha} \quad (4.5)$$

With a typical spectral index $\alpha = 0.75$ for $p = 2.5$, the particles lose energy due to the power emitted in Eq.(4.1), with a characteristic timescale of τ is given by Eq.(4.47) that is obtained from induction equation of magnetized plasma during evolution of magnetic field and electric

field for negligible diffusion. Gyration electrons move faster than gyrating ions inside strong magnetic field region.

Generally, electrons and ions drift across the magnetic field lines due to high gradients of magnetic field, steep gradients of electrostatic potential and plasma density gradient. The plasma may be high collision magnetized plasma or collision-less magnetized plasma, it depends on the region of solar atmosphere. At low density and collision-less highly magnetized plasma region, orbit theory contributes a significant effect on *cyclotron radiation*, *synchrotron radiation*, *shock wave radiation* and other *non-thermal radiation* process. However, in high collision dense and strongly magnetized plasma region, orbiting of charged particles around magnetic field lines suffer several deflecting and scattering problems. Energy is dissipated due to high collisional process, viscosity effect and electrical resistivity. These kinds of process may be effective interior of star and at photosphere.

However, in stellar atmosphere, plasma is expected as highly in-homogeneous magnetized and collision-less. From ground based and space born observations, stellar magnetic flux tube migrates from place to other place at solar atmosphere and is emerged from stellar deep region of photosphere [257, 258]. The intensity of magnetic pressure is higher in specified direction towards low plasma dynamic pressure region. We assumed that background radiation pressure depends on plasma temperature gradients and magnetic field gradient. However, foot points of strong magnetic fluxes migrate at deep photosphere through the stratified photosphere plasma [259]. The mechanism for migrating of foot points of magnetic flux tube is not clear. When charged particles are injected in to magnetic flux tube the amount of plasma inside magnetic flux tube is increased by the injected amount of plasma. The plasma inside the magnetic flux tube is perturbed due to additional injected plasma and the thermal and non-thermal acceleration process.

At equilibrium condition plasma's charged particle gyrate around the guiding center of magnetic field line and also moves along the guiding center for homogeneous and uniform magnetic fields with velocity equals to or greater than the thermal velocity of charged particles along the magnetic field. However, electrons and ions are oscillated around the guiding center of magnetic field line due to inhomogeneity of magnetic field lines, plasma gradients, induced electric fields and injection of electrons and ions from outside of diffusing plasma. The

perturbing gyro-radius of charged particles leads to drifting of charged particles across the guiding center. The electric current produced on magnetic flux tubes is greater than thermal electron current. When the induced current is higher than the thermal current, it is associated with fast moving shock wave fronts.

When plasma fluids flow fast along magnetic field lines, the dominant electric current is longitudinal current. This intense parallel electric current induces an azimuthal micro magnetic field on its surface in cylindrical coordinate. Radius of the stellar (solar) magnetic flux tube is smaller at its foot points because the azimuthal micro magnetic flux around the current carrying magnetic flux squeezes the original magnetic flux tubes. The surrounding dynamic plasma also squeezes the magnetic flux at photosphere. When the electron current along magnetic flux tube is so strong, the induced azimuthal magnetic flux prevents incoming electrons and ions from outside which were injected in to magnetic flux tubes. No more plasma particles penetrate the surface of magnetic flux in this case. Then the induced azimuthal magnetic field is so strong, electrons and ions may be trapped by azimuthal magnetic field lines and other secondary azimuthal electron current is created.

We can classify the magnetic flux of this system as poloidal and toroidal magnetic field flux. At static equilibrium situation, the azimuthal induced (toroidal) magnetic field is vanished. Flowing of plasma inside magnetic flux tubes is highly influenced by motion of source plasma at deep stellar (solar) atmosphere. The magnetic surface of current carrying flux tube is a good site for shock wave formation due to overloading of the same families of waves. The nonlinear effect creates shock surface on magnetic surface. When electron and ion move along magnetic field lines in helical path, micro electric current is produced. This micro electric current is also induces micro magnetic field. Due to introduction of micro magnetic field over the original magnetic field, the resultant field becomes non-potential magnetic field because some where part of magnetic field is annihilated and also at other somewhere part of magnetic field is increased instantly. Due to such kinds of process, the magnetic field line oscillates in helical fashion.

A non-linear wave is created due to interaction of magnetic field and charged particles. This is known as *Alfven wave*. This kind of wave is a traverse wave which propagates along magnetic field lines. Alfven wave is a low frequency wave at slowly perturbed magnetized plasma due to smallness of induced micro magnetic field over strong magnetic field. On surface

of strong current carrying magnetic flux, overloading of Alfvén phase velocity is expected due to poloidal and toroidal Alfvén's phase velocity associated with instantaneous plasma charge separation leads to formation of plasma surface current layer on magnetic surface. A discontinuity in physical quantities at magnetic surface leads to existence of shock wave surfaces see in chapter 2 and 3.

Let us consider magnetic flux tube is filled with dense fast flowing hydrogen plasma. Plasma density inside magnetic flux tube is higher than the surrounding un-magnetized plasma. The total plasma pressure inside magnetic flux tube is balanced by external plasma pressure and azimuthal magnetic pressure. When the fast flowing plasma inside magnetic flux tube is suddenly stopped, part of magnetic flux behind intense current is suddenly deformed at small region. The deformed part of magnetic flux creates strong disturbance and intense pulse. The intense pulse makes electrons and ions to change their velocity instantly. A strong shock wave is developed inside the magnetic flux tubes. The current carrying magnetic flux is highly unstable and suddenly bursts. Generally, current carrying magnetic flux tube is exploded suddenly or it may be characterized by emitting radiation.

4.2. Dynamics Stellar of Magnetic Flux Tubes

The solar dipole field is a tremendous complicated, very inhomogeneous, intermittent, and highly dynamic nature of field. However, the overall average solar surface magnetic field intensity is approximated about 1G. A group of polar magnetic fields being quite irregular and variable at short timescales shows remarkably regular pattern at large timescales. The solar magnetic flux of a dipole periodically weakens and subsequently undergoes a reversal of polarity in period of 11 years is directly related to periodic change in sunspot numbers observed [27, 260, 261]. Based on observational evidences, the reversal of a dipole polarity marks the abrupt changes in the configuration of star-spot (sunspots) and active regions over the entire solar surface. New sunspot groups being appeared at high latitude of both solar hemispheres. Those star-spots (sunspots) migrate towards solar equator; with sunspot velocity is larger at beginning and slower later [262]. Solar scientists believed that Sunspots are huge conglomerates of magnetic flux concentrations seen as dark spots characterized with their extremely complex nature. Their temperature is about a thousand degrees lower than the average surface temperature [263, 264]. Sunspot formation and their appearance at a visible surface is a gradual process that

may take hours and days. The mechanism for formation of sunspot is the emergence of extremely strong bundles of magnetic flux tubes from solar interior. The group of magnetic fluxes emerged from local solar surface region penetrates solar surface plasma.

However, there is no evidence and theory that supports formation of discrete bundle of magnetic flux tubes at small local region interior the star. Based on kinetic theory of magnetized plasma, magnetic field lines could not diffuse and stored in small local region interior of the star. To know the source of intense local magnetic field, a deep further research is needed. Whatever the source of magnetic flux tubes interior of the star, we are concentrating here, on the dynamic and phenomena appeared on stellar atmospheric plasma coupled with complex force free magnetic field. The stellar (solar) magnetic flux tubes are in-homogeneously distributed on its atmosphere. The foot points of magnetic flux tubes are anchored at solar photosphere. There are two kinds of solar magnetic flux tubes. There are closed magnetic flux tubes and opened magnetic flux tubes. The size of magnetic flux tubes varying from small scale to large scale that extends to interplanetary space. The magnetic flux tubes are hot flux tubes, warm magnetic flux tubes and cold magnetic flux tubes [265].

Evidences from SOHO, YOHKOH, LASCO, and SDO...etc, indicates that hot plasma flows through magnetic flux tubes. When new magnetic flux tube has been emerged via solar photosphere, it may grow up to large scale of interplanetary space. Open and closed magnetic flux tube exerts a magnetic pressure on surrounding plasma as they grow. Deformation of magnetic flux tubes at solar photosphere is inevitable if the flowing plasma's dynamic pressure is higher than that of flux tube magnetic pressure.

4.3. Deforming and Twisting Magnetic Flux Tubes at Stellar Atmosphere

Most probably, solar magnetic flux tubes may be deformed at the lower region of atmosphere, photosphere, because of horizontal and vertical external flowing of ionized plasma, magnetic flux collision followed by fast reconnection process. When the plasma flowing on stellar (solar) it exerts strong enough dynamic pressure, as it pushes the wall of magnetic flux tube the weaker magnetic flux tube may be deformed while flowing plasma bounce back at wall of strong magnetic flux tube. In this case the dynamic plasma pressure is characterized by electrons and ions pressure.

However, motion of neutral particles is not influenced in presence of magnetic field. As the oscillating and convective local stellar (solar) surface plasma is highly ionized in the presence of strong magnetic field, this local region is specified by particle magnetic field interaction. Some plasma particles are trapped by magnetic flux surface, and others may be reflected back. Thus, the flowing completely ionized plasma may sweep out the weak magnetic flux. At the interface boundary surface between magnetic flux surface and colliding plasma element, a shock wave is generated due to effects of non-linear waves. If the external flowing plasma element has high enough density, collisional effect plays a vital role at the interface boundary surface. Most probably this kind of process may be happened at foot points of magnetic flux tubes, at photosphere region. Even the magnetic flux tube would be non-deformable; plasma magnetic flux tube interaction is obvious. Here, due to magnetic flux and dense plasma interaction principle, most of the time, the foot points of magnetic flux tube are hotter than their upper part [266, 267].

4.4. Plasma Flow through Magnetic Flux Tubes

As magnetic flux tube has been emerged from solar surface, it is filled by electrons and ions from the background medium. The growing magnetic flux tube sucks electrons and ions of surrounding medium. The injecting amounts of electrons and ions in to magnetic flux tube are determined by strength of radial gradients of magnetic field flux tube. When external surrounding plasma pressure is balanced by radial magnetic pressure at dynamic boundary surface, the magnetic flux tube may continue its life. However, due to continuous production of its intensity from its source, the magnetic flux tube grows toward the lower density space.

Let us consider a closed magnetic flux tube has an arcade shape situated at stellar (solar) atmosphere in magneto-hydrostatic situation. The static magnetic flux tube is assumed in cylindrical coordinate. Completely ionized plasma elements are pumped from stellar (solar) interior, most probably from lower region of photosphere. The pumping plasma flows through magnetic flux tubes and provides parallel electric current and perpendicular electron current, see *section 4.1*.

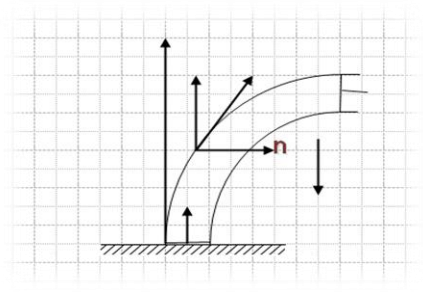


Fig.4.1a Static magnetic flux tube

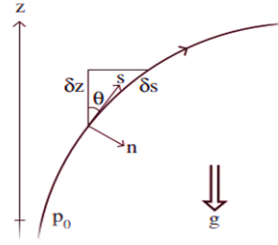


Fig.4.1b Static magnetic field line

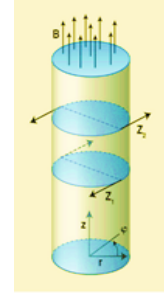


Fig.4.1c Magnetic flux

In magneto-hydrostatic situation, the inertial force is neglected when the plasma flowing velocity inside magnetic flux tube is much smaller than plasma sound speed, $(\gamma p/\rho)^{1/2}$, Alfven velocity, $B_0/(\mu_0 \rho)^{1/2}$ and gravitational free fall speed $(2gh)^{1/2}$ for the characteristic height of flux tube of incompressible ionized plasma fluid. To understand the nature of static magnetic flux tube, evaluating the magnetic plasma beta, $\beta = 8\pi p/B^2$ is mandatory. Let us assume here, the magnetic plasma beta, β inside magnetic flux tube is constant, the ratio of plasma static pressure to static magnetic pressure remains constant inside magnetic flux tube. The pressure distribution and corresponding temperature distribution inside static magnetic flux tube are specified by Eqs.(4.6) and (4.7) respectively that are obtained from equation of motion in steady state condition or at equilibrium condition.

$$p = p_0 \exp \left\{ - \left[\frac{1}{\beta} + \frac{z}{H} \right] / \left[1 + \frac{1}{\beta} \right] \right\} \quad (4.6)$$

$$T = \left(\frac{n_0}{n} \right) \exp \left\{ - \left[\frac{1}{\beta} + \frac{z}{H} \right] / \left[1 + \frac{1}{\beta} \right] \right\} \quad (4.7)$$

Where $H = k_B T/mg$ scales height, independent of position inside static magnetic flux tube. If the constant parameter $\beta \ll 1$, the static magnetic flux tube is characterized by non-thermal electron and ion acceleration. If plasma density inside static magnetic flux tube is much lower than outside, the magnetic flux tube may collapse suddenly for $\beta \ll 1$ condition is sufficed. When if $\beta \gg 1$ and plasma density interior of magnetic flux tube is much higher than surrounding, the static magnetic flux tube may burst suddenly due to entrance of un-stability. If stellar (solar) magnetic field suffices $\vec{j} \times \vec{B} = 0$ condition, the magnetic field is force free magnetic field. The force free magnetic field may be current free $\vec{j} = 0$ or potential magnetic field. Magneto-hydrostatics is relevant to a variety of solar structures that appear to remain

motionless or move slowly for long periods of time. It has been applied, for example, to active-region loops or the global structure of the coronal magnetic field, which often appear stationary for times that are long compared with the Alfvén travel time (e.g., Sakurai 1989) [170, 268, 269].

When the electrons and ions dynamic pressure is dominated by magnetic pressure, the magnetic field also is known as force free magnetic field. At the upper region of solar atmosphere (i.e., solar corona), the magnetic field is force free. If plasma dynamic pressure interior of magnetic flux tube is much smaller than magnetic pressure, the magnetic flux tube is force free flux tube. When plasma moves through magnetic flux tube, electron current inside flux tube is generated. If the longitudinal motion of plasma is collision-less, a discontinuity in pulse along magnetic field creates a shock wave. The discontinuity in pulse is created due to unstable nature of collision-less flowing plasma.

4.5. Force Free Magnetic Flux of Stellar Atmosphere

When electrons and ions flow through magnetic flux tube, along magnetic field lines, the induced micro-magnetic field interacts with the original magnetic field lines of flux tube. Magnetic field lines may be braided, deformed and twisted inside magnetic flux tubes due to original magnetic field line and induced magnetic field line interaction inside magnetic flux tubes. Longitudinal and transverse Alfvén waves are created due to current produced by charged particles during interaction process at magnetic flux tube. The curling of magnetic field lines inside flux tube is specified by $\vec{\nabla} \times \vec{B} = \alpha \vec{B}$ inside ionized plasma. Where, $\alpha = \alpha(r, \varphi, z, t)$ a scalar functions of dimensionless parameter which determines the nature of parallel current inside solar magnetic flux tube at solar atmosphere. To minimize complexity, let us choose α is constant of space and time, the local isolated magnetic flux tube of solar atmosphere is in steady state condition or in static equilibrium.

Generally, the force free magnetic field can be expressed in terms of radial unknown function of axial component, B_φ and B_z of force free magnetic field given by Eq.(4.13) in terms of un known function of radial position in steady state. Verifying equations of $\vec{\nabla} \times \vec{B} = \alpha \vec{B}$ for force free magnetic flux tubes, we obtain the *radial*, *azimuthal* and *axial* components of curl of magnetic field by Eqs.(4.8), (4.9) and (4.10) respectively.

$$\frac{1}{r} \frac{\partial B_z}{\partial \varphi} - \frac{\partial B_\varphi}{\partial z} = \alpha B_r \quad (4.8)$$

$$\frac{\partial B_r}{\partial z} - \frac{\partial B_z}{\partial r} = \alpha B_\varphi \quad (4.9)$$

$$\frac{1}{r} \left(\frac{\partial}{\partial r} (r B_\varphi) - \frac{\partial B_r}{\partial \varphi} \right) = \alpha B_z \quad (4.10)$$

Differentiating Eq.(4.9) with respects of φ and also differentiating Eq.(4.10) with z and manipulating them results the following Eq.(4.11) that is described below.

$$\frac{1}{r} \frac{\partial}{\partial z} \left(\frac{\partial}{\partial r} (r B_\varphi) \right) - \frac{1}{r} \frac{\partial}{\partial \varphi} \left(\frac{\partial B_z}{\partial r} \right) - \frac{\alpha}{r} \frac{\partial B_\varphi}{\partial \varphi} - \alpha \frac{\partial B_z}{\partial z} = 0 \quad (4.11)$$

By differentiating Eq.(4.8) with respects to z and multiplying with Eq.(4.9) and followed by eliminating B_r from the equating equations yield the following Eq.(4.12).

$$\frac{\partial}{\partial z} \left(\frac{1}{r} \frac{\partial B_z}{\partial \varphi} \right) - \frac{\partial^2 B_\varphi}{\partial z^2} - \alpha \frac{\partial B_z}{\partial r} - \alpha^2 B_\varphi = 0 \quad (4.12)$$

In order to solve Eqs.(4.11) and (4.12), we assume that B_φ and B_z can be separated in to radial (r) function and non-radial function of (φ, z) coordinates denoted by Eq. (4.13) for positive value of n and m in harmonic mode.

$$B_\varphi = f_{nm}(r) e^{\pm i[nz - m\varphi]} \quad (4.13a)$$

$$B_z = g_{nm}(r) e^{\pm i[nz - m\varphi]} \quad (4.13b)$$

Substituting Eq.(4.13) in to Eq.(4.12) the radial unknown function of azimuthal magnetic field is obtained as,

$$f_{nm}(r) = - \frac{mn}{(n^2 - \alpha^2)} \frac{g_{nm}}{r} + \frac{\alpha}{(n^2 - \alpha^2)} \frac{\partial g_{nm}}{\partial r} \quad (4.14)$$

Using the same procedure, substituting Eq.(4.13) in to Eq.(4.11) we get Eq.(4.15),

$$\frac{\partial f_{nm}}{\partial r} + \frac{1}{r} \left[1 + \frac{\alpha m}{n} \right] f_{nm} + \frac{m}{n} \frac{1}{r} \frac{\partial g_{nm}}{\partial r} - \alpha g_{nm} = 0 \quad (4.15)$$

So as to solve the radial unknown function g_{nm} , by substituting Eq.(4.14) in to Eq.(4.15) we get modified Bessel differential equation of Eq. (4.16).

$$\frac{\partial^2 g_{nm}}{\partial r^2} + \frac{1}{r} \frac{\partial g_{nm}}{\partial r} + \left[k^2 - \frac{m^2}{r^2} \right] g_{nm} = 0 \quad (4.16)$$

The constant parameter, $n^2 - \alpha^2 = k^2$, is modified Bessel differential equation which has solution given by Eq.(4.17) that is described below.

$$g_{nm}(r) = A_{mn}J_m(rk) + B_{mn}Y_m(rk) \quad (4.17)$$

Substituting Eqs.(4.14) and (4.17) in to Eq.(4.8) and using Eq. (4.13) we have verified the radial magnetic field in terms of Bessel functions that is described by Eqs.(4.18), (4.19) and (4.20).

$$B_r = \mp \frac{im}{k^2} \left[\left(\frac{k^2 - n^2}{\alpha r} + \frac{n}{r} \right) A_{mn}J_m(kr) - \frac{nk}{m} A_{mn}J_{(m+1)}(kr) + \left(\frac{k^2 - n^2}{\alpha r} + \frac{n}{r} \right) B_{mn}Y_m(kr) - \frac{nk}{m} B_{mn}Y_{(m+1)}(kr) \right] e^{\pm i[nz - m\varphi]} \quad (4.18)$$

The azimuthal and axial magnetic fields are simply obtained as

$$B_\varphi = \frac{\alpha}{(n^2 - \alpha^2)} \left[\left(\frac{m}{r} - \frac{mn}{\alpha r} \right) A_{mn}J_m(rk) - A_{mn}J_{(m+1)}(kr) + \left(\frac{m}{r} + \frac{mn}{\alpha r} \right) B_{mn}Y_m(rk) - Y_{(m+1)}(kr) \right] e^{\pm i[nz - m\varphi]} \quad (4.19)$$

$$B_z = [A_{mn}J_m(rk) + B_{mn}Y_m(rk)] e^{\pm i[nz - m\varphi]} \quad (4.20)$$

The flowing plasma through magnetic flux tube generates intense current associated with that force free magnetic field. We verified the curl of force free magnetic field $\vec{\nabla} \times \vec{B} = \mu_0 \vec{J}$ that yields Eqs.(4.21), (4.22) and (4.23) of current components.

$$\vec{J}_r = \mp \frac{im\alpha}{\mu_0 k^2} \left[\left(\frac{k^2 - n^2}{\alpha r} + \frac{nk}{kr} \right) A_{mn}J_m(kr) - \frac{nk}{m} A_{mn}J_{(m+1)}(kr) + \left(\frac{k^2 - n^2}{\alpha r} + \frac{nk}{kr} \right) B_{mn}Y_m(kr) - \frac{nk}{m} B_{mn}Y_{(m+1)}(kr) \right] e^{\pm i[nz - m\varphi]} \hat{r} \quad (4.21)$$

$$\vec{J}_\varphi = \left[\left(\frac{m}{r} - \frac{mn}{\alpha r} \right) A_{mn}J_m(rk) - A_{mn}J_{(m+1)}(kr) + \left(\frac{m}{r} + \frac{mn}{\alpha r} \right) B_{mn}Y_m(rk) - Y_{(m+1)}(kr) \right] \frac{\alpha^2}{\mu_0(n^2 - \alpha^2)} e^{\pm i[nz - m\varphi]} \hat{\varphi} \quad (4.22)$$

$$\vec{J}_z = \frac{\alpha}{\mu_0} [A_{mn}J_m(rk) + B_{mn}Y_m(rk)] e^{\pm i[nz - m\varphi]} \hat{z} \quad (4.23)$$

This indicates that the intense electron current has parallel and perpendicular components relative to direction of magnetic field lines. The Eqs.(4.21), (4.22) and (4.23) describes that stellar (solar) magnetic flux tubes carry strong parallel and perpendicular electric current. Early studies indicate that longitudinal currents are excited in the magnetic loops due to the complicated motion of sunspots and the surrounding photosphere plasma motion [27, 270]. Colliding of the current carrying magnetic flux tubes bring stellar/solar flares associated with fast magnetic reconnection (FMR) process at stellar/solar atmosphere. The FMR gives rise to sudden enhancements of the loop emission observed in soft X-rays [271, 272]. The FMR process brings impulsive flare followed by CMEs is observed with all kinds of spectrum as observer is situated above the Earth's atmosphere [273, 274]. The existence of high energy flares with estimated kinetic temperature range from about $10^6 K$ to $10^7 K$ is observed from microwave and x-ray observation [275].

4.6. Perturbation of Solar Magnetic Flux Tubes

Solar magnetic flux tube is a bundle of magnetic field lines which carries completely ionized plasma. Most probably, electrons and hydrogen ions move along solar magnetic flux tubes. If the gradient of magnetic flux tube is strong or additional inertial force is important, electrons and ions may be diffusing across magnetic field lines. Plasma element flows inside closed magnetic flux tubes in three ways. These are,

- i. Plasma flows from one foot point to other foot point
- ii. Plasma flow from both foot points to top of magnetic flux tube
- iii. Plasma flows from top to both foot points

When magnetic field lines of stellar (solar) magnetic flux tube is constant in some local region along its path, a strong surface current creates induced magnetic field around its current surface. This induced micro-magnetic field which propagates outward and squeezes the magnetic flux tubes itself. The induced micro-magnetic field interacts with the magnetic flux tubes and the surface current. The surface of magnetic flux creates a mechanical wave which waves the surface. This mechanical wave is created due to interaction of surface current and magnetic field. Due to this kind of process that surface of magnetic flux tube is characterized by its oscillatory nature. As evidences from observation indicate, the solar magnetic flux tubes are oscillating [276]

- 278]. If the magnetic flux tube carries intense current parallel and perpendicular to magnetic field lines is in steady state, its cross section area remains constant. Most probably, the cross section area of magnetic flux tube is smaller at foot points of magnetic flux tubes. When the current flow through magnetic flux tube is variable, the magnetic flux tube would be unstable. The unstable magnetic flux tube may provide a flare [279, 280]. When the induced micro-magnetic field is strong enough, in determining the plasma motion, the particle orbit theory is no longer applicable on magnetic surface of current carrying magnetic flux tubes for $\beta \gg 1$ situation. If the parallel velocity of charged particles is higher than its Larmor velocity, the longitudinal electric current is unstable inside flux tube as well as on its surface. A boundary layer is created at a radius R of cylindrical magnetic flux tube. The magnetic field lines of flux tube and electrons and ions which are injected from outside interacts at dynamic boundary of magnetic surface.

However, the micro-magnetic field which is produced by surface current due to scalar magnetic potential inside force free magnetic flux tube. The surface of magnetic flux tube is characterized by its oscillating nature. The oscillating magnetic surface generates a fast moving shock wave fronts. The propagating micro magnetic field lines are reflected back, due to surrounding plasma if the surrounding dynamic pressure is strong enough. The micro-magnetic field fluxes are accumulated between the current carrying magnetic flux tube and the surrounding plasma fluid. Longitudinal Alfvén waves and transversal Alfvén waves are interacted at the surface boundary layer. Due to non-linear effect of interacting physical quantities and overloading of the same families of phase waves anomalous plasma resistivity is developed. This surface magnetic boundary layer is the site of shock wave formation on surface of magnetic flux tube. Slow moving electrons and ions do not penetrate the wall of strong magnetic surface, and no field penetrates with frequency less than frequency of constant surface magnetic field and surface electron frequency. Electrons and ions are accelerated at the dynamic boundary layer due to formation of gradient of electrostatic potential, magnetic field (i.e., Fermi acceleration) and electrostatic shock waves.

The shock wave that is created at magnetic boundary propagates in to center line of magnetic flux tube and also to surrounding ambient un-magnetized plasma. The imploding shock wave fronts across magnetic separatrices, most probably reflected back at axial line of flux tubes.

Let we consider cylindrical solar magnetic flux tube is situated at solar atmosphere that extends from the deep photosphere to upper layer of solar corona. Suppose the magnetic fields of the flux tube are constant along vertical $z - axis$ with almost constant of cross section area of radius, R at boundary layer. Let assumed, the magnetic flux tube is an isolated local system surrounded by vacuum associated with surrounding induced micro magnetic field lines due to intense surface current. Magnetic field inside flux tube is assumed to be constant of position and time, axially, which is uniformly distributed on its cross section area, for the sake of simplicity. For strong static current of vertical magnetic flux tube, the effect of gravitational force is negligible below stellar (solar) corona region.

The force free magnetic field of flux tube is assumed to be force free field and also approximated by Eqs.(4.18), (4.19) and (4.20) at stellar (solar) atmosphere in steady state situation. Plasma flows through magnetic flux tube due to small perturbation in physical quantities interior as well as at exterior of flux tube. The small perturbation in physical quantities is associated with small perturbation with force free magnetic field lines of flux tubes and the corresponding current. The ionized plasma flowing through magnetic flux tubes provides intense current inside magnetic flux tube investigated by Eqs.(4.21), (4.22) and (4.23) that interacts with surrounding un-magnetized plasma at dynamic magnetic surface boundary.

Let us assume that physical quantities of static magnetic flux tube are perturbed by small quantity. Dynamic pressure of ionized plasma, density, magnetic field, velocity and electric fields are perturbed about the equilibrium point of magnetic flux tube. Evaluating the first order linearized form of continuity equation and momentum equation, results the Bessel differential equation of Eq.(4.24) in cylindrical coordinate that is described below similar to modified Bessel differential equation of Eq.(4.16) so as to evaluating force free magnetic field of flux tube.

$$\left[\frac{d^2}{dr^2} + \frac{1}{r} \frac{d}{dr} - \left(k^2 + \frac{m^2}{r^2} \right) \right] \xi_z(r) = 0 \quad (4.24)$$

The perturbed displacement of ionized plasma fluid coupled with magnetic field lines is described by $\vec{\xi}(\vec{r}) = [\xi_r(r), \xi_\phi(r), \xi_z(r)] e^{i[m\phi + kz]}$ at local isolated system. Here, the plasma fluid is taken as incompressible plasma fluid. For which solution of Eq.(4.24) has no singularity at $r = 0$ is given by Eq.(4.25).

$$\xi_z(r, \varphi, z) = \xi_z(R) \frac{I_m(kr)}{I_m(kR)} e^{\pm i[m\varphi + kz]} \quad (4.25)$$

The function $I_m(kr)$ denotes Bessel's modified function of first kind is order of m and R is the radius of flux tube at equilibrium of constant cross section. Using the perturbed magnetic field we can evaluate the equation of motion, from Newton's second law. From radial and azimuthal components of momentum equation, using Eq.(4.25) we got the radial and azimuthal perturbing displacement components of physical quantities, as solutions of Eq.(4.24).

$$\xi_r(r, \varphi, z) = \frac{ik^2 B_0^2}{(\rho_0 \mu_0 \omega^2 - k^2 B_0^2)} \frac{\xi_z(R)}{I_m(kR)} \left[\frac{m}{kr} I_m(kr) - I_{m+1}(kr) \right] e^{\pm i[m\varphi + kz]} \quad (4.26)$$

$$\xi_\varphi(r, \varphi, z) = - \frac{ikmB_0^2}{r(\rho_0 \mu_0 \omega^2 - k^2 B_0^2)} \frac{I_m(kr)}{I_m(kR)} \xi_z(R) e^{\pm i[m\varphi + kz]} \quad (4.27)$$

Combining Eqs.(4.25), (4.26) and (4.27), the perturbing particles displacement inside magnetic flux tube is described by Eq.(4.28) shows the instability of plasma elements along magnetic flux tube column.

$$\vec{\xi}(x_i, t) = \xi_z(R) \frac{I_m(kr)}{I_m(kR)} \left[\frac{ik^2 B_0^2}{\rho_0 \mu_0 \omega^2 - k^2 B_0^2} \frac{I'_m(kr)}{I_m(kr)} \hat{r} - \frac{ikmB_0^2}{r(\mu_0 \rho_0 \omega^2 - k^2 B_0^2)} \hat{\varphi} + \hat{z} \right] e^{i[m\varphi + kz + \omega t]} \quad (4.28)$$

Separating the space and time dependence of perturbing displacement given by Eq.(4.28) is expressed as $\vec{\xi}(x_i, t) = \vec{\xi}(x_i)T(t)$ for sinusoidal perturbing motion of physical quantities, $T(t) = e^{i\omega t}$, the equation represents the eigenvalue problem in which the boundary condition determines the possible value of ω^2 in momentum equation. From Eq.(4.28) we understand that the axial perturbing plasma fluid inside magnetic flux tube leads to instability condition of lux tube (i.e., shock wave formation). Thus, the longitudinal current creates a periodic pulse inside as well as on the surface of perturbing magnetic flux tubes. The general solution of oscillatory perturbing displacement corresponds to normal mode is defined by Eq.(4.29).

$$\vec{\xi}(x_i, t) = \sum_n \vec{\xi}_n(x_i) e^{i\omega_n t} \quad (4.29)$$

Since $\vec{\xi}_n(x_i)$ the normal mode that corresponds to normal frequency ω_n that is described in Eq.(4.29), it measures the stability and un-stability of magnetized plasma. For all normal frequency $\omega_n^2 > 0$, then all the modes are periodic. This means that the system oscillates about its equilibrium point monotonously. In other hand the normal frequency $\omega_n^2 < 0$, the

corresponding normal mode will grow exponentially and the equilibrium configuration is unstable, see Eq.(4.29). The property of real eigenvalue is directly related to the conservation of energy in the local system. Here we apply the normal mode analysis to determine the stability of stellar magnetic flux tube that is filled with dense ionized plasma fluid and surrounded by vacuum region.

We assumed that the cross section area of magnetic flux tube remains constant at equilibrium situation. For incompressible plasma fluid interior of flux tube, $\vec{\nabla} \cdot \vec{\xi} = 0$, leads to vanishing change in dynamic pressure, $P_1 = 0$ if and only if P_0 is position independent. From first order linearized form of momentum equation, the small perturbation of force free magnetic field depends on perturbing space coordinate is described by Eq.(4.30) in case of incompressible plasma fluid interior magnetic flux tubes.

$$\vec{B}_1 = ikB_0\vec{\xi} \quad (4.30)$$

The plasma elements are displaced by position vector field $\vec{\xi}(\vec{r}, t)$ associated with magnetic field lines about the equilibrium position of magnetic field. The complex number in Eq.(4.30) indicates that the system is isolated and the perturbation provides particle oscillation about the equilibrium point. The magnetic flux tube is characterized by electromagnetic field oscillation and charged particle oscillation. The interaction of field and particle creates a mechanical wave production, Alfven wave and shock waves.

Here, let us assume that the magnetic flux tube is surrounded by low density region and the electric current density is approximated as $\vec{j} = 0$ at stellar (solar) atmosphere. The instant scalar magnetic potential that provides the perturbing magnetic field is verified from the concept of $\vec{\nabla} \cdot \vec{B}_1 = 0$ and using the idea of oscillation mode, $\Phi = \Phi(r)e^{\pm i[m\varphi + kz]}$, using variable separation method. By solving the Poisons equation of scalar magnetic potential, we get that

$$\Phi(\vec{x}, t) = \Phi(R) \frac{Y_m(kr)}{Y_m(kR)} e^{\pm i[m\varphi + kz + \omega t]} \quad (4.31)$$

The functions, $\Phi(R)$, surface scalar magnetic potential of perturbing magnetic flux tube and $Y_m(kr)$, the modified Bessel function of second kind of order m . The perturbing magnetic field that is propagating through surrounding vacuum is obtained from scalar magnetic potential.

Using the boundary condition we can evaluate the interaction of surface region of magnetized plasma and surrounding vacuum. At the intersection curved plane, $\vec{r} = \vec{R}$, of axial magnetic field and azimuthal magnetic field, a shock wave is continuously produced. The Eq.(4.31) represents the source of perturbing magnetic field intensity arises from generation of propagating shock waves through magnetic flux tubes. Thus, the center of magnetic flux tube is specified by high density of hot plasma.

On the other hand, highly accelerated electrons and ions have no time to stay at the low density boundary layer of magnetic surface boundary of flux tubes. Due to instantaneous formation of low density thin region, vacuum layer (PVL) at dynamic boundary surface of magnetic flux tube, electrons and ions are sucked with velocity higher than background plasma sound speed in to VL. Those electrons and ions have a tendency split out from the guiding magnetic field at the magnetic surface and also from azimuthal micro magnetic field line. The PVL sucks electrons, ions and neutrals due to its negative dynamic potential. Suddenly, their momentum is changed at the dynamic boundary layer. Charged particles are heated instantly and gain enough kinetic energy. Fluctuating axial surface current leads to the perturbation of azimuthal magnetic pressure around the magnetic flux tube see Eqs.(4.32) and (4.32). The VL which is created between axial magnetic surface and azimuthal micro magnetic field enables charged particles to accelerate intensely.

Let we consider two dynamic boundaries of VL surrounding magnetic flux tubes. These are boundaries between axial magnetic surface and VL is first boundary. The second boundary is situated between VL and external micro magnetized plasma, consists of induced micro magnetic field lines. The induced micro-magnetic field part is stronger inside VL and decreases its magnitude far away from flux tubes. The perturbing magnetic fields of surrounding vacuum and interior magnetic flux tube as obtained from Eq.(4.31) using the concept of vanishing divergence of magnetic field are given by Eqs.(4.32) and (4.33) respectively.

$$\vec{B}'_1 = -\Phi_m(R) \frac{K_m(kr)}{K_m(kR)} \left[\left[\frac{m}{r} - k \frac{K_{m+1}(kr)}{K_m(kr)} \right] \hat{r} + \frac{im}{r} \hat{\phi} + ik\hat{z} \right] e^{i[m\phi+kz+\omega t]} \quad (4.32)$$

$$\vec{B}_1 = -kB_0\xi_z(R) \frac{I_m(kr)}{I_m(kR)} \left[\frac{k^2 B_0^2}{\rho_0 \mu_0 \omega^2 - k^2 B_0^2} \frac{I'_m(kr)}{I_m(kr)} \hat{r} - \frac{kmB_0^2}{r(\mu_0 \rho_0 \omega^2 - k^2 B_0^2)} \hat{\phi} - i\hat{z} \right] e^{i[m\phi+kz+\omega t]} \quad (4.33)$$

The Eqs.(4.32) and (4.33) indicate that the perturbation of magnetic field is determined by small perturbation in particles displacement that is described by Bessel functions associated with surface generated scalar magnetic potential, see Eq.(4.31). As we have seen from Eqs.(4.32) and (4.33), the perturbing exterior magnetic field is unstable in radial perturbing component while the perturbing interior magnetic field is only stable in axial component. So as to minimize complexity, let us consider that the equilibrium field interior of magnetic flux tube and its surrounding vacuum are given by the following Eqs.(4.34) and (4.35).

$$\vec{B}_0 = B_0 \hat{z} \quad (4.34)$$

$$\vec{B}'_0 = B'_\phi(r) \hat{\phi} + B'_z \hat{z} \quad (4.35)$$

The magnetic field functions, B_0 and B'_z are position independent interior and exterior of static magnetic flux tube while B'_ϕ is radial position dependent exterior of magnetic flux tube. Here, the magnetic field interior of flux tube is assumed as force free magnetic field, it is constant. The intense current flowing through magnetic flux column is dominated by its parallel component. The micro-magnetic field propagating through surrounding vacuum is assumed to be produced by the longitudinal current of magnetic flux tube. The longitudinal surface current responsible for production of surrounding magnetic field $\vec{B}'_0$ can be evaluated force free magnetic field at dynamic magnetic surface, here neglect effects of VL.

$$J'_{sur} = \frac{1}{\mu_0} \left[\frac{\partial B'_\phi}{\partial r} \Big|_{r=R} + \frac{B'_\phi}{R} \right] \quad (4.36)$$

However, the surrounding magnetic field is related with force free magnetic field interior of the magnetic flux tube at equilibrium condition by surface resultant current. The unknown function $\alpha(x)$ can be determined at surface of magnetic flux tubes for non-vanishing value of magnetic fields at surface of magnetic flux tube.

$$\alpha(R) = \frac{1}{B_0} \left[\frac{\partial B'_\phi}{\partial r} \Big|_{r=R} + \frac{B'_\phi}{R} \right] \quad (4.37)$$

The perturbation of total pressure interior of magnetic flux tube and perturbation of total pressure exterior of magnetic flux tube interacts at the dynamic boundary surface of flux tube. The first

order perturbing total pressures interacting at boundary of magnetic flux tube is described by Eq.(4.38).

$$P_1 + \frac{1}{\mu_0} \vec{B}_0 \cdot \vec{B}_1 = \frac{1}{\mu_0} \vec{B}'_0 \cdot \vec{B}'_1 + (\vec{\xi} \cdot \vec{\nabla}) \frac{1}{2\mu_0} B_0'^2 \quad (4.38)$$

Evaluating the Eq.(4.38) at dynamic boundary surface of magnetic flux tube results Eq.(4.39) for incompressible plasma fluid confined by force free magnetic flux surface during perturbation, and using boundary condition in steady state situation.

$$ikB_0^2 \xi_z(R) = - \left[\frac{im}{r} B_\varphi(R) + ikB_z \right] \Phi_m(R) + \xi_r(R) \frac{B_\varphi^2(R)}{R} \quad (4.39)$$

At the dynamic boundary surface of magnetic flux tubes, the perturbed normal magnetic field is continuous across the dynamic boundary surface. Thus, the perturbing normal magnetic field is vanished at surface boundary.

$$[\vec{B}'_1 + (\vec{\xi} \cdot \vec{\nabla}) \vec{B}'_0] \cdot \hat{n} + \vec{B}'_0 \cdot \hat{n} = 0 \quad (4.40)$$

Based on the Eqs.(4.34) and (4.35), the given value of magnetic field at equilibrium, non-radial value of $\vec{B}'_0$ the term $\vec{B}'_0 \cdot \hat{n}$ is vanished. By substituting Eq.(4.26) in to Eq.(4.40) and verifying the surface induced scalar magnetic potential in Eq.(4.39) that satisfies the magnetic dynamic boundary condition, the magnitude of surface phase velocity can be expressed in terms of Bessel function described by Eq.(4.41) that specifies surface phase velocity, oscillation velocity of perturbing magnetic surface.

$$v^2 = v_{Ai}^2 - v_{Ae}^2 \left[\left[\frac{m}{kR} + \frac{B_z}{B_\varphi(R)} \right] \frac{1}{kR} \frac{I'_m(kR)}{I_m(kR)} \frac{K'_m(kR)}{K_m(kR)} - \frac{1}{kR} \frac{I'_m(kR)}{I_m(kR)} \right] \quad (4.41)$$

Where $B_0^2/\rho_0\mu_0 = v_{Ai}^2$ and $B_\varphi^2(R)/\rho_0\mu_0 = v_{Ae}^2$ are axial Alfven velocity due to interior field and azimuthal Alfven velocity due to external field respectively. The oscillation velocity of magnetic surface of the flux tube coupled with position independent scalar magnetic potential is determined by interacting longitudinal and azimuthal Alfven waves at the magnetic surface boundary. The longitudinal Alfven velocity is given by $\vec{v}_{Ai}$ which is arisen due to effects of force free magnetic field situated interior of magnetic flux tube at equilibrium condition. The azimuthal Alfven velocity is determined due to effects of exterior perturbing magnetic field. The

modified Bessel function of second kind order of m and its derivative introduce the instability of magnetic flux tube. In this special case both the internal axial and external longitudinal fields, B_0 and B_z respectively, enhance stability while B_ϕ has the opposite effect.

When charged particles pass through the dynamic boundary surface of magnetic flux tube, they enter to shock surface coupled with surface electrostatic potential field *see section 4.7* associated with FMR theory. When the external azimuthal magnetic field is higher than the axial magnetic field, the external magnetic pressure on the plasma surface is increased where the perturbation squeezes the plasma into a neck and is decreased where the perturbation fattens the plasma into a bulge. Change of gradient in the external magnetic field causes the perturbation to grow and, without an internal field, the necks contract to the axis, giving a sausage-like appearance to the plasma; hence it is known that *sausage instability*. Generally, due to small perturbation of surface magnetic flux tube, several kinds of instability are developing. Some of them are kink instability, sausage instability, interchange instability, *Rayleigh–Taylor instability*, and *Pressure-driven instabilities* are expected on oscillating stellar (solar) magnetic flux tube surface most probably occurred at foot points of flux tubes.

4.7. Fast Magnetic Reconnection (FMR) model

The term magnetic reconnection was introduced by Dungey (1953) who was interested in the problem of particle acceleration in the Earth's magnetosphere [281, 282]. Earlier studies (Giovanelli, 1946; Hoyle, 1949) had considered the acceleration of particles at magnetic neutral points in the presence of an electric field produced by plasma convection, but these studies did not include the magnetic field that is produced by the current associated with the motion of the particles [76]. Using the framework of MHD, Dungey argued that this current would take the form of a thin sheet in which the diffusion of the magnetic field would necessarily dominate. Furthermore, this diffusion would cause field lines passing through the current sheet to change their connectivity to one another. This process was described as field line disconnection followed by reconnection of magnetic field lines. The importance of thin current sheets as a site for plasma heating and particle acceleration in solar flares was also recognized by Cowling (1953) at about the same time [283, 284].

Let we assumed that the magnetic field in stellar atmosphere is force free magnetic field. Longitudinal strong current lies along magnetic field line see sections 4.1 and 4.5. The current carrying magnetic field lines form bundles of magnetic flux tubes through the high conductivity plasma medium. These magnetic flux tubes are oscillating about the equilibrium point. The surface of magnetic flux tube is oscillating with velocity is given by Eq.(4.41) in special case, see, section 4.6. When magnetic flux tube is pushing the surrounding low pressure plasma, most of electrons exterior of flux tube are accelerated by normal surface electric field and fast shock wave that is generated at dynamic boundary surface of magnetic flux while ions are decelerated.

To define the dynamic nature of the stellar atmosphere, we do not have a clear evidences whether magnetic reconnection process is occurred or not interior of the star (sun). However, based on theory of plasma physics, charged particles could not diffuse fast enough across strong magnetic field lines through high density plasma medium for negligible inertial force. The longitudinal motion of charged particles is also determined by the plasma density and stability nature. Since the induced electric current along magnetic flux is mass independent, its strength is specified by velocity of fast moving electrons and gradients of the physical quantities. From ground based and space born observations, a group of magnetic flux tubes emerge from stellar surface [285, 286]. The growing magnetic flux tube interacts at small local region where flares are existed [287]. This leads us to suggest that flares associated with magnetic field decaying is created at small local region due to fast magnetic reconnection process through high conductivity plasma medium.

Based on our new model of solar flare (i.e., SWIF-2SAR model, see chapter 3) the life time of magnetic reconnection depends on the strength of continuously propagating shock wave fronts in front of magnetic surface. At this small local region, a non-linear process of particle-field interaction, particle-wave interaction, and particle-particle interaction makes the process is so complex. The small local region where reconnection process is performed may be volume even point like, may be plane or line. The FMR is naturally and three dimensional somewhere at small local region. The mechanism for FMR process at high conducting medium is fast propagating shock waves through high conducting magnetized plasma medium. Plasma particles are interacting with moving or stationary shock wave fronts. Neutrals and charged particles may be reflected, trapped, heated or accelerated by the shock wave fronts.

The outer surface of solar magnetic flux tube is invaded by oscillating electrons. Thus, magnetic surface of flux tube generates electrostatic potential as functions of radial position coordinate. When plasma density interior of flux tube is much higher than exterior, the surface electron induced electric field would be strong enough for generation of shock surfaces and electron runaway or ion runaway process. The dynamic boundary surface of magnetic flux tube is a good site where shock surface is generated continuously. The strength of generated shock wave depends on the strength of induced radial surface electric field, micro-magnetic field, longitudinal current and VL.

When the oscillation velocity of dynamic boundary surface coupled with thin electron cloud is higher or equals to electron acoustic velocity or ion acoustic velocity, production of shock waves at the dynamic surface is inevitable. Both imploding and exploding shock waves are generated at the dynamic magnetic boundary surface. The reflected shock wave is interacting with the next imploding shock fronts. This makes the process is so complex and the central part of flux tube is hotter than its apex. The exploding shock wave fronts are propagating radially outward to surrounding region. The exploding shock waves exterior magnetic flux tubes accelerate the surrounding particles in addition to surface induced electric field. The plasma density surrounding magnetic flux decreases drastically. However, the cross sectional area of magnetic flux tube remains constant except nearly periodic oscillation in steady state situation. Due to plasma instability conditions and effects of shock waves intense longitudinal electric current along flux tube generate surrounding magnetic field lines. The squeezing process interior of magnetic flux tube creates a perturbation in dynamic pressure interior of flux tube. This instability process may lead to flare at some part of magnetic flux tube.

4.8. Motion of Magnetic Flux Tube

Magnetic flux tube at high conductivity stellar (solar) atmosphere may grow from small arcade shape up to infinitely large scale and it may form an opened magnetic flux tube that may extend to interplanetary region. However, solar scientists could not get a best theory that explains a mechanism of continuous growing magnetic flux tubes at solar atmosphere. The dynamic motion of magnetic flux tubes at solar atmosphere leads to topological change in magnetic flux tubes. This topological change is observed after some flares that accompanied by releasing of stored energy from small local region. In reality the motion of magnetic flux tube is so complex

at the in-homogeneously magnetized solar atmosphere. Most probably, magnetic flux tube may move through high conductivity medium from high plasma density region to lower plasma density region. Considering the charged particle distribution on stellar atmosphere, population of charged particles near equator is expected higher than polar region but average plasma density containing neutrals is greater at polar region, see chapter 2, *section 2.2* in steady state.

This indicates that the polar region suffice a preferable condition for magnetic flux tubes to emerge simply and grow infinitely from most probably open flux tube while the region near equator prohibits magnetic flux tube from emerging to atmosphere and most of emerged magnetic flux tubes remained closed loop. The blocking of magnetic flux tube is arisen from strong pressure of surface charged particles confined by surface induced non-radial magnetic fields; see Eqs.(2.24), (2.25a) and (2.25b). Magnetic flux tubes may migrate from polar region to equatorial region due to inhomogeneous horizontal dynamic pressure distribution at deep photosphere region.

However, it is not clear that the mechanism it makes the foot points of magnetic flux to move from their original place interior of the star (sun) that suffice the magnetic reversal condition, it needs a current research. The moving magnetic flux tubes most probably meet at region between polar and equator forms a topological change. Here, we suggest that most of solar flares and explosive events are appeared at regions between poles at equator, coronal region for strong explosive events, see Fig.3.3. The magnetic flux tube that exerts high magnetic pressure pushes the surrounding charged particles. Let consider that two or more than two nearby opposite polarity magnetic flux tubes are approaching each other. They could meet at some region; this region may be point like region, plane or line. When the approaching magnetic flux tubes meet at the converging region, the reconnection process becomes fast even at high density plasma region. At the low density local region, magnetic fluxes change their topology.

However, the low density plasma region is surrounded by high density ambient plasma. This magnetic reconnection may be collisional magnetic reconnection or collision-less magnetic reconnection process in reality, see *section 4*. Plasma particles are accelerated at the interface region of magnetic fluxes of opposite polarity due propagating shock wave fronts before reconnection due to surface induced electric fields, surface magnetic fields and propagating shock waves. When the approaching opposite polarity magnetic flux meets at some region,

plasma particles move from the contact boundary surface to nearby surrounding. The contact surface becomes nearly vacuum region (VR) and Alfvén kinetic energy becomes dominant before annihilation of magnetic field lines of the approaching magnetic surface. The shock waves propagating in front of moving magnetic surfaces from both sides meet at convergence point, plane or line before magnetic surfaces are contacted. This VR is assumed as local cavity or vacuum layer (VL) between the contacting magnetic surfaces. The VR is created at the convergence region as we have seen in chapter 2, SWIF-1SQR model and chapter 3, SWIF-2SAR model. The VR is surrounded by oscillating electron plasma instantly. The oscillating surface of ionized local plasma creates a double current layer. This double current layer is coupled with generation of fast moving shock wave fronts.

Here, it is difficult to predict the nature of shock waves but that is a nice idea to predict energy conversion at small local region with in fraction of seconds [288 - 290]. Magnetic field lines are annihilated at the local VR with in small fraction of time, as soon as magnetic pressure is vanished at VR, the cut off magnetic field line reconnects with another opposite polarity magnetic field lines at dynamic boundary of VR so as to rearrange the topology of magnetic flux. The reconnected magnetic field is shrunk its length and recede from the VR surrounded by dense ambient plasma with Alfvén velocity that is associated with trapped charged particles. The VR is created at the interaction region of magnetic field lines before magnetic annihilation process is occurred. The local VR is characterized by strong VP and null magnetic field region accompanied by strong current of double layer. The strong VP collapses the double current layer instantly that helps the diminishing magnetic pressure inside VR.

The complexity of collapsed local region is increased and magnetic field energy is converted in to heat energy, kinetic energy and radiation energy. Thus, the complex shock wave converts magnetic energy in to other form of energy at small local region followed by reconnection. The annihilated part of magnetic field lines is stored at a point, plane or line instantly. During collapsing of VR, the fast moving shock wave converts magnetic energy in to other forms of energy. As a result of magnetic reconnection, a powerful stream of plasma ejects out from small local region, due to releasing process of stored magnetic energy. A magnetic bomb (MB) is created at the time of magnetic reconnection process results stellar flares and CMEs.

It is a good idea that the contacting magnetic flux tubes are perturbing with phase velocity is given by Eq.(4.41) in special case, *see section 4.6*, is complex, the dynamic magnetic surface may not stable. The un-stability of magnetic surface is arisen from acceleration of charged particles at dynamic boundary. Generally, in this section we investigate the nature of magnetic flux associated with evolution of electric field and magnetic field. The perturbing ionized hydrogen plasma elements can be frizzing and diffusing through force free magnetic fields of contacting magnetic flux tube. Here, let we assume that the physical quantities through magnetic flux tube is assumed as oscillatory, $A = A_0 e^{i[\vec{k} \cdot \vec{r} + \omega t]}$ that is space and time dependent. The oscillation small displacement of plasma fluid inside magnetic flux tube leads to investigate the oscillation velocity of magnetic flux tube. The oscillation velocity of magnetic flux tube is verified from momentum equation provides Eq.(4.42) that suffice adiabatic process.

$$\vec{v} = -\frac{\vec{k}}{\omega} \left[\frac{c_s^2}{\gamma \omega^2} + \frac{v_A^2}{\omega^2} \right] \quad (4.42)$$

When the Alfven speed in Eq.(4.42) is greater than or equal to electrons acoustic speed or ions acoustic speed, the Alfven wave is the agent of shock waves inside magnetic flux tubes. The induced micro-magnetic field inside the magnetic flux tube interacts with the original magnetic field. By considering that the electrostatic potential remains position independent, $\vec{\nabla} \phi = 0$, the vector magnetic potential is influenced by convective motion and diffusive motion of charged particles. Verifying the magnetic induction equation, the force free vector magnetic potential is decaying or growing exponentially due to convective and diffusive effects through magnetic flux tube for $\hat{n} \cdot \hat{A} = 1$ in Eq.(4.43), where the velocity vector field, $\vec{v}$ is parallel to magnetic vector field, $\vec{A}$.

$$\vec{A}(\vec{r}, t) = \vec{A}(\vec{r}, 0) \exp \left\{ \pm \frac{\alpha}{k} \cos(\omega t) - \frac{\eta}{\mu_0} \alpha^2 t \right\} \quad (4.43)$$

where the unit vector $\hat{n}$ is obtained from cross product of velocity vector and vector magnetic potential, and $\hat{A}$ is unit vector along vector magnetic potential. At VR region, the diffusive term is vanished because electrons and ions enter to electron runaway system or ion runaway system. The opposite polarities contacting magnetic surfaces create propagating shock wave fronts. The imploding magnetic surface decays spontaneously at the contacting magnetic surface. The rate of magnetic reconnection is determined by velocity of imploding separatrices reach at convergence

region of separatrices surface. The surface instability of magnetic flux tube plays a crucial role during magnetic reconnection process. For the parameter $\alpha(r)$ is only position dependent and static vector magnetic potential at dynamic boundary surface of VR, the surface induced electrostatic potential is determined by the magnitude of force free magnetic field strength at dynamic boundary layer. The collapsing VR, the imploding velocity of separatrices is approximated by imploding fast moving shock surface associated with oscillating electron current, minimum limit of shock velocity.

$$\phi = \left[V\alpha \sin \theta - \frac{\eta}{\mu_0} \right] B \quad (4.44)$$

The Eq.(4.44) shows that the surface electrostatic potential is proportional to force free magnetic field surrounding layer of VL plane or VR. The oscillating longitudinal vector potential produces steady electrostatic potential. This steady electrostatic potential creates a spontaneous acceleration of charged particles. Here, we theorized that the concept of force free fields of isolated local system take parts in fast magnetic reconnection process at VR. The kinetic energy of oscillating electrons near the dynamic boundary of VR region behind separatrix is verified from induction equation during plasma diffusion is approximated by Eq.(4.45), where $\eta_1 = \eta/\mu_0$ diffusive resistivity.

$$E_{kin} = -\frac{1}{2}\rho\alpha^4\eta_1^2 \left[\frac{1-\beta}{k} \right]^2 \quad (4.45)$$

The plasma kinetic energy coupled with phase velocity of diffusing magnetic field is vanished at situation is preferable for magnetic pressure balanced by plasma dynamic pressure, $\beta = 1$ near the convergence point, line or plane. The kinetic energy of frizzing charged particles coupled with moving magnetic field lines is influenced by collisional effects. The Eq.(4.45) indicates that the charged particles stop motion at a point where $\beta = 1$ for non-vanishing η_1 most probably behind the dynamic separatrix. In Fig.4.2a we show that kinetic energy is vanished at $\beta = 1$ and very large at $\beta \gg 1$ for non-vanishing η_1 on the magnetic surface. Fig.4.2b indicates that as β increasing in quadratic form, the density of kinetic energy increases to infinity on the magnetic surface.

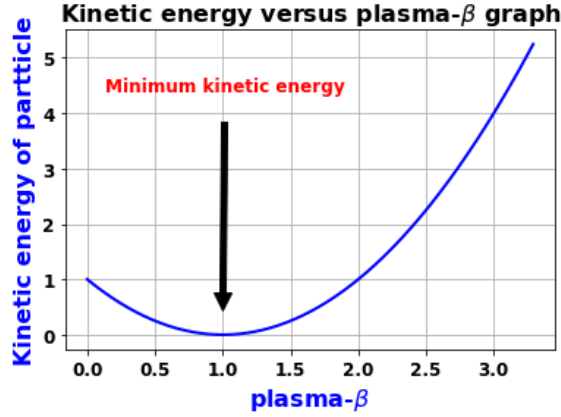


Fig.4.2a Kinetic energy of diffusing charged particles through magnetized

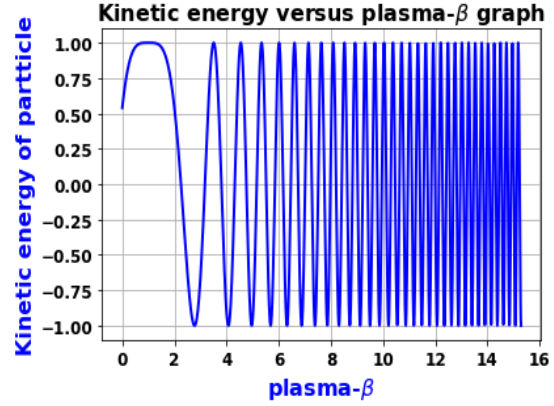


Fig.4.2b As plasma- β increases the kinetic energy density increase

From Eqs.(4.43), (4.44) and (4.45) we can understand that the magnetic reconnection process is independent of magnetic diffusivity, η_1 at contacting surface. Magnetic reconnection implies a new connection of cutoff magnetic field lines or magnetic fluxes and therefore requires a violation of Ohm's law in a very small region of VR or VL. In other words, magnetic reconnection is a process in which plasma is transported across a separatrix surface that implies the violation of the frozen-in condition because plasma elements, which were originally connected by a field line, are later found on separate field lines at dynamic boundary of collapsing convergence region. Using Eq.(4.42) and Eq.(4.45) the characteristic evolution of length scale of oscillating plasma elements is given by Eq.(4.46) that describes for $\alpha = 1/L$ is constant characteristic evolution length scale.

$$L^2 = \frac{\gamma\eta}{\mu_0 k^2} \frac{[\beta-1]}{c_s^2 + \gamma v_A^2} \quad (4.46)$$

On the length scale of the diffusing and freezing plasma, the boundary layer may be treated a discontinuity in plasma and field variables and, depending on the strength of the flow velocity, this discontinuity may be appeared as a shock wave. The quantity η represents plasma resistivity, $\eta = 1/\sigma$, inverse of conductivity in evolution of magnetic field $\vec{B}$ and dynamic pressure, p through magnetic flux tubes. We can evaluate the induction time scale or evolution time scale of local magnetized plasma system as follow

$$\tau = \tau_f [1 - \tau_f / \tau_d] \quad (4.47)$$

Where, $\tau_f / \tau_d < 1$ the quantities τ , τ_f and τ_d are the characteristic time during evolution of magnetic field, frozen-in characteristic time and diffusion characteristic time respectively. The magnetic diffusivity excluding the VL or VR of collapsing convergence is obtained from the induction equation and obtained for non-steady state situation described in Eq.(4.48) below.

$$\eta = \frac{\mu_0}{\alpha} \left[v - \frac{E}{B} \right] \quad (4.48)$$

The second term inside bracket at the right hand side Eq.(4.48) is electric drift velocity which is independent of charged particles mass. When magnetic field is diffusing through magnetic field and the induced electric field is vanished inside the magnetized plasma fluid, the diffusing coefficient corresponding to Eq.(4.48) is described by Eq.(4.49) in steady state that is obtained from the diffusivity of induction equation.

$$\eta = \frac{\mu_0 \varepsilon_{ijk}}{\alpha A^2} T^{ijk} \quad (4.49)$$

Where T^{ijk} a tensor that represents the cross products velocity vector field and vector magnetic potential at the imploding magnetized plasma surrounding the VR region. However, the VR region is determined by collision-less plasma particles that convert at convergence plane or point. Inside the collapsing cavity or VR the magnetic vector potential remains position and time independent or zero if VR is static. This leads to vanishing of force free magnetic field lines inside VR before collapsing electron beam. The magnetic diffusivity at surrounding region of contacting magnetic flux tubes before collapsing of VR is obtained by solving diffusive term induction equation during evolution of magnetic fields. The solution of diffusive term is given by Eq.(4.50).

$$\vec{B}(r, t) = \vec{B}(r, 0) \exp(-t / \tau_{dif}) \quad (4.50)$$

The variable $\tau_{dif} = \mu_0 L^2 / \eta$ denotes diffusive time scale behind imploding magnetic separatrix. Let us consider that force free magnetic flux tubes are approaching each other with velocity of $\vec{v}_1$ and $\vec{v}_2$, meeting at convergence point or plane of VL, approximately at middle point of L for equal approaching velocity, see Fig.4.2 below.

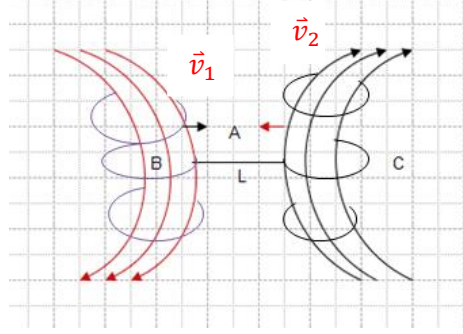


Fig.4.3. Approaching opposite polarity magnetic flux tubes attracted each other

For instance, the moving magnetic flux tubes filled with plasma are moving on xy –plane until they meet at convergence region or plane. When they meet at convergence plane, xz –plane, the decaying or annihilating velocity of collapsing parts of magnetic flux tube depends on the reconnection rate of magnetic field lines. The intense electric current of force free magnetic flux tubes is broken at the convergence region, VR or plane, VL even during collapsing. Discharging of ionized plasma is occurred at the convergence point so as to develop VR due to normal surface electric field and fast normal moving shock waves. The instantaneous charge separation process creates intense complex magnetic field that decays and builds some part of force free magnetic field separatrices of magnetic surfaces simultaneously.

A discontinuity in force free magnetic field is occurred at contacting region or convergence region. The contacting surface of colliding opposite polarity magnetic flux tubes become less in density than the non-magnetized surrounding region. Since electrons and ions are under the control of strong magnetic field lines, Alfven kinetic energy makes the process is so complex. On magnetic separatrix, a slow moving shock is created due to Alfven kinematic process. Alfvenic shock wave is created due to overloading of alfvenic wave families. The Alfvenic shock wave gets discontinuity at contacting force free magnetic surface region or plane. Magnetic field lines of contacting surface fluxes become free of charged particles and the reconnection process is fast and trivial at VR or VL followed by collapsing of ambient plasma.

On other hand, the contacting part of magnetic flux tube is annihilated by fast shock waves suddenly. The shock wave is generated at the contacting surface or VR. At initial stage of this process, plasma particles shift from contacting surface back to surrounding region across successive magnetic separatrices. The small cavity is surrounded by high density plasma

associated with formation fast moving shock wave fronts. As soon as the VP is strong enough at center of convergence point or plane, the surrounding plasma fluid will be collapsed suddenly. During collapsing, charged particles cross quickly the magnetic field lines due to strong VP of convergence region. The magnetic field lines decay by micro-magnetic field of fast flowing electron beam and complex shock wave process during collapsing. The fast moving shock wave fronts are propagating across magnetic separatrices. The propagating fast moving shock wave fronts are reflected back at foot of magnetic surface wall of flux tube from interior. The charged particles absorb enough heat energy from shock waves and are accelerating in random direction inside magnetic flux part of contacting region. The process increases its complexity, and magnetic field lines are reconnecting at dynamic boundary of small collapsing region of flux tubes. The second kind of reconnection process creates a relaxation of compacted or confined plasma particles. At surrounding surface of compacted region, magnetic pressure term is vanished while magnetic tension force is dominant. As the reconnection process is conducted, the reconnected magnetic field line recedes from the compacted region. The receding velocity is approximated by Alfvén speed of reconnected field lines. This reconnection process may be collision-less reconnection (i.e., first kind FMR) or collisional reconnection (i.e., second kind FMR). The collision-less reconnection process is expected as much faster than collisional reconnection process. The corresponding shock wave that is participated in collision-less reconnection process at the small local region is a collision-less moving shock.

In reality, this unsteady fast magnetic reconnection process is natural and three dimensional starts at small contacting surface or collapsing convergence region. The instability of the contacting surface or convergence region is determined by strong interaction of particle-waves and particle-field interaction. The propagating shock wave engulfs the surrounding imploding magnetized plasma to convergence surface or region. The oscillating electrons and ions at the contacting dynamic boundary are squeezed infinitely and the contacting opposite polarity magnetic field lines decay due to increasing production of fast propagating shock wave fronts. The squeezed electron beam generates spontaneous induced magnetic field that makes the process is so complex. The reconnection rate of magnetic field line may be dependent of gradient of magnetic field of collapsing flux tube. The fast propagating shock wave creates a strong turbulence of plasma particles and magnetic field lines. This turbulent shock wave creates a

dispersion wave burst. During magnetic reconnection process a violation of frozen-in condition is occurred at the collapsing cavity or collapsing VL of contacting plane.

However, the magnetic diffusivity is vanished at VL since charged particles have entered to charged particle runaway condition and negligible electrons collision at low density region of stellar atmosphere. When current carrying opposite polarity magnetic flux tubes is colliding at VL, the contacting current carrying *separatrices* generate a propagating shock wave fronts. The shocked plasma is emanating from contacting *separatrices* to non-magnetized surrounding region. Some part of the shocked plasma is driven out by the reconnected magnetic field lines. Electrons and ions are instantly accelerated from contacting *separatrices* and they are free of magnetic field lines. Part of the longitudinal surface current breaks suddenly at contacting *separatrices*, and the corresponding magnetic surfaces are annihilated there. Thus, electrons and ions suddenly enter to charged particle runaway condition. The next imploding opposite polarity *separatrices* is also annihilated. The process of annihilating contacting part of opposite polarity magnetic flux is fast process. Here, we have two reasons for FMR theory through high conducting ionized plasma.

1. Stationary electrostatic shock wave is generated at the contacting part of *separatrices* (i.e., first kind of FMR theory)
2. A fast propagating shock wave is produced at across contacting surface of *separatrices* (i.e., second kind of FMR theory)

4.9. Electrostatic Shock Waves at Contacting Part of Separatrices

Since VL is created at the contacting part of *separatrices*, the created VL is specified as a site of electrostatic shock wave of negligible thickness in comparison to diameter of contacting magnetic flux tubes. The electrostatic surface shock waves may be turbulent shock waves (i.e., significant in collisional shock waves) or laminar shock waves (i.e., May be significant in collision-less shock waves guided by electron runaway condition even at first kind of FMR theory) at the contacting *separatrices*. The electrostatic shock waves engulf the imploding part of magnetic flux tubes near the *separatrices* surface associated with plasma elements. The negative pressure associated with the electrostatic shock waves pulls the surrounding plasma coupled with the magnetic surfaces to convergence region. The convergence plane may not be a smooth plane.

Here, we assumed that the charged particles flow out from convergence region to surrounding region because of acceleration process, shock wave acceleration and Fermi process acceleration, see section 4.10.

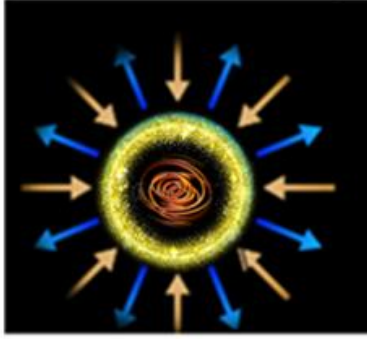


Fig.4.4 Collapsing magnetized cavity

The imploding magnetic surface or *separatrices* surface are annihilated at the convergence region. The magnetic reconnection rate is determined by the surrounding squeezing pressure. The annihilated part of magnetic field is stored at small convergence region. The convergence region is collapsed suddenly and a huge stored energy is liberated from the small region. The dynamic pressure at central part of convergence region where magnetic field is

annihilated there and approximated by Eq.(4.51) using the energy conservation law for position independent instantaneously collapsing dynamic pressure.

$$p = p_0 \left(\frac{v_0}{v} \right)^\gamma \quad (4.51)$$

The quantities v_0 and p_0 are the initial velocity and initial dynamic pressure inside VR before collapsing is started. The dynamic pressure is negative inside VR, and force free magnetic field and longitudinal electric current are vanished at convergence region for position independent dynamic pressure and the direction of velocity is assumed as $+\vec{v}$ for explosion and $-\vec{v}$ for imploding cases. Here we assumed that the imploding and exploding ions and electrons are in collision-less regime due to charged particle runaway condition. Before collapsing, the VR is growing with velocity $+\vec{v}$ and it reaches a maximum stage. When the VR increases in volume, the dynamic pressure at center of convergence region suddenly changes its direction of gradient pressure, and the VR is collapsing to center of convergence. During growing process of VR, the dynamic pressure inside is described by Eq.(4.52) in case of growing in side of VR.

$$p = (v/v_0)^\gamma p_0 \quad (4.52)$$

If the initial growing velocity of VR is proportional to corresponding dynamic pressure, $p_0/v_0^\gamma = 1$ leads to the integration constant is vanished, $c = 0$ during evolution of VR. For spontaneous process the initial value of velocity and dynamic pressure is very small quantities, the dynamic

pressure of growing VR region corresponds to Eq.(4.51) is expressed by Eq.(4.53) for spontaneous exploding.

$$p = v^{-\gamma} \quad (4.53)$$

While for spontaneous collapsing of VR region, the dynamic pressure corresponding Eq.(4.52) expressed by Eq.(4.54). The instant dynamic pressure p is the spontaneous collapsing gradient of velocity potential of VR between the contacting opposite polarity of magnetic flux tube.

$$p = v^{\gamma} \quad (4.54)$$

Here, we conclude that the dynamic pressure of collapsing convergence region is proportional with the collapsing velocity magnitude of imploding dynamic boundary, $p = v^{\gamma}$ and for exploding or growing VL region case also given by $p = v^{-\gamma}$, see Eqs.(4.51) to (4.54), and we assumed that the sink in magnetic field part at contacting surface region. Plasma particles are instantly accelerated at convergence region during collapsing of VR. Thus, the magnetic separatrixes and corresponding electric current sink at contacting convergence region. The surrounding magnetized plasma exerts a strong pressure that squeezed the VR from outside. The collapsing velocity of VR can be verified from pressure balance at dynamic boundary of collapsing VR. Let the surrounding squeezing dynamic pressure is denotes as p_e at inner side dynamic boundary of VR. The growing velocity of VR decreases till to reach its maximum stage at which its growing velocity is vanished.

Thus, using continuity equation for position independent density and dynamic pressure inside VR, the growing velocity of dynamic boundary of VR is verified from Eq.(4.51) results the Eq.(4.55) that describes the velocity of electrons during VR formation against the surrounding squeezing pressure. The initial functions v_0 and p_0 are the initial value of velocity and dynamic pressure inside VR of dynamic boundary before collapsing is started. For spontaneously growing of VR and collapsing of VR between contacting magnetic flux tubes, the growing radial velocity and collapsing radial velocity is given by Eqs.(4.55) and (4.56) respectively.

$$\vec{v} = 2^{-1/\gamma} v_0 \left[\frac{p_e}{p_0} + \frac{B^2}{2\mu_0 p_0} \right]^{-1/\gamma} \hat{r} \quad (4.55)$$

$$\vec{v} = 2^{1/\gamma} v_0 \left[\frac{p_e}{p_0} + \frac{B^2}{2\mu_0 p_0} \right]^{1/\gamma} \hat{r} \quad (4.56)$$

Here, we use the symmetry condition for identical collapsing force free magnetic flux tubes. From Eqs.(4.55) and (4.56), we understand that growing velocity of VR is inversely proportional to total pressure power of $1/\gamma$ inside VR while the collapsing velocity of VR is directly property to total pressure power of $1/\gamma$ evaluated at dynamic boundary. During collapsing of VR, electrons and ions that are free of magnetic force enter to electron runaway or ion runaway condition and the collapsing process is collision-less. The collapsing and growing process of VR is under the control of external or surrounding dynamic pressure and magnetic pressure of squeezing magnetic flux tubes.

By considering position independent plasma density of VR, using continuity equation, verifying Eq.(4.55) and (4.56) to describe electron density of growing or collapsing VR is given by Eq.(4.57) and the instantaneous electron density distribution of dynamic boundary for both growing and collapsing VL region remains the same.

$$\rho = (2\gamma)^{1/\gamma} \rho_0^{(\gamma-1)/\gamma} c_e^{-2/\gamma} \left[p_e + \frac{B^2}{2\mu_0} \right]^{1/\gamma} \quad (4.57)$$

The quantities of ρ_0 and c_e are electron density and electron acoustic speed at initial state of growing or collapsing VR. This shows that the electron density changes rate of imploding or exploding dynamic boundary that is determined by surrounding squeezing pressure terms.

4.10. Particle Acceleration during FMR Process

Let we consider two opposite polarity magnetic flux tubes that are approaching to each other with velocity of $\vec{v}_1$ and $\vec{v}_2$ see Fig.4.5a and Fig.4.5b below. The approaching magnetic flux tubes exert magnetic pressure on their front surface of ambient surrounding plasma. Let the separation distance between the approaching opposite polarity magnetic flux tubes at initial time is denoted by L , see Fig.4.3. The moving magnetic flux tubes generate propagating shock wave surfaces in front of the pushing magnetic surface.

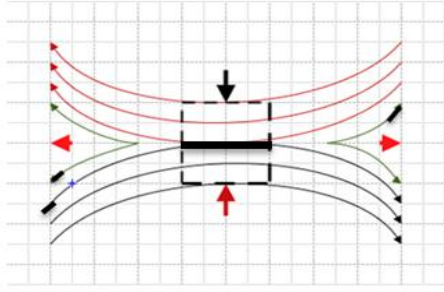


Fig.4.5a First kind FMR

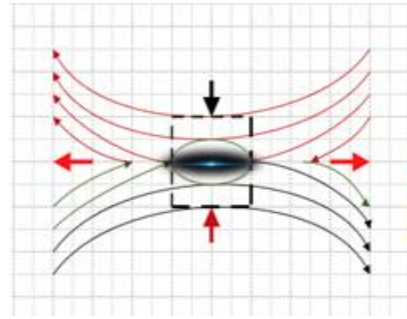


Fig.4.5b second kind FMR

Generally, the expanding magnetic flux loop generated a surrounding shock wave through low density ambient plasma [291]. The shock wave propagates with velocity $\vec{V}$ faster than the moving magnetic flux tubes through the high conductivity lower density atmospheric plasma, exterior the magnetic flux tube. Plasma particles are accelerated at the region between the approaching opposite polarity magnetic flux tubes.

Here we assumed that the region between the approaching opposite polarity magnetic flux tubes is un-magnetized region or weak magnetic field region. The induced magnetic field may influence the behavior of plasma at the region between the approaching magnetic flux tubes. This is true if and only if the longitudinal current is strong enough. However, the charged particles of un-magnetized plasma region gain high kinetic energy from fast propagating shock waves and particle field interaction process. The accelerated charged particles collide with wall of moving magnetic flux tubes after shock passage. The region on the front head surface of magnetic flux tubes is characterized by shock acceleration and Fermi acceleration process [292].

Let us consider the charged particle at weak magnetic field region has velocities of $\vec{u}_1$ and $\vec{u}_2$ before shock wave and behind shock wave passage respectively. The accelerated particle behind of shock wave passage enters to Fermi acceleration process. This makes the acceleration process is so complex behind shock wave passage as well as associated with shock process simultaneously. The charged particle passes continuous trains of shock wave fronts at the weak magnetic field region through high conductivity neutral plasma medium. When N numbers of nodes of shock wave surfaces that are passed continuously through high conductivity plasma, the normal velocity of plasma fluid behind of shock wave trains is obtained from Eq. (3.84a) and which is characterized by the invariable shock wave front.

$$\vec{u}_2 = \vec{u}_1 \pm \frac{2}{\gamma+1}(N-1)\vec{V} \quad (4.58)$$

The Eq.(4.58) relates flow of high conductivity plasma before shock wave passage and behind of shock wave passage in stationary frame for un-magnetized plasma. The continuous trains of shock wave fronts are assumed to be identical and propagate with constant velocity $\vec{V}$ through high conductivity plasma. The integer N number of nodes has $(N-1)$ number of shock wave fronts. The neutral particles are accelerated by shock wave only before ionization process is started and finally become ionized and accelerated due to effects of magnetic field, electric field, pressure gradient and shock waves.

However, charged particles enter to charged particle runaway condition if collision of particles density is rare at PVR and also enter to Fermi acceleration process when charged particles are colliding with surface of magnetic flux tube [293]. In general for acceleration of charged particles through electromagnetic field is described by Eq.(4.59) behind trains of shock wave passage. The shocked ionized plasma element enter to magnetic flux region, while the dynamic pressure remains constant of space time coordinate at surface of approaching opposite polarity magnetic flux tubes, the equation of motion of charged particles is described by Eq.(4.59) below.

$$\vec{a}_2 = \frac{q}{\gamma_v m} \vec{E} + \frac{q}{m\gamma_v} \vec{u}_1 \times \vec{B} \pm \frac{2}{\gamma+1} \frac{q}{m\gamma_v} (N-1) \vec{V} \times \vec{B} \quad (4.59)$$

The Lorentz factor parameter of $\gamma_v = (1 - u_2^2/c^2)^{-1/2}$ is velocity dependent and $\vec{a}_2 = d\vec{u}_2/dt$ is acceleration of charged particles behind continuous shock wave. The functions of $\vec{E}$ and $\vec{B}$ are treated behind shock wave passage. This process is most probable happened when shocked plasma particles are injected into magnetic flux tube region from VR behind shock wave. The annihilated part of magnetic field lines of flux tube is calculated by Petschek 1964, in his FMR theory in steady state situation that is supported by evidences from space satellites, during solar flare events as well as supported by evidences from laboratory plasma on Earth [284, 294].

In case of non-relativistic system, $u_2 \ll c$, the parameter $\gamma_v \approx 1$ and the radiative effect is negligible. However, $\vec{u}_1$ and $\vec{B}$ have no connection in space time coordinate during evolution of accelerating charged particles on magnetic surface behind shock wave that is described by Eq.(4.59) for spontaneous process. The angle between shock wave velocity and magnetic field is

denoted by ϑ and the non-thermal acceleration is given by Eq.(4.59) for non-variable shock wave fronts. The acceleration mechanism can only be associated either with non-stationary electric field or magnetic field. In static magnetic field work is not done but if magnetic field is time varying, work can be done on the particle by the induction field associated with $\partial \vec{B}/\partial t$ across the shock wave. At steady state, when the VR is created between the contacting surfaces of magnetic surface flux before magnetic annihilation, the instantaneous electrostatic potential accelerates charged particle on the magnetic surface behind of shock wave.

$$\phi(X) = \pm \frac{2}{\gamma+1} (N-1) XVB \sin \vartheta \quad (4.60)$$

Here, we use $(\vec{V} \times \vec{B}) \parallel \vec{X}$ behind of moving shock waves. The Eqs.(4.59) and (4.60) tells us that the source of electrostatic potential on magnetic surface is the interaction of propagating shock waves with magnetic fields in steady state situation. The shock induced electric field is vanished when the angle ϑ is vanished. If shock wave velocity $\vec{V}$ and magnetic field $\vec{B}$ remain position independent, the characteristic displacement is denoted by $\vec{X}$ corresponds to non-vanishing gradient of electrostatic potential. The minimum limit of N is 2 that is $N \geq 2$ for continuous trains of moving shock wave fronts. The thickness of shock wave may contain several trains of $(N-1)$, shock wave fronts.

When shock accelerated charged particles enter to magnetic field region, they are accelerated non-thermally. This non-thermal acceleration may be cyclotron and synchrotron acceleration. Cyclotron and synchrotron acceleration process becomes effective on the nearby contacting magnetic surface region. Cyclotron radiation is electromagnetic radiation emitted by accelerating non-relativistic charged particles deflected by strong magnetic field [295]. When the dynamic pressure of plasma remains constant, the Lorentz force on the particles acts perpendicular to both the magnetic field lines and the particles motion through them, creating an acceleration of charged particles that causes them to emit radiation as a result of the acceleration they undergo as they spiral around the lines of magnetic field. Cyclotron radiation is emitted by all charged particles travelling through magnetic field. Synchrotron emission is the radiation of high energy relativistic particles gyrating in a magnetic field. The energy loss or gain of emitting electrons on magnetic surface is given by Eq.(4.61) that describes the behavior of shocked

electrons enter to magnetic field region take part in synchrotron radiation for $u_1 \ll V$ on surface of magnetic flux.

$$-\left(\frac{dE}{dt}\right) = \frac{16}{3} \frac{\sigma_T}{c} \left[\frac{(N-1)}{\gamma+1} \pm \frac{u_1}{V} \right] \frac{(N-1)}{\gamma+1} \gamma_v^2 V^2 \frac{B^2}{2\mu_0} \quad (4.61)$$

The ' + ' sign in Eq.(4.61) denotes the energy lose rate while the ' - ' shows the energy gain rate of electrons. For specific condition of $\vec{u}_1$, $\vec{B}$ and $\vec{V}$ are time independent, the characteristic time of electron energy loss or gain is approximated from Eq.(4.61) and is described by Eq.(4.62) below when electron behind of single shock wave surface, $N = 2$ enters to magnetic field region.

$$\tau = \frac{3}{4} \frac{c}{\sigma_T} \frac{E}{E_{ks}} \left[\frac{u_1}{V} \pm \frac{2}{\gamma+1} \right]^{-2} v_A^{-2} \quad (4.62)$$

The quantity $E_{ks} = \frac{1}{2} \rho_e V^2$ denotes electron shock kinetic energy. The shock kinetic energy and Alfven kinetic energy determines the characteristic time of electron energy loss or gain inside magnetic field region. The shock accelerated particles collide with the walls of magnetic flux tubes between the approaching magnetic flux tubes. The opposite polarity magnetic flux tubes are approaching with velocity of $\vec{v}_1$ and $\vec{v}_2$ and they will meet at convergence plane. Here, we assumed that the shock accelerated charged particles are colliding with the moving surface of magnetic flux tubes. The colliding charged particles are further accelerated due to Fermi acceleration mechanism. The energy lose rate of electron behind shock due to Fermi acceleration mechanism, collision effect on magnetic surface of flux tube is obtained by Eq.(4.63).

$$-\frac{dE}{dt} = 4\mathcal{M} \left(\frac{v_1}{c}\right)^2 E \pm 4\mathcal{M} \frac{v_1}{c} \left[\frac{u_1}{c} + \frac{2}{\gamma+1} (N-1) \frac{V}{c} \right] E \quad (4.63)$$

The parameter $\mathcal{M}$ is number of collision per second. If $\vec{v}_1$, $\vec{u}_1$, $\vec{V}$ and $\mathcal{M}$ are time independent, by integrating Eq.(4.63) we obtain Eq.(4.64).

$$E = E_0 \exp \left\{ \pm 4\mathcal{M} \left(\frac{v_1}{c}\right)^2 \left[1 - \frac{u_1}{v_1} - \frac{2}{\gamma+1} (N-1) \frac{V}{v_1} \right] \tau \right\} \quad (4.64)$$

The accelerating electron loses or gains energy due to Fermi process is given by Eq.(4.64) exponentially on the region between the approaching magnetic flux tubes. Generally charged

particles are accelerating at the magnetic surface of approaching flux tubes and at the low density region between approaching magnetic flux tubes.

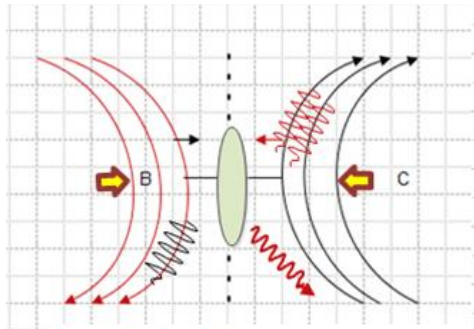


Fig.4.6 local PVR between approaching magnetic flux tubes

Density of plasma particles at contacting surface of opposite polarity magnetic flux decreases suddenly before annihilation of magnetic field. The surface generated shock wave propagates through the annihilating region of magnetic flux tubes, see Fig.4.6. From Fig.4.6, if the shocked electron enters to region B and region C, it is accelerated non-thermally. The plasma particles inside magnetic flux

tubes before annihilation of magnetic field separatrices at contacting region are accelerated by shock waves; see Eq.(4.58). Since electron has been injected in to regions of B and C behind of shock wave, the acceleration of injected electron is given by Eq.(4.59). The plasma inside the annihilated part of magnetic flux tube becomes superhot at annihilating part of magnetic flux tubes. The superhot plasma particles flows in both sides magnetic flux tubes slightly far away from the annihilating part of magnetic flux tube. A cylindrical magnetic cavity (MC) is created at the annihilating part of magnetic flux tubes that is supported by second kind FMR theory. The cylindrical cavity, MC, is surrounded by superhot completely ionized plasma. The surrounding superhot plasma creates polarization electric field due to instantaneous charge separation mechanism. A strong VP is created inside the cylindrical cavity. The plasma density near contacting surface is decreasing fast. The propagating shock wave accelerates plasma particles and compresses the magnetic field in to contacting magnetic surface. The shock wave compressed part of magnetic field is stored at small converging vacuum region. The opposite polarity magnetic separatrices are annihilated at contacting VL trivially. The annihilation of magnetic field at contacting region is followed by collapsing of surrounding superhot dense plasma suddenly. The instant stored magnetic energy is released abruptly, it causes a MB explosion. During explosion of magnetic bomb, the contacting magnetic flux changes their topological structure at both end sides of contacting cylindrical cavity during collapsing.

Generally, we suggest that magnetic reconnection is trivial inside high conductivity plasma medium if and only if the pressure of magnetic flux is higher than the surrounding

dynamic pressure. However, the magnetic reconnection rate in rare dense plasma is slightly slower than reconnection in vacuum. The reconnection rate inside plasma fluid depends on strength of magnetic pressure and generation of fast moving shock waves on pushing front magnetic surface. Based on FMR model, the rate of magnetic reconnection is rapid at upper layer of stellar (solar) atmosphere, corona of force free magnetic field.

4.11. Coronal Mass Ejections (CMEs)

CME is a sudden explosion of giant cloud of solar plasma associated with magnetic field lines that are blown away from the sun during strong, long-duration solar flares and filament eruptions and seen as bright features that move outward through the solar corona at speeds from 10 to about 2,000 km/s. They involve the expulsion of substantial quantities of plasma from large regions of the corona [296 - 298]. A coronagraph produces a solar eclipse by occulting the Sun with a small disk, see Fig.4.7a and Fig.4.7b. CMEs are very faint and cannot be observed with our naked eyes. The SOHO and STEREO missions have white-light coronagraphs onboard to detect CMEs [299 - 301]. CMEs are the prime source of strong geomagnetic storms on Earth atmosphere. CMEs can escape from the Sun during eruptions on the star/Sun such as solar flares and filament eruptions. However, not every event has a CMEs accompanied with it. Strong flares (M and X-class) are likely candidates to launch CMEs. C-class solar flares can also produce CMEs but only the long-duration and stronger C-class flares might be possible [302].

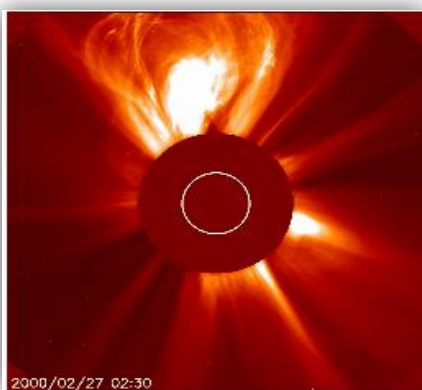


Fig.4.7a Solar Maximum activity, Credit: NASA

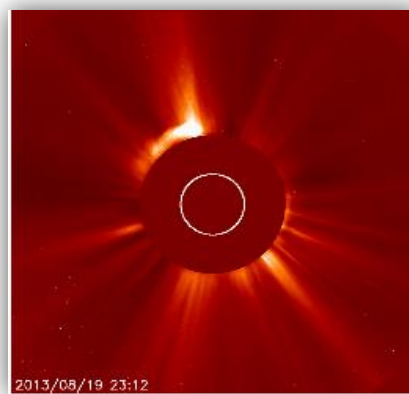


Fig.4.7b Solar Minimum activity, Credit: NASA

Depending on the location of the eruption, the blast could either miss Earth, be partially or fully Earth-directed [32]. Earth-directed CMEs will look like partial or full-halo CMEs on the images from SOHO [32, 33]. When this happens the CMEs will arrive at Earth after 24 hours or more (depending on the speed) and will likely cause a geomagnetic storm with observable auroral displays. The animation Fig.4.7a and Fig.4.7b shows a full halo CMEs as seen by SOHO/LASCO [303, 304]. When the Sun isn't very active during solar minimum, CMEs are rare [305]. There might only be one CME every week. When the Sun's activity increases towards solar maximum, CMEs become more common and we can see multiple CMEs every day [306, 307].

4.12. Mechanism of CMEs

Several observational and theoretical researches have been conducted on solar CMEs. The solar CME has very sophisticated dynamical nature. During CMEs enormous charged particles are wrapped by closed clump of magnetic fluxes that is ejected from solar surface or even from solar atmosphere to surrounding outer space. Still now, there could not be a clear theory that supports the mechanism for formation of CME on solar atmosphere. The temporal relationship between CMEs and associated solar flares is of great importance to understanding the origin of CMEs, but it has been difficult to study owing to the nature of CME detection [264]. The occurrence of flare radiation in the radio and X-ray wavebands clearly established the presence of heated plasmas and non-thermal particles arising from the rapid release of energy.

In contrast, the coronal material of CMEs observed in white-light coronagraphs is assumed not to be substantially heated above the ambient coronal temperature. In fact, a coronagraph observation in H_α line has established that cool prominence material is often observed in the cores of CMEs (Athay & Illing 1986) [308]. The helical kink instability of a force-free coronal magnetic flux rope, anchored in the photosphere, is expected as a source of solar eruptions associated with CMEs [309].

4.13. Summary

Fast magnetic reconnection (FMR) theory is more important to theorize the stellar (solar) explosive events through magnetized and high conductivity plasma atmosphere. The FMR is occurred at rare density plasma fluid; with reconnection time scale is as long as Alfvén time

scales but longer than the time required for magnetic reconnection through vacuum, trivial. FMR is occurred when stellar (solar) magnetic field lines are deformed, twisted and braided associated with fast propagating shock surfaces. When completely ionized plasma flows through magnetic field lines, the current carrying magnetic field lines form bundles of magnetic flux tubes. The surface of current carrying magnetic flux tube generates shock wave fronts. The magnetic surface induced shock wave may be stationary or fast moving shock wave fronts. The enhancement of shock wave fronts at contacting magnetic surface of opposite polarity magnetic fluxes makes the reconnection process is fast, near to trivial reconnection process. As we theorized in chapter 4, electromagnetic wave burst occurred on magnetic flux tubes (i.e., most probably at top of closed magnetic flux tube and foot points) due to FMR theory, as thin magnetic flux tubes are twisted and braided integrated with generation of shock waves. Based on shock wave theory integrated with FMR theory, SWIF model is developed in this thesis work. The natural model, SWIF model, provides a new sight of stellar (solar) explosive events at least in its fulfillment of minimum requirement.

CHAPTER 5

5. RESULT AND DISCUSSION

On stellar (solar) atmosphere, the primary energy release mechanism is the shock mode instability of streaming electron which gives rise to strong electric current associated with electron runaway condition. The SWIF model should explain that the flare energy is contained in particles accelerated to energies of the order of 10 meV to 10 GeV . The quantitative theory-data comparison is helpful to establish the expected mechanism of stellar (solar) eruptions, particularly the driving force of flares, CMEs and the evolution of their magnetic fields. Thus, the new theoretical SWIF model with testable prediction is looking to model the stellar, in particular solar, explosive events and formation of CMEs.

Based on the observational and theoretical understanding of stellar flares and CMEs, the main mechanism of stellar, solar, explosive events is non-linear behavior of streaming high conductivity plasma, separated electrons and ions, with velocity higher than plasma acoustic velocity in aligned direction, see section 2.14. Using multi-wavelength analysis we can determine the physical characteristic of flare sources that governs the role of energetic electrons in flare dynamics. When a low density cavity is formed in high conductivity plasma, a velocity shock potential (VSP) creates a strong discharging of electrons. From Eqs.(2.58a) and (2.58b), it is clearly shown that shock surface is created when electron beam is streaming through high conductivity plasma. When the condition $n_e/n_0 \geq 1$ and $e\phi_s/KT \geq 1$ is fulfilled in Eqs.(2.58a) and (2.58b) the fast moving shock wave triggers a flare, see sections 2.9 – 2.14, in chapter 2.

Imploding electron current density

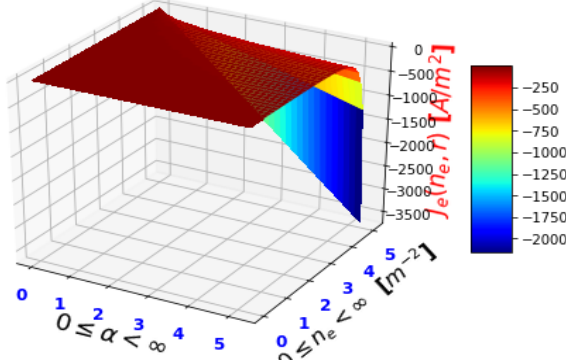


Fig. 5.1a Imploding shock current

Imploding current induced magnetic field

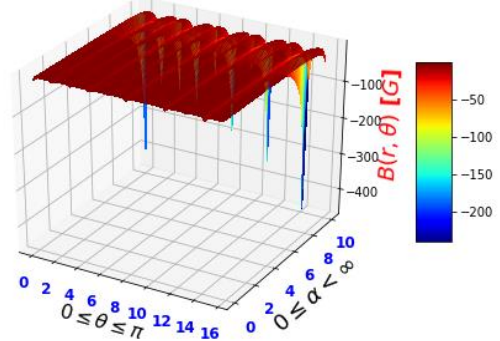


Fig. 5.1b Shock induced magnetic field during imploding

Imploding current induced magnetic field

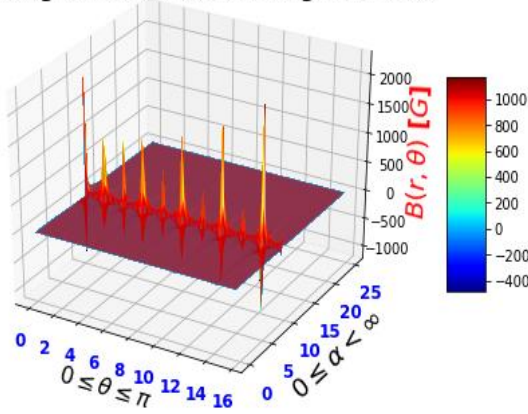


Fig. 5.1c Shock induced magnetic field surrounding collapsing region

Imploding current induced magnetic field

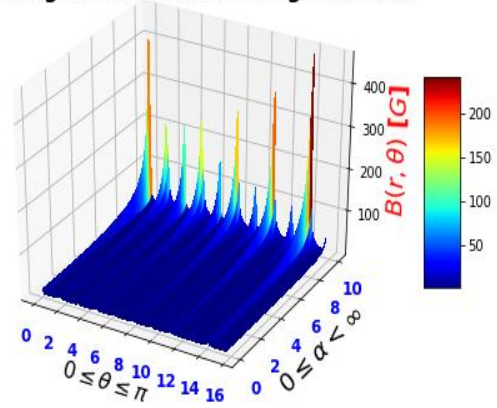


Fig. 5.1d Shock induced magnetic field during explosion

Imploding current induced magnetic field

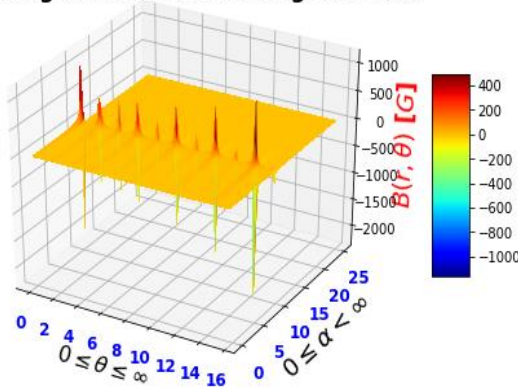


Fig. 5.1d Shock induced magnetic field behind of exploding plasma

$\vec{B}$ versus θ raph

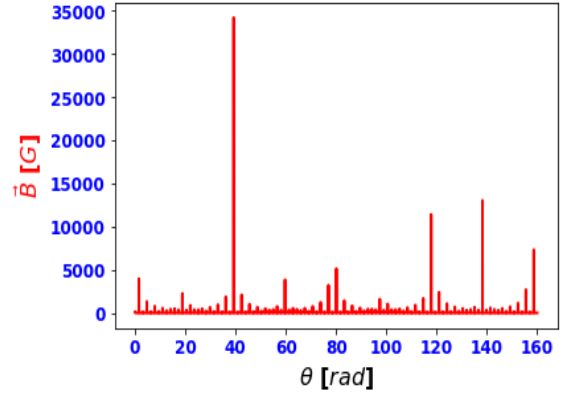


Fig. 5.1e Shock induced polar dependent oscillating magnetic field

In Fig.5.1a, we show imploding shock current, streaming of electrons that depend on imploding electron number density and radius of collapsing cavity. The corresponding shock induced magnetic field is described by Fig.5.1b and Fig.5.1d in cases of imploding and exploding beam of electrons respectively. This shock induced non-radial magnetic field is organized behind of imploded or exploded electrons. The built-up magnetic field has maximum peak amplitude and minimum peak behind of shock passage. The maximum and minimum peaks indicate formation of magnetic field near dynamic boundary of imploding or exploding electron beam. From Figs. 5.1b – 5.1d, we show that the polar magnetic field is vanished at $\theta = i \tanh^{-1}(1/\sqrt{\pi})$, on the complex plane. Here, the corresponding radius of convergence is approximated by $r = 0.6389$ units at angle of $\theta = 90^\circ$. The oscillating amplitude of induced polar magnetic field at

constant radius is shown in Fig.5.1e. Fig.5.1e illustrates the oscillatory behavior of polar dependent shock surface induced magnetic field at fixed radius of behind exploding shock surface. The Fig.5.1a - Fig.5.1e are plotted from Eqs.(2.54b) and (2.55b) by normalizing the constant coefficients to unity.

The Fig.5.1a - Fig.5.1e tells us that CMEs can be created from small local region behind strong implosion or explosion of runaway electrons. The wave behavior of magnetic field coupled with CMEs may be a mechanism of non-thermal particle acceleration. The non-thermal charged particle acceleration is expected to arise from synchrotron resonance. Here, we suggest that flares are thought to be caused by beams of electrons that momentarily stream through high conductivity stellar (solar) atmosphere with velocity in the range of electron acoustic velocity and velocity of light. During advancement of shock wave fronts, PVR is radially collapsing followed by sudden explosion, the built-up of non-radial complex magnetic field increases its instability non-linearly. When we illustrate Eqs.(2.54b) and (2.55b), the instability of magnetic field, see Figs.5.1b – Fig.5.1e, for imploding or exploding electrons sufficing runaway condition.

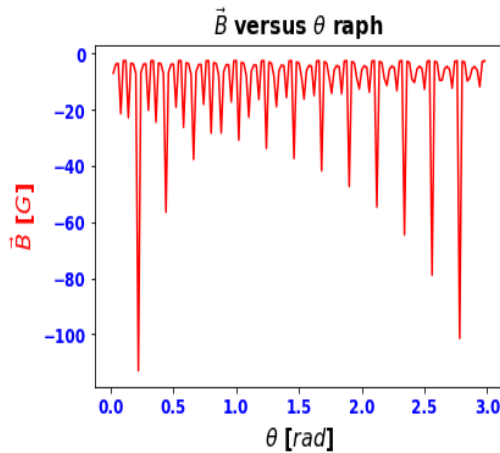


Fig. 5.2a Varying amplitude of imploding shock induced magnetic field

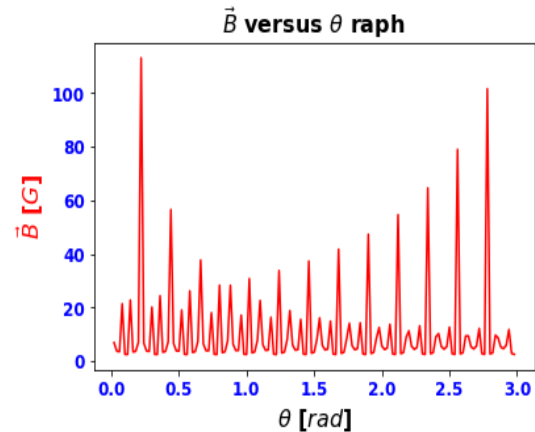


Fig. 5.2b Varying amplitude of exploding shock induced magnetic field

As we have seen from Fig.5.2a and Fig.5.2b the shock induced magnetic field interacts with running away charged particle which provides non-linear behavior of the system. The plots of Fig.5.2a and Fig.5.2b show a sudden drop in amplitudes of magnetic field arise due to non-linear nature of shock wave fronts. Some part of induced magnetic field may interact with pre-exist force free magnetic field. In Fig.5.2a and Fig.5.2b, the shock induced polar dependent magnetic

field has minimum amplitude near $\pi/2$ and maximum value near 0 and π , polar position, both for implosion and explosion. The shock induced built-up magnetic field is a mechanism for CMEs. The interaction between shock induced magnetic field and pre-exist magnetic field may lead to formation of huge CMEs associated with electromagnetic burst.

5.1. Flashing phase of stellar flares

Based on plasma theory and shock theory, the flashing phase of stellar (solar) flare is occurred during streaming of electron runaway process. On basis of SWIF model, the first flashing phase of flares increases during implosion of streaming electrons to convergence point, see section 2.8 in chapter 2. The imploding shock fronts associated with streaming oscillating electrons generates heat and radiation, observed as first flash. The second flash of flare is also expected during spreading of hot electrons, ions and neutral from the compacted convergence region, as soon as the imploding electrons are bouncing back. The intensity of second phase of flash gradually decreases and final ceased. Here, we imagine that the first flash of a flare is observed at onset of imploding electron runaway to convergence point. At this time we can observe a first flash or first light sparks from small local region.

In chapter 3, we have formulated Eq.(3.29) which shows heat energy is generated from velocity shock potential (VSP), including magnetic field and self-consistent electric field. For instance let we imagine that low density spontaneously collapsing magnetized cavity is developed on solar photosphere. Using estimated electron number density at photosphere $n_e \approx 10^{19} m^{-3}$, for dynamic boundary of collapsing PVR, we can manipulate Eq.(3.29) in order to predict the generated heat energy during implosion of electrons. The temperature and magnetic field relation is obtained as $T = 3.76 \times 10^{14} B^2 [m^2 K/T^2]$ during collapsing phase. Here, if we take the pre-existed magnetic field is $2G$ inside the collapsing cavity (PVR) associated with shock Mack number $M_s = 1$, a temperature of $T = 3.76 \times 10^6 K$ is produced at photospheric local region. This manifests the fast imploding shock wave converts magnetic energy to heat energy, see Fig.5.3a and Fig.5.3b. From convergence region, hot electrons are radiating out with non-thermal acceleration.

Here, we estimated corresponding radiation frequency is calculated as $\nu = 7.83 \times 10^{18} Hz$ behind of imploding compressive shock wave. This indicates that imploding

compressive shock wave generates extreme ultraviolet and soft X-ray short lived spectrum at first flash. The duration of first flash depends on the strength of VSP. The VSP which is framed in chapter 2 of Eq.(2.110) used to simulate the streaming electron runaway current during implosion or explosion of running away electrons. The VSP is strongly coupled with instantaneous local charge separation process, see chapter 2 of section 2.8 and 2.9. The spontaneously generated temperature across moving shock wave is proportional to square of pre-existed magnetic field. The graph of Fi.5.3a illustrates the generated temperature from magnetic field across fast moving shock fronts.

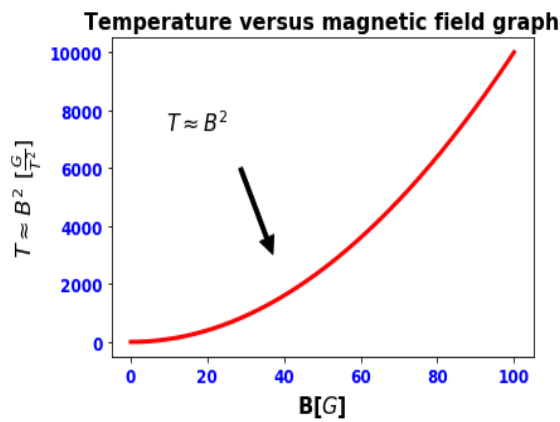


Fig.5.3a Magnetic field is converted in to heat across fast moving shock fronts

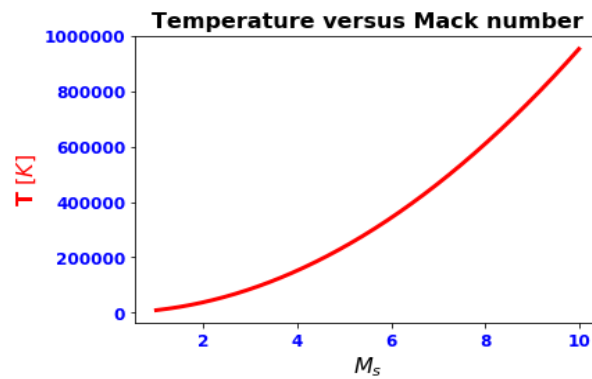


Fig.5.3b Heat energy is generated from shock kinetics

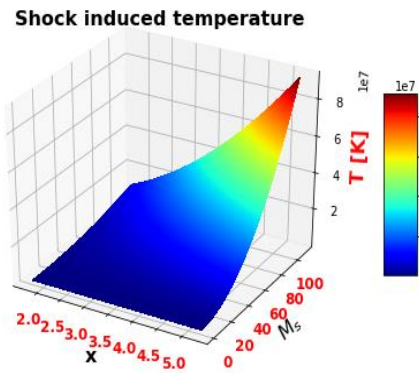


Fig.5.3c Temperature generated by oscillating shock fronts and self-consistent electric field

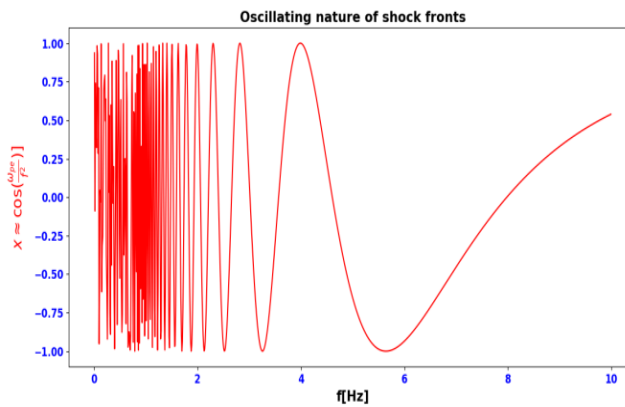


Fig.5.3d Oscillatory nature of shock trains in comparison to electron

The Fig.5.3a – Fig.5.3d are illustrated from Eq.(3.29) for spontaneous compression of local plasma at small region passed by shock waves. Fig.5.3a and Fig.5.3b illustrates the spontaneous

generation of temperature from pre-existed magnetic field and VSP respectively. Fig.5.3c shows temperature is produced when oscillating shock surface propagates through high conductivity plasma. The interaction of oscillating electrons and fast propagating shock fronts produces heat and radiation. The Fig.5.3d illustrates the nature of oscillating shock fronts in comparison with electron plasma frequency.

Here, we imagine that the oscillation of fast propagating shock front is slower than electron beam frequency at dynamic boundary at beginning. When the fast propagating shock surface is oscillating through high conductivity plasma, the medium is continuously changing its behavior. Thus, the oscillatory behavior of fast propagating shock fronts provides the non-thermal acceleration of particles. In Fig.5.3d, the dimensionless parameter represents the ratio of electron plasma frequency to shock front frequency, $x = \omega_{pe}^2/f^2$ where $f = 1/t$, t is oscillating time of shock fronts. Generally, during the phase of first flash, spontaneous heat and radiation are generated by strong compressive shock surfaces.

On the basis of SWIF model, when background electrons are streaming at sonic Mach number of photosphere, chromosphere and corona of negligible pre-exist magnetic field, the temperature of $T = 9.533 \times 10^3 K$, $T = 1.399 \times 10^5 K$ and $T = 1.4 \times 10^6 K$ are spontaneously generated respectively, from calculation. This ensured that as streaming electrons obtains Mach number much greater than unity, they are accelerated non-thermally. When continuous trains of shock fronts are passing through high conductivity plasma, the instability increases infinitely, see Fig.5.4a and Fig.4b. This shows non-linear temperature production across fast propagating shock surfaces through high conductivity magnetized plasma.

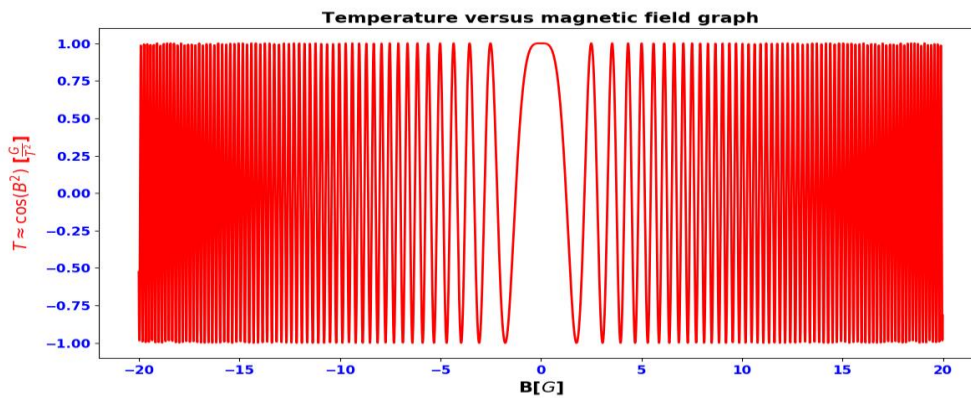


Fig.5.4a Temperature obtained from pre-existed magnetized across shock trains

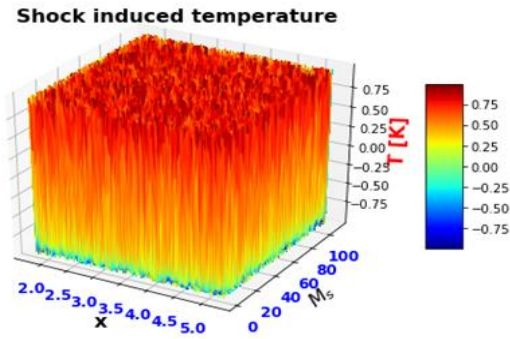


Fig.5.4b Temperature obtained from interaction of shock wave trains and oscillating running away electron beam

The Fig.5.4a and Fig.5.4b shows temperature distribution behinds of continuously passing trains of shock fronts. Fig.5.4a describes that as infinite number of shock wave fronts are passing through magnetic field, huge amount of heat energy is generated from magnetic energy. In graph of Fig.5.4a, at initial state, value of magnetic field is nearly zero that produces small heat energy. When magnetic field strength increases through identical trains of shock fronts, more heat energy is generated; this is clearly shown at both sides of Fig.5.4a. This profoundly describes the increasing phase of first flash which reaches maximum peak as increment of shock trains is considered. The Fig.5.4b shows that heat energy is created from both fast propagating oscillating shock fronts and self-consistent electric field at same time for negligible magnetic field. In general form, this is formulated in chapter 3, Eq.(3.29) for compressive shock or explosive shock waves. The first phase of flashing is agreeably described by SWIF model when imploding electrons obtain velocity higher than acoustic velocity. Migration of electrons with velocity higher than acoustic velocity is triggered by VSP.

Here, SWIF model investigates that as runaway electrons are streaming with velocity greater than electron acoustic velocity, the compressive shock produces electron instability in the absence of particle collision. By manipulating Eq.(3.81b) for magnetic field containing terms that are smaller than $\gamma + 1$, the plasma density compression ratio of upstream to downstream is limited between 1 and near zero. This shows that the electron number density behind of shock wave is infinitely smaller than upstream region. Generally, the electron number density ratio behind of continuous trains of shock fronts for large integer value of magnetic term is compressed or rarefied infinitely, see Eq.(3.80a). The electron number density compression ratio has oscillatory behavior about equilibrium point of $\gamma = -2.33$, see Fig.5.5b where a sudden change occurred. As we have seen from Fig.5.5b, the trains of shock surface open a discontinuity on the electron number density. The saddle point on Fig.5.5b indicates the property of jump

condition due to fast moving shock waves. Based on advanced SWIF-1SQR model, the variable $y = F + G \approx -[1 - 1/M_s^2]$ provides effects of compression or rarefaction of plasma in case of $\vec{B} \approx 0$ and $M_s > 1$, see Eq.(3.81b). The Fig.5.5a illustrates the electron density ratio performed by compressive shock front ensured by SWIF-1SQR model.

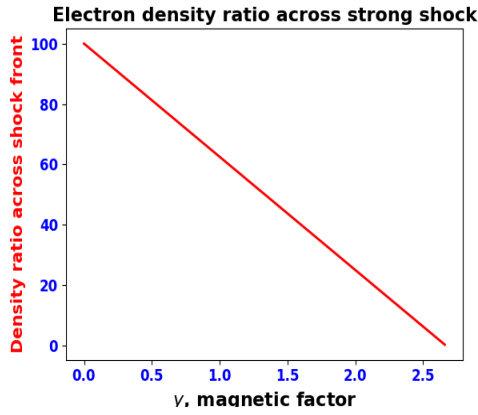


Fig.5.5a Density ratio in the ranger of $0 \leq y \leq 2.767$ across shock wave

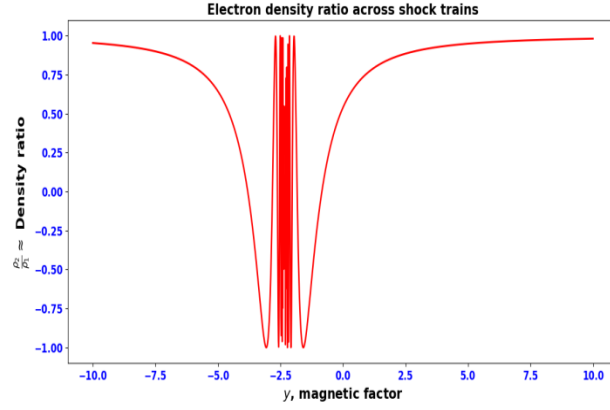


Fig.5.5b Density ratio in the ranger of $-10 \leq y \leq 10$ across continuous trains of shock fronts

The graph of Fig.5.5b describes the density compression ratio nature across continuous trains of shock fronts when the magnetic factor, y contains large magnitude. This implies that the magnitude of Alfven Mack number is greater than shock Mack number. The magnetic field is highly influenced by fast propagating shock fronts. The enhancement of strong magnetic field in to fast propagating compressive shock makes the pressure compression ratio of downstream to upstream be highly complex.

When the Alfven wave behind shock front is much less than the Alfven velocity before shock and if the shock kinetic is dominant, the pressure ratio can be illustrated from Eq.(3.82b) as shown in Fig.5.6a and Fig.5.6b. The graphs of Fig.5.6a show the pressure ratio of downstream to upstream that is determined by shock Mack number and Alfven Mack number. The Fig.5.6a coincides with the idea of SWIF-1SQR model when shock kinetic is dominant. When the Alfven kinetic is dominant over shock kinetic, the Fig.5.6a is also concomitant with SWIF-2SAR model. When continuous trains of shock fronts are passing through high conductivity medium, the compressive shock generates a blast wave. As we have seen from Fig.5.6b, when infinite trains

of shock fronts pass through high conductivity plasma, the plasma behind of shock is infinitely compressed or infinitely rarefied.

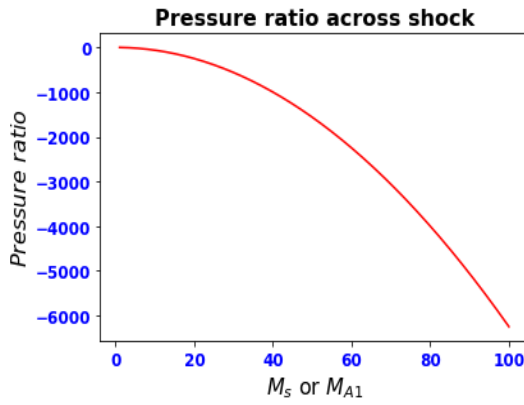


Fig. 5.6a Pressure ratio across shock front for dominant shock Mack number or Alfven Mack number

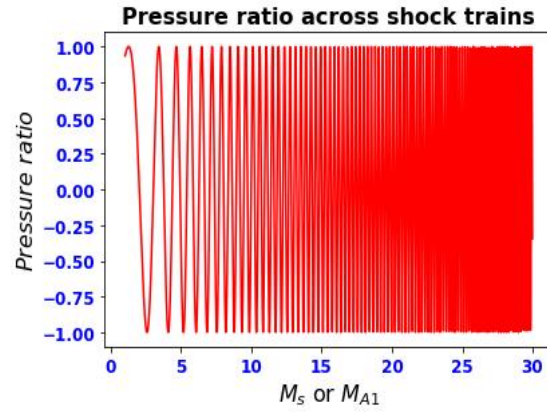


Fig. 5.6b Pressure ratio across continuous identical shock front trains for dominant shock Mack number or Alfven Mack number

Here, we assumed that the identical continuous trains of shock fronts have oscillatory behavior. When continuous trains of normal shock fronts are propagating through magnetized plasma, the magnetic field may be grow or decay across the shock front. This is formulated in chapter 3, as SWIF-2SAR model is advancing. Electrons are accelerated behind of shock fronts due formation of spontaneous kinetic energy obtained from Eq.(3.62) described as $E_k \approx \frac{1}{2} m_e [(\Delta p_e + \Delta p_m) / \rho_e V]^2$, where Δp_e , Δp_m and E_k are change in electron dynamic pressure, change in magnetic pressure and kinetic energy of electrons respectively.

When local PVR is collapsed suddenly to a point like region during the first phase of a flare, higher density plasma is compacted at convergence point. The imploding electron induced magnetic pressure is well organized and compresses the compacting plasma. A secondary shock wave is developed instantly due to non-linear particle field interaction principle. Here, we assumed that the process is collision-less at high conductivity plasma. The imploded streaming electrons are bounced back quickly at the convergence point. The secondary shock generates heat energy associated with instant electrostatic potential at the convergence region; see section 2.14 in chapter 2. During this complex process, we imagine that the electrical energy is balanced by thermal energy. Running away electrons are streaming radially out followed by impulsive

blast wave. The exploding critical electron current is derived in chapter 2, Eq.(2.76b) in the absence of pre-existed magnetic field.

When we assume that the imploding streaming electrons are reflected with velocity twice of the imploding shock velocity, the exploding shock induced critical electron current is approximated by $J_e \approx 3.46n_e ec_1 M_s$ where c_1 and M_s are sound speed before shock and shock Mack number respectively. The exploding streaming of electrons creates a second flash during flaring, observed as spreading of lights; this is well illustrated by SWIF-1SQR model. The enhancement of pre-existed magnetic field intensifies the flaring process. If pre-existed magnetic field is there at the compressed and compacted local convergence region, the imploding electron current is approximated by $J_e \approx n_e^{3/2} ec_1 M_s \beta^{-1/2}$ where β represents plasma magnetic beta at convergence region. Here, we assumed that $\beta \ll n_e$ at exploding convergence region. In case of presence of pre-existed magnetic field the shock induced electron current differs by a factor of $0.289 (n_e/\beta)^{1/2}$ from vanished pre-existed magnetic field; this second phase of flare is well described by SWIF-2SAR model.

To simulate the exploding electron current from small local region that brings second phase of flash, let we assume that the exploding current starts from a point like convergence region of radius r_0 coupled with electron current density J_0 . The streaming out electron current decreases its intensity as $J_e \approx 1/r^2$ where $\vec{r}$ is the radial distance traveled by streaming out surface of electron beam. The SWIF-1SQR model defines the spreading electron current that bears second flash as $J_e \approx 3.46n_e ec_1 M_s / r^2$ while the SWIF-2SAR model describes the spreading electron current as $J_e \approx n_e^{3/2} ec_1 M_s \beta^{-1/2} / r^2$ during explosion. The exploding electron current density is vanished at infinity. The over voltage of electron current creates discharging of electrons and formation of electromagnetic burst.

During the second flash, the exploding electron currents are highly influenced by the presence of pre-existed magnetic field. The plots of Fig.5.7a - Fig.5.7d shows the shock induced electron current is exponentially decaying during sudden streaming out of electrons. Fig.5.7a describes a maximum current limit occurred at surface boundary of compacted region during sudden explosion. When explosion is on progress as second flash is observing; the electron current decays exponentially and vanished at large distance. Here, we assumed that the streaming

out electron current is decaying exponentially while shock velocity remains constant for unvariable shock surface. Fig.5.7b defines that the pre-existed magnetic field during explosion highly controls the streaming out electron beam. At region where the value of plasma- β is vanished, the electron current has maximum amplitude, see Fig.5.7b.

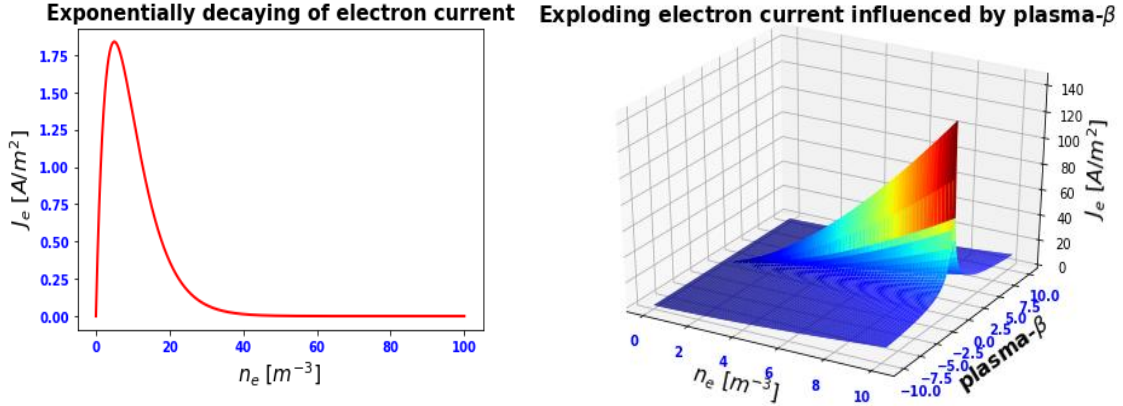


Fig.5.7a Exponentially decaying electron current during electron explosion for first flash.

Fig. 5.7b Exponentially decaying electron current influenced by pre-existed magnetic field.

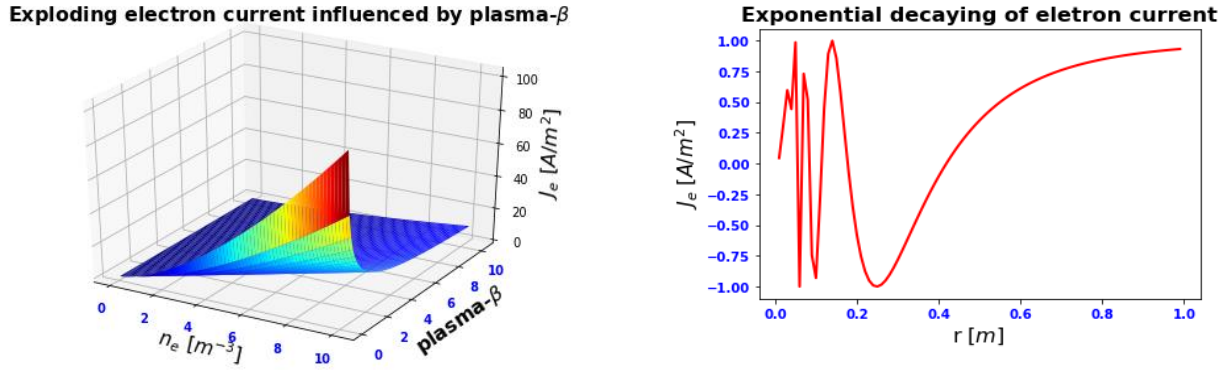


Fig. 5.7c Exponentially decaying electron current during explosion for $\beta > 0$, second flash

Fig. 5.7d The exponentially decaying electron current during explosion remains constant at infinity

The Fig.5.7c shows the effects of pre-existed magnetic field for $\beta > 0$ at electron dynamic pressure dominant region. The variation of magnetic field associated with exponentially decaying of shock induced electron current is described by Fig.5.7c. The Fig.5.7d describes the exponentially decaying shock trains induced electron current that highly fluctuating at convergence region during explosion. And, the fluctuation becomes small at large distance. Here, on basis of SWIF model, the observable first and second flash phase of stellar (solar) explosive

event is described by natural and physical theoretical model. The SWIF model predicts how flares, CMEs and electromagnetic wave burst are naturally occurred on stellar atmosphere.

At initial phase, the velocity shock potential (VSP) compacts the ambient plasma in to small local region. Throughout compacting of high conductivity plasma process, coupled with primary shock, the imploding shock wave function grows exponentially. Here, we illustrated Fig.5.8a - Fig.5.8d from Eq.(2.119b), so as to understand the imploding and exploding shock wave fronts. When the continuous trains of shock fronts are assumed to be identical, the propagating shock wave is exponentially decaying or growing. In Fig.5.8a - Fig.5.8d, the blue color shows that shock wave propagates to convergence point, near to zero; while the red color represents the exploding shock wave. The primary imploding shock is reflected at convergence point.

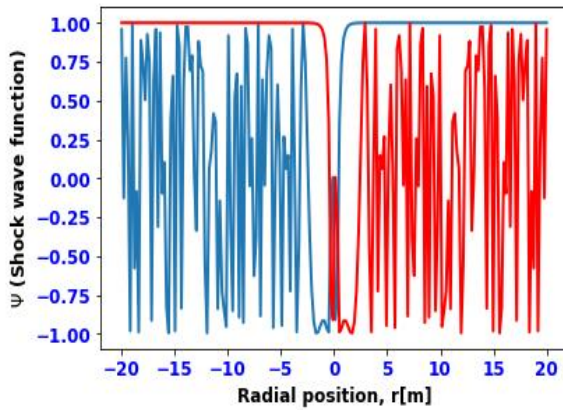


Fig. 5.8a Imploding shock wave converges at point while diverging shock converges at infinity.

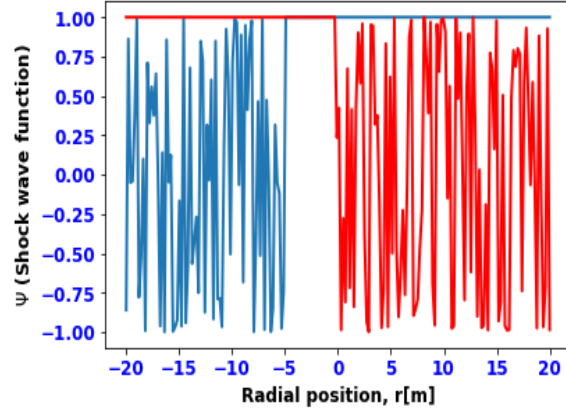


Fig.5.8b Phase change in imploding primary shock wave and exploding shock wave fronts.

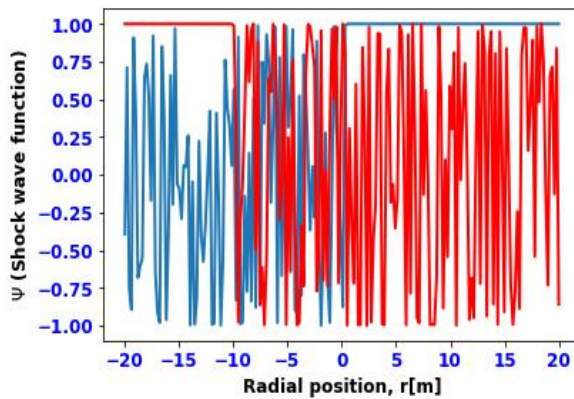


Fig.5.8c Interaction between imploding and exploding shock wave is inside pre-collapsed volume.

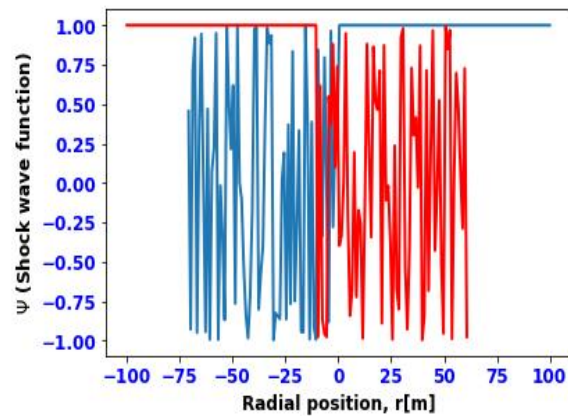


Fig.5.8d Velocity shock potential is constant at region far away from collapsing cavity.

Fig.5.8a shows that annihilation of primarily imploding shock wave and creation of exploding shock surface is occurred at convergence point. As we have seen from Fig.5.8a, a small amplitude shock wave is existed at outer part of convergence region. The phase change between imploding and exploding shock wave is illustrated in Fig.5.8b. The phase change creates a jump in shock potential gradient during collapsing process of magnetized plasma. When the imploding shock wave interacts with the exploding, particles are expected more accelerating. Fig.5.8c describes that the interaction between imploding and exploding shock is occurred inside collapsing PVR or at convergence region. Fig.5.8d shows that the imploding strong shock wave is converged at a point while the exploding shock wave converges at infinity.

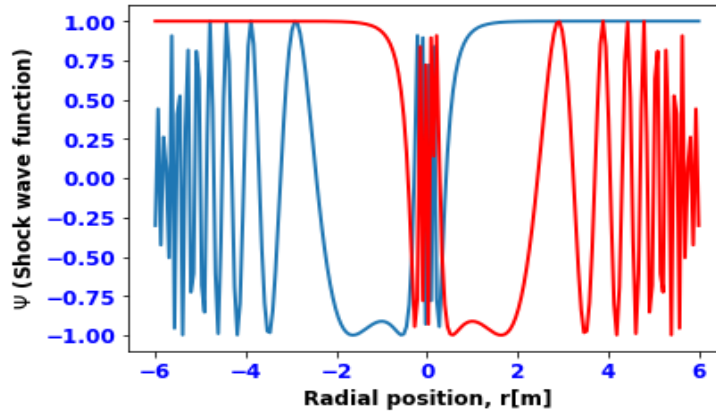


Fig.5.8d Small amplitude shock followed by sudden change of amplitude is occurred at convergence point.

In Fig.5.9 we show that a weakening of shock wave is occurred near the convergence point. As imploding shock is reflected at convergence point, its amplitude remains constant, see the blue colored plot in Fig.5.8d. In Fig.5.8d, the red colored plot shows that amplitude of shock wave remains constant after reflection; see the negative value for position region. The red colored plots on Fig.5.8a - Fig.5.8d and Fig.5.9 shown that exploding shock wave is created at convergence region and dynamic boundary and propagates out. While the blue colored plot indicates that the imploding shock wave is produced at dynamic boundary of collapsing cavity.

5.2. Endorsement of SWIF-1SQR model Associated with CMEs

The SWIF-1SQR model, physical and theoretical model, agreeably describes the occurrence of frequently observed stellar (solar) explosive events. It is mainly designates appearance of flares and CMEs at high conductivity solar atmosphere of weak magnetic field

region, Nano flares and micro flares most probably. The SWIF-1SQR model is the first part of SWIF model that is advanced based on the behavior of particle dynamic and particle-field interaction principle in the absence of pre-existed magnetic field. In 2013, a standard flare model in three dimensions which was simulated to confirm the upper limit of flare energy was approximated up to 10^{36} *erg*, flares in active Sun-like stars [310].

However, this standard three dimensional flare models was developed based on the stored magnetic energy only, the candidate stored energy for stellar explosive events is the slow process of storing magnetic energy. Based on G. Aulanier's standard flare model, so as to create a single stellar flare on stellar atmosphere that was based on the old flare theory associated with slow magnetic reconnection theory, it needs a time of 10^7 years to appear once [140, 311]. Moreover, from observational point of view, solar flares are processed within average duration time of 2 to 300 seconds, for instance a burst of photons from 40 keV to 40 MeV are coincident to within ± 1 second [312, 313].

We expect that the SWIF-1SQR model solves this problem partially to fulfill the minimum requirement based on the dynamical nature of completely ionized plasma and particle-field interaction principle coupled with the non-linear effects with no pre-existed magnetic field. However, the shock wave induced magnetic field makes the flaring process is so complex, plasma is highly compressed and internal energy, electrical energy, magnetic energy and shock potential energy is stored at small local region.

5.3. Current limit on stellar (solar) atmosphere during flaring

Still now, the best evidence of electric current in the solar atmosphere was come from measurements of magnetic field only. This current is a vertical electric current can exist in neighborhood of sunspot with amount of 10^{11} A (Ampere) which is a maximum limit of electric current interconnected with magnetic field [113, 314]. The solar flare model proposed by P. Carlqvist, 1968 was flares based on presence of slow emerging magnetic flux only. This model does not support the natural behavior and creations of all kinds of flares that exist at weak magnetic field region of stellar atmosphere even at strong magnetic field region of high conductivity plasma, because of slow magnetic reconnection theory.

However, the SWIF-1SQR model, natural theoretical model addresses the drawback of stellar explosive events models that are processed within instant of time, at weak magnetic field region. SWIF model agreeably predicts the formation of both of weak and impulse flares and CMEs proceeded by flares, wherever at stellar atmosphere. SWIF model also predicts electromagnetic wave burst from very small local region at stellar atmosphere, at convergence point. During flaring process, taking the lower limit of Mach number is unity, $M_s \approx 1$ corresponds to fast moving sonic shock wave; a minimum limit of electron current is obtained as $J_e \approx 10^5 A$ per unit area in the absence of pre-existed magnetic field, as cavity is collapsed. When we take the upper limit of Mach number, $M \approx 10^3$ corresponds to near-relativistic strong shock wave; the lower limit of electron current reaches up to $J_e \approx 10^8 A$, where $n_e \approx 10^{19} m^{-3}$ (i.e., lower electron limit at photosphere) and electron acoustic speed is approximated with the minimum photosphere sound speed, $c_s \approx 10^5 m/s$.

When we take the electron number density at stellar atmosphere is $n_e \approx 10^{23} m^{-3}$ equivalent to photosphere plasma number density, the upper limit of photosphere electron current limits corresponding to non-relativistic and near-relativistic strong shock waves respectively, are approximated by $J_e \approx 10^9 A$ and $J_e \approx 10^{12} A$ at solar photosphere. When we consider propagating slow shock wave, the electron current limit for non-relativistic slow shock wave and near-relativistic slow shock wave are obtained as $J_e \approx 10^5 A$ and $J_e \approx 10^{7.5} A$ respectively for $n_e \approx 10^{19} m^{-3}$ electron number density.

When we use maximum electron number density, $n_e \approx 10^{23} m^{-3}$, the maximum electron current limits corresponds to slow near-relativistic shock wave are approximated by $J_e \approx 10^9 A$ and $J_e \approx 10^{10.5} A$ respectively. The over-voltage electron current flow at small local region of stellar atmosphere releases a huge amount of energy even in the absence of pre-existed magnetic field. The SWIF-1SQR model, natural model predicts both lower limit and upper limit of intense electron current that triggers stellar explosive events. SWIF-1SQR model supports that the source of stellar explosive energy is the intensely unstable current flowing through high conductivity medium in connection with non-linear effects of fast propagating mechanical wave fields and electromagnetic field. Let we consider a flare is formed at small local region of radius 100m spherical coordinated.

Using the concept of plasma imploding to convergence region that fulfills spherical symmetry of radial motion during the first phase of flare as a precursor of impulse flare predicts the flare intensity. Table-1, clearly explains the electron current limit of first phase of flaring process followed by CMEs at negligible pre-existed magnetic field region of star. On the basis of SWIF-1SQR model, the primary flash stage of flare emits a short lived electromagnetic wave; see the last column of Table-1 that foresees the shock induced radiation frequency (Hz).

Solar flares at	Minimum current (J_e) limit (amp)	Maximum current (J_e) limit (amp)	Induced magnetic field (B) minimum limit (G)	Induced magnetic field (B) minimum limit (G)	Shock induced radiation frequency (Hz)
Photosphere	10^5	10^{12}	6.29×10^4	6.29×10^{10}	9.92×10^{13} to 9.92×10^{16}
Chromosphere	3.45×10^3	3.45×10^6	2.17×10^3	2.17×10^6	3.1×10^{15} to 3.1×10^{18}
Corona	3.45	3.45×10^3	2.17	2.17×10^3	3.09×10^{17} to 3.09×10^{20}

Table-1: *The upper and lower expected limits of electron current and shock wave induced magnetic fields associated with shock induced radiation frequency (calculated values).*

The Table-1 is established from Eq.(2.98), specifically for first phase of flaring may be followed by erupting of CME at negligible pre-existed magnetic field region. The non-thermal radiation, shock induced radiation, frequency of electromagnetic wave spectrum is obtained from Eq.(2.98). It indicates the electromagnetic wave burst during flare and CMEs at negligible pre-existed magnetic field region.

Here, we assumed that the electron number density limit associated with fast imploding shock surfaces is approximated based on observational evidences order of $n_e \approx 10^{19} m^{-3}$, $10^{16} m^{-3}$ and $10^{12} m^{-3}$ for photosphere, chromosphere and corona respectively. The electron temperature distribution that suffices a minimum requirement are approximated as $4.2 \times 10^3 K$, $2.0 \times 10^5 K$ and $2.0 \times 10^6 K$ of photosphere, chromospheres and corona respectively, calculated value. Based on calculated data at Table-1, when a shock wave induced stellar (solar) flare is occurred at photosphere, electromagnetic wave in the range of spectrum band between infrared to ultraviolet is emitted. At chromosphere electromagnetic wave in the range of spectrum band between visible light and soft x-ray is emitted during flaring time, first stage of flare. At rare

dense solar corona the primary shock wave induced flares emit hard x-ray and soft x-ray at first phase of flare stage.

This analytically predicted data is strongly supported by several observational evidences obtained from NASA. The first radio astronomical observation of the sun at 160MHz was conducted by Grote Reber in 1943 [315]. Nowadays, ground-based radio telescopes observe the sun in frequency range from 15MHz up to 400GHz. The fast development of radio astronomy revealed new peculiarities on the stellar activities such as explosive events related to flares. Microwave bursts which occurred 1–4 minutes before the onset of flares have spectral fine structures with relatively weak intensities and very short timescales is observed from solar atmosphere. The dynamic microwave spectrum during the pre-flare and impulsive phases in the frequency range from 0.2 to 1.4 GHz also analyzed [316]. These observationally detected frequencies are the range we predicted by SWIF model, see Table-1 and Table-2.

The interpretation of electron dominated shock process is a primary channel of energy conversion mechanism. The electron dominated shock process may be followed by proton dominated shock process at flash stage of flares. As we have formulated the SWIF model before, in chapter 2 -3, the flare radiation emission can be predicted from range of radio spectrum to gamma ray spectrum, see Table-1 and Table-2. This theoretical energy prediction is strongly supported by the observational evidences. Solar flares have been observed on the Earth through the range of radio wave lengths capable of penetrating the Earth's atmosphere, from $\lambda \approx 4mm$ to $\lambda \approx 60 m$ [317]. During flaring time energy recorded by Gamma-Ray Spectrometer (GRS) on SMM is in the range from 0.3 to 10 MeV and beyond with a tendency to flatten around 1 MeV, and the contribution of nuclear lines above 1 MeV is clearly observed [318]. Table-2 shows the amount of predicted stored magnetic energy at 100m radius local spherical cavity triggered by strong imploding shock surfaces in the absence of pre-existed magnetic field.

Solar flares at	Induced magnetic field (B) minimum limit (G)	Induced magnetic field (B) minimum limit (G)	Stored magnetic energy (ergs) minimum limit	Stored magnetic energy (ergs) maximum limit	Shock induced cyclotron frequency (Hz)
Photosphere	6.29×10^4	6.29×10^{10}	1.72×10^{14}	1.72×10^{27}	1.76×10^{11} to 1.76×10^{17}
Chromosphere	2.17×10^3	2.17×10^6	1.87×10^{11}	1.87×10^{17}	6.1×10^9 to 6.1×10^{12}
Corona	2.17	2.17×10^3	1.87×10^5	1.87×10^{11}	6.1×10^6 to 6.1×10^9

Table-2: *The magnetic energy stored at small local region associated with corresponding cyclotron frequency due to gyro-resonance of energetic electrons.*

The shock wave induced magnetic field is highly compressed by the imploding ambient plasma. When the compressible shock induced magnetic field is organized, built up, it releases, suddenly, the stored magnetic energy of $1.87 \times 10^5 \text{ ergs}$ to $1.72 \times 10^{27} \text{ ergs}$ at stellar atmosphere, see Table-2, estimated value. This induced magnetic energy is enough to built-up flares and CMEs in the absence of pre-existed magnetic field. At the first phase of the flare, electrons are non-thermally accelerated due to shock surface (i.e., frequency range $9.92 \times 10^{13} \text{ Hz}$ to $3.09 \times 10^{20} \text{ Hz}$) and induced magnetic field (i.e., frequency range $6.1 \times 10^6 \text{ Hz}$ to $1.76 \times 10^{17} \text{ Hz}$) for negligible pre-existed magnetic field.

As we have seen from Table 2, the flying CMEs may be created at lower part of solar atmosphere and it emits radio wave (i.e., radio wave burst). The primary strong shock wave at stellar corona emits x-ray spectrum (i.e., 3.1×10^{17} to 3.1×10^{20}) from small local region radius, see Table-2. This theoretical energy prediction is strongly supported by the observational evidences, see chapter 1. The SWIF-1SQR model legalizes the formation of stellar flares associated with CMEs in the absence of pre-existed magnetic field. The observed energy from flares associated with CMEs is predicted by SWIF-1SQR model in the absence of pre-existed magnetic field, quite solar region. Moreover, the shock induced magnetic field is organized within small fraction of time that makes the flare to be intense enough before its decaying. The hard x-ray telescope detected gradual increases of flaring in $13 - 23 \text{ keV}$ [319]. Here, we proposed that the shock induced magnetic field is in a self-organized state that provides a strong magnetic pressure forms CMEs during flaring. We believe that measuring the life time of small

flares, flare duration time, which is modeled by SWIF-1SQR model is so difficult. However, we can predict that duration of flare is faster than the time evolution on plasma acoustic velocity.

5.4. Endorsement of SWIF-2SAR model Associated with CMEs

The second part of SWIF model, SWIF-2SAR, also agreeably describes the stellar (solar) explosive events in general form. The enhancement of strong pre-existed magnetic field in to SWIF-1SQR model makes the process is so complex and energetic. During evolution of SWIF-2SAR model, the accelerated charged particles are interacted with the pre-existed magnetic field and fast propagating shock waves. The pre-existed magnetic field can be decayed or grow by the propagating fast moving shock surfaces. The pre-existed magnetic field develops instability and can interact with the shock induced magnetic fields and propagating shock waves through high conductivity medium. In SWIF-2SAR model the Alfvén kinetic plays a crucial role in particle acceleration and electromagnetic wave burst process. As we have seen in chapter 3, section 3.10, when the pre-magnetized PVR is developed at local region, a huge amount of magnetic energy is stored and released suddenly in the form of heat energy, radiation energy and kinetic energy.

For instance, let consider a 100m radius of magnetized PVR is created at stellar atmosphere of 1G magnetic field intensity. The stored magnetic field is assumed as consisting of non-deformed magnetic field lines associated with imploding electron number density, dynamic boundary layer, order of 10^{19} , 10^{16} and 10^{12} m^{-3} on photosphere, chromosphere and corona respectively. The imploding magnetized electrons emit energy of 1.24 *meV* to 1.24 *keV* at first phase of the flare; see Table-3, below. Table-3 explains the Alfvén wave, emitted radiation energy and non-thermal frequency range of accelerated electrons through magnetized plasma during flaring. This is modeled by SWIF-2SAR, as the primary flash is detected by telescopes. A second phase of flash is followed it, and it decays exponentially as time in progress.

Solar flares at	Alfven velocity (m/s)	Electron emitted energy (eV)	Stored pre-existed magnetic field (T)	Electromagnetic Spectrum range	Non-thermal radiation frequency (Hz)
Photosphere	2.95×10^4	1.24×10^{-3}	1.0×10^{-4}	Microwaves to infrared waves	3.0×10^{11}
Chromosphere	9.34×10^5	1.24	1.0×10^{-4}	Visible light	3×10^{14}
Corona	9.34×10^7	1.24×10^3	1.0×10^{-4}	Ultraviolet to soft x- rays	6.1×10^{17}

Table-3: The spectrum range and non-thermal radiation frequency is calculated for 1G pre-existed magnetic field during the expected first flash of flaring process at solar atmosphere.

When the pre-existed magnetic field is compressed by fast propagating shock wave at small local region, charged particles are accelerated non-thermally, see Table-3. The SWIF-2SAR model predicts the flare energy reaches up to order of 10^{36} ergs, it depends on strength of compressing shock wave trains associated with electron number density and pre-existed magnetic field. The predicted impulse flare energy is strongly supported by observational evidences [320].

The fast propagating shock wave integrated with fast magnetic reconnection (FMR) intensifies the stored magnetic energy, $B^2/2\mu_0$, induced electric field energy, $\epsilon_0 E^2$, and velocity shock potential, VSP, of the local system. The evolution of SWIF-2SAR model is so complex in nature. Moreover, using the measurement of magnetic field over SWIF model at stellar (solar) atmosphere can predict the released amount of energy from small local region; see chapters 2, 3 and 4.

The SWIF-2SAR model well describes and predicts the amount of released energy at upper region of stellar (solar) atmosphere, corona, where inhomogeneous magnetic field is dominant. For instance if the lower current limit, $J_e \approx 10^5$ A is predicted by SWIF-1SQR model, that flows along stellar (solar) magnetic flux tubes in-connection with corresponding fast propagation shock surfaces, charged particles will be accelerated non-thermally. And, the magnetic flux is burst due to development of anomalous resistivity. Considering the induced magnetic field surrounding current carrying magnetic field, B_ϕ is independent of ϕ and B_z is independent of z parameters, the azimuthal current induced magnetic field is calculated as $B_\phi = 6.285 \times 10^4$ G at a distance of 100 m away from surface of current carrying magnetic flux

tubes. The surface induced magnetic field B_ϕ is higher than the expected star-spot (sunspot) magnetic field.

When we assumed that $J_e \approx 10^{11} A$ the electron current flowing through stellar (solar) magnetic flux tube, the surrounding induced magnetic field is approximated by $B_\phi = 6.285 \times 10^{10} G$ at a distance of $100 m$ away from surface of current carrying magnetic flux loop. This is much stronger than the current carrying strength of magnetic field. This surface induced magnetic field strongly squeezed the current carrying force free magnetic field. However, the old standard flare model does not answer the question what triggers the intense electron current up to $10^{11} A$ at large length scale of the stellar atmosphere rather the position independent approximation. The SWIF model answers this question clearly with the help of particle kinematic theory in-connection with non-linear behavior of particle and field interaction principle. The top and foot point of closed magnetic flux tubes emit radiation [321]. The energy stored at small local region behind of sonic shock, imploded shock, is predicted from Eq.(3.82c). Here, we took that $M_{A1} > 1/(F + G)$ and $M_{A1} < c_1$ on photosphere, chromosphere and corona with corresponding electron number order of $10^{19} m^{-3}$, $10^{16} m^{-3}$ and $10^{12} m^{-3}$ respectively.

Solar flares at	Alfven Mach number (M_{A1})	Pre-shock magnetic field (T)	Electron mass density (kg/m^3)	Stored energy (ergs) per second (s)	Energy carried by accelerated electron (eV)
Photosphere	23.3	3×10^{-2}	9.11×10^{-12}	-8.22×10^{26}	$-21.8 meV$
Chromosphere	132	3×10^{-2}	9.11×10^{-15}	-1.43×10^{29}	$-2.29 keV$
Corona	1320	3×10^{-2}	9.11×10^{-19}	-1.43×10^{33}	$-2.29 GeV$

Table-4: The amount of released magnetic energy and electron radiation energy is calculated in the presence of pre-existed magnetic field during first phase of faring on solar atmosphere.

The negative sign in Table-4 shows the energy is released from small local compacted region. Energy is stored by compressing and sucking the local material coupled with field and is prepared for intense explosion. When the sonic shock is triggered a flare at photosphere, chromosphere and corona, the accelerated electron carries energy of $21.8 meV$, $2.29 keV$ and $2.29 GeV$ respectively, see Table-2. Table-4 indicates that the SWIF-2SAR model predicts the amount of stored and released energy on stellar (solar) atmosphere. The predicted valued of flare and CMEs energy is strongly supported by the observationally recorded data. So, the SWIF-2SAR model is valued to predict the solar explosive events based on dynamical nature of particle

field interaction principle. The predicted energy range in Table-4 is strongly compatible with observational evidences. From observations, the data of interest are the calibrated concurrent measurement of HXR ($\epsilon \geq 10 \text{ keV}$) and EUV (10-1030Å) emission from a large sample of medium and solar flares obtained by Kane and Donnelly [322]. The plasma motion occurs at length-scales so small that it is soon damped by the turbulence and the by viscosity. In such away the energy is quickly converted in to heat, and conducted by free electrons along the magnetic field lines closer to the place where Nano flare switches on. So as to heat a region of high X-ray emission, a Nano-flare of 10^{17} J should happen where every 20 seconds, and 1000 Nano flares per second should occur in a large active region of $10^5 \times 10^5 \text{ km}^2$.

On the basis of this theory, the emission coming from a big flare could be caused by a series of micro-flares and Nano-flares, not observable individually [323]. Current instruments, such as the Extreme-Ultraviolet Imaging Spectrometer on board Hinode, are not adequately sensitive to the range in which this faint emission occurs, making a confident detection impossible [324]. Recent evidence from the EUNIS sounding rocket has provided some spectral evidence for non-flaring plasma at temperatures near 9 MK in active region cores [325]. The SWIF model well predicts the nature, and energy of Nano-flare and micro flares theoretically.

5.5. Character of FMR incorporated with SWIF model

The concept of fast magnetic reconnection (FMR) theory is mandatory in SWIF model, specifically SWIF-2SAR model, which predicts the released amount of energy, suddenly, on solar atmosphere. The process of magnetic reconnection (MR) is fast that occurred at low density of charged particle region. The shock wave that is generated at magnetic surface makes the duration of reconnection process is as faster as Alfven time scale. The magnetic reconnection process is occurred when the magnetic pressure is much higher than electron and ion dynamic pressure. Based on observational evidences, the magnetic process is occurred in time of 1s to 300s, coupled with small and large flares [226]. This evidences supports our FMR theory incorporated with SWIF model most probably applicable at stellar (solar) active region.

In SWIF model, the FMR theory predicts the reconnection time depends on the intensity of propagating shock wave fronts and charged particle density behind of shock passage. The reconnection time is in the range of between reconnection time in vacuum and Alfven time scale.

On the basis of SWIF-1SQR model, magnetic reconnection process is performed at low density region of high conductivity plasma. The enhancement of fast propagating shock wave makes the reconnection process is fast.

5.6. Endorsement of SWIF model Associated with CMEs

We expect that development of the first part SWIF-1SQR model bears the formation of CMEs from small local region of stellar (solar) atmosphere in the absence of pre-existed force free magnetic field. For instance if the collapsing of PVR is carried on small space scale of 100 m radius local spherical cavity, the imploding electron current in steady state suffices the minimum electron current limit, $J_e \approx 10^5\text{ A}$, see sections 5.2 and 5.3. The imploding strong shock leaves about $B \approx 7.44 \times 10^4\text{ G}$ of minimum limit magnetic field associated with CMEs. This shows that the strength magnetic field of smallest CME is order of one higher than strength of star-spot (sunspot) magnetic field approximated by $3 \times 10^3\text{ G}$ [327].

During collapsing of local PVR if the process is strong enough with upper limit of electron current limit, $J_e \approx 10^{12}\text{ A}$ per unit scale in case of non-relativistic shock wave, the collapsing leaves magnetic field of $B \approx 7.44 \times 10^8\text{ G}$ behind of fast imploding shock wave. This strongest clamp of magnetic field carries huge amount of charged particles approximated up to mass of 10^{17} gm [328]. At the beginning, the emerging CME from the solar surface is very small in size and it grows drastically in size and recedes from surface. It travels a long range distance beyond to Earth's orbit. The flying CME emits non-thermal accelerated charged particles and electromagnetic radiation on its way.

The SWIF-2SAR model is the further phase of SWIF-1SQR model added strong enough magnetic energy integrated with FMR theory through rare dense high conductivity plasma of stellar atmosphere. Based on SWIF-2SAR model, part of force free magnetic field of flux tube moves with the floating CMEs on the atmosphere. This phenomena makes the nature of CME is so complex with variable features of moving huge magnetized plasma dense cloud on the atmosphere. The SWIF-2SAR model nicely describes formation of intense solar flares, CMEs and electromagnetic wave burst at rare plasma density upper region of solar atmosphere, corona.

5.7. Prediction of Electromagnetic Wave Burst from Stellar Flares and CMEs

Based on SWIF model, during existence of solar flares and CMEs, electromagnetic wave burst and particle acceleration would be anticipated. The electromagnetic wave which is emitted from solar flares and CMEs is detected in all kinds of spectrum, as space born observational evidences indicated. The accelerated particles are thermal and non-thermal accelerated particles. The minimum requirement for electromagnetic burst is proposed from the first SWIF-1SQR model, during implosion or explosion of PVR on solar photosphere. For instance, when $n_e \approx 10^{19} m^{-3}$ electron number density is imploded to convergence point associated with sonic shock wave fronts, the shock wave induced electromagnetic wave frequency is calculated as $\nu_r \approx 6.87 \times 10^{12} Hz$ in infrared region of electromagnetic spectrum with corresponding radiation energy of $0.281 meV$, (calculated value). When electrons are imploded to convergence region with high shock Mach number $M_s \approx 10^3$, the calculated electromagnetic wave frequency and corresponding energy are given by $\nu_r \approx 6.87 \times 10^{15} Hz$ (i.e., between visible light and ultraviolet range frequency) and $28.1 eV$ respectively.

When the imploded electrons are reflected at convergence point, the electromagnetic radiation spectrum generated by fast propagating weak shock front also calculated. During explosion, sonic shock produces frequency and energy range $\nu_r \approx 8.25 \times 10^{13} Hz$ (i.e., between visible light and infrared frequency range) and $0.34 eV$ respectively. In case of near relativistic exploding shock wave the frequency spectrum and energy range are calculated as $\nu_r \approx 8.25 \times 10^{14.5} Hz$, (i.e., frequency range between ultraviolet and visible light) and $10.7 eV$ respectively. Generally, the SWIF-1SQR model is agreeably predict the electromagnetic burst during flaring time and releasing of CMEs from solar quite region. Most probably, the electromagnetic wave spectrum in the range between ultraviolet and infrared is investigated from the SWIF-1SQR model due to non-linear effects fast migrating electrons enter to electron runaway condition. The SWIF-1SQR model also predicts the non-thermal charge acceleration due to shock wave induced magnetic field lines.

When the appeared CME has a magnetic field of $B \approx 7.44 \times 10^4 G$ corresponding to minimum shock induced electron current, electrons are accelerated from CME with cyclotron frequency of $\omega_e \approx 4.41 \times 10^7 Hz$ between microwave and radio wave range spectrum. When

the shock wave induced magnetic field associated with CME has $B \approx 7.44 \times 10^8 G$ at initial phase corresponding to maximum limit of shock wave induced electron current, CME emits electromagnetic wave of frequency $\omega_e \approx 4.41 \times 10^{11} Hz$ between infrared and microwave spectrum range. The enhancement of force free magnetic field in to SWIF-1SQR model brings the SWIF-2SAR model. The presence of pre-existed magnetic field increases radiation intensity. The SWIF-2SAR model describes the formation of high frequency electromagnetic waves during flaring, rising of CMEs and magnetic reconnection process. For instance, if $10^{11} A$ current flows through closed magnetic flux tube, the surface induced magnetic field $B = 6.285 \times 10^{10} G$ surrounding magnetic flux tube emits $\omega_e \approx 3.73 \times 10^{13} Hz$ in the spectrum range between visible light and infrared.

Generally, the SWIF model predicts the electromagnetic waves starting from radio wave up to ultraviolet wave on solar photosphere during flaring and rising CMEs. At the upper region of stellar (solar) atmosphere, corona, the SWIF model predicts the formation of high frequency electromagnetic wave, X-ray and gamma ray during impulse flaring and CMEs. The SWIF model predicts where a huge mass ejection, known as CMEs is released not only from corona but also possible from surface that is photosphere.

5.8. Fitting of SWIF model with Space Experiment

The SWIF model is characterized by plasma implosion of small local region followed by strong explosion. Since the imploding process which is described by SWIF model is fast in very small local region, it may be difficult to detect during observation. The most detectable energetic eruptions on the stellar (solar) atmosphere are the activity carried on during explosion of localized plasma. The explosion covers a large area that insures flares and CMEs. In 2012, Dr. Nat Gosplwamy reported that by measuring the geometrical properties of CMEs flux rope and the leading shock observed on 2010 June 13 by the *Solar Dynamics Observatory (SDO)* mission's Atmospheric Imaging Assembly he determine the Alfvén speed and the magnetic field strength in the inner corona at a heliocentric distance of $\sim 1.4R_{\odot}$. He derived and found the Alfvénic Mach number (M) declined from 3.7 to 1.5 indicating shock weakening within the field of view of the imager. The shock formation coincided with the appearance of a type II radio burst at a frequency of ~ 300 MHz (harmonic component), providing an independent confirmation of the shock. As he investigated, the shock compression ratio derived from the

radio dynamic spectrum was found to be consistent with that derived from the theory of fast-mode MHD shocks.

On the basis of space experiment, this is a best evidence to theorize the shock wave induced flares on stellar (solar atmosphere). He found that by deriving the upstream plasma density from the emission frequency of the associated type II radio burst, he determined the coronal magnetic field to be in the range 1.3–1.5 G. The derived magnetic field values are consistent with other estimates in a similar distance range. This work demonstrates that the EUV imagers, in the presence of radio dynamic spectra, can be used as coronal magnetometers [329]. The experimental values which are recorded from solar atmosphere such as radiation frequency, energy during flare time can be predicted by using SWIF model. For instance the type II radio burst at a frequency of ~ 300 MHz, reported in 2012, [329], is in the range estimated in Table-2 on solar coronal during first phase of flare process.

By relating our theoretical work of modeling with space experimental work, the enhancement of Alfvénic kinetic energy makes the flare process is so complex and highly energetic. Another important observational work shows that three types of low-frequency non-thermal radio bursts are associated with coronal mass ejections (CMEs): Type III bursts due to accelerated electrons propagating along open magnetic field lines, type II bursts due to electrons accelerated in shocks, and type IV bursts due to electrons trapped in post-eruption arcades behind CMEs [330].

5.9. Summary

As we have discussed in chapter 5 sections 5.1 and 5.6, the predictable physical phenomena, by SWIF model, is concomitant with the observable space experiment. On the basis of observational evidences, the second flash phase covers large volume in comparison with first flash. The SWIF model predicts the formation of stellar flares associated with CMEs and electromagnetic wave burst during the first and second flash. In chapters 2, 3 and 4, we have formulated many mathematical formulas which describe and predict the observable physical quantities to relate with space experiment. In this preceded chapters, we introduced a new idea of that explains how stellar flare, CMEs and electromagnetic wave burst are occurred. On basis of SWIF model, all kinds of electromagnetic wave spectrums are emitted from stellar (solar flare).

The enhancement of pre-existed magnetic field makes the flare associated with CMEs is so strong and complex. The amount of flare energy is estimated in the range of 10^{11} erg to 10^{33} erg , see Table-2 and Table-4. The theoretical predictable physical quantities are attendant with the result obtained from space experiments, see sections 5.2 – 5.7 in chapter 5.

Generally, we suggest that the theoretical SWIF model of stellar (solar) flare associated with CMEs model describes the solar explosive events at both solar maxima and minima activities.

CHAPTER 6

6. CONCLUSION AND REMARKS

As we mentioned in chapters 2 and 3, the surface of uniformly rotating star (sun) at steady state situation generates instantaneous static electric field and surface magnetic field. Charged particles are instantly separated enough on stellar surface. The strength of surface induced electric field and magnetic field is determined by the strength of instantaneous charge separation process. Thus, the strength of surface induced electric field and magnetic field depends on the age of star. As we theorized, the surface charged particle distribution creates electron plasma sheath, thin non-thermal electron cloud layer, most probably in steady state. The quasi-neutrality plasma principle is violated on the stellar surface, electron plasma sheath; we called it critical layer, CL. The thickness of CL is approximated by Debye length, *see* chapter 2, Eq.(2.6a), (2.7) and (2.8) for negligible effects of centrifugal force, surface magnetic field and surface gravitational force in steady state condition.

However, the surface electron distribution is determined by the ratio of non-thermal surface mechanical energy to thermal surface energy. When the stellar surface thermal energy is smaller than the surface non-thermal mechanical energy, the surface electron distribution is in non-thermal situation, *see* chapters 2 and 3. This kind of star is known as cool surface star, it may not be included the young active sun. The cool surface of star is most probably not convective star. The stellar explosive events are expected rare phenomenon at surface of cool star. For deep understanding, *see* Fig.2.1, in case of negligible surface magnetic fields in chapter 2. And, the presence of deformable surface magnetic field makes the situation is complex, *see* in chapter 3. The small perturbation of stellar surface electron cloud brings small and large explosive events. The stellar atmospheric explosive events have been modeled in chapters 2, 3 and 4, theoretically. This theoretical model is natural and three dimensional that describes all kinds of stellar (solar) explosive phenomenon both in the absence of magnetic field as well as in the presence of magnetic field.

The small perturbation of surface plasma, CL, associated with the surface periodic oscillation, plasma convection, and formation of radial electric current introduces non-linear behavior of stellar surface; *see* chapters 2 and 3, sections 3.6 and 3.7. Using the concept of polar

and azimuthal symmetry condition, the radial surface electric current (i.e., electron current) generates non-radial magnetic field on the stellar surface. This non-radial surface induced micro magnetic field interacts with the pre-existed magnetic flux that is emerged from stellar interior. In chapter 2, we have driven the purely non-radial surface induced magnetic field, *see* Eqs.(2.24), (2.25a) and (2.25b) that confined the surface charged particles. The main mechanism for induction of non-radial surface magnetic field is the tendency of electron migration to outer layer of stellar surface before radiation occurred at surface. The surface plasma convection process triggers electron diffusion because heat energy is transported from interior to surface adiabatically, *see* chapter 2, section 2.10 and chapter 3, section 3.5 and 3.6. Generally, the non-radial components of force free magnetic field exterior of the star (sun) confines the surface ionized plasma or material from dispersing to surrounding of high vacuum potential (VP) space against the gravitational force.

Because of the small disturbance at the surface, Alfven wave and sound wave are discontinuous; of course there is no demarked boundary like sold body. This discontinuity creates a jump in physical quantities on the stellar surface. The agent of the discontinuity is the plasma dynamics that creates a steep gradient in physical quantities in steady state. The sound wave propagates from stellar interior outward is reflected back at the surface, CL. The Alfven wave that is propagated from deep photosphere to outer region critically is changed its magnitude at stellar surface. The discontinuity in Alfven wave and sound wave creates turbulence on surface, CL. Thus, the surface is characterized by propagating shock waves, for brief understanding, *see* chapter 2, section 2.6 and 2.7, in chapter 3, sections 3.6 - 3.8. The motion of plasma observed on surface is supported by the theory aforementioned a moment before. The dynamical nature of surface plasma associated with electromagnetic fields and radiation process is the expected sources of stellar explosive events at small local region. In chapter 2, we have developed the model of stellar explosive events independent of magnetic field, SWIF-1SQR model. The SWIF-1SQR model well describes the existence of Nano flares and micro flares at stellar surface, most probably occurred at photosphere and chromosphere as well as impulsive flares. Since SWIF-1SQR model is independent of effects of pre-existed magnetic field, it may cause mounting CMEs at quite region, behind of implosive shock waves associated with imploding electron beam.

However, the closed loop of magnetic flux tubes may hinder this kind of flares from appearing. In this case, the occurrence of CMEs may be clearly observable rather than the appearance of flares in the absence of pre-existed magnetic field. Based on observational evidences, this phenomenon seems that appearance of CMEs is independent of solar flares. Although, flare are expected to be occurred at deep photosphere are not observable, a clamp of magnetized plasma, CMEs, is ejected out from surface to surrounding space, see Eqs.(2.100a) and (2.100b) that confines the floating clamp of plasma on solar atmosphere. CMEs emit electromagnetic radiation and particle radiation. Generally, the SWIF-1SQR model is independent of pre-existed magnetic reconnection (MR) process at higher plasma beta (i.e., $plasma - \beta > 1$) region of stellar atmosphere. The radiation emitted from CMEs is shock wave induced radiation, cyclotron radiation and synchrotrons radiation, see chapter 5. The occurrence of CMEs varies during the stellar (solar) activities cycle as evidences are observed from SOHO, YOHKOH, LASCO, and SDO... etc. To explain the nature of intense stellar explosive events, it is mandatory to see for magnetic field activities.

Throughout evolution of SWIF-1SQR model, the instantaneous charge separation theory, a small displacement migration of charged particles that suffice charged particle runaway condition is the heart of SWIF-1SQR model. The oscillatory nature of charged particles at convergence region and dynamic boundary of cavity, spherical harmonic nature, provides electromagnetic wave burst and particle radiation process. We have investigated that the SWIF-1SQR model well explains the stellar (solar) explosive event such as Nano-flares and micro flares even impulsive flares and CMEs. The SWIF-1SQR model is developed based on the solar observational evidences of solar quiet region (weak magnetic field region). The SWIF-1SQR model estimates the electrical energy required for flares and electromagnetic wave burst associated with CMEs, detectable by telescopes. The concept of SWIF-1SQR model can be applied on the Earth atmosphere for lightning (i.e., due to strong charge migration theory), formation of atmospheric blast wave (i.e., due to mechanical velocity shock potential) and for building of nuclear explosive weapons from plasma fluid. We believe that the SWIF-1SQR model explains the nature of almost all flares of young stars such as Sun. And, the SWIF-1SQR model enables us to predict the amount of mass ejected from sun during eruption, to predict energy carried by accelerated charged particles and CMEs that may heat the Earth atmosphere.

As we have discussed in chapter 3, the SWIF-2SAR model, that models the strong solar eruptive events that are intensified by the stiff force free magnetic field. The propagating shock wave is the main mechanism that triggers sudden explosion and particle acceleration at high conductivity plasma medium. The fast moving non-thermal electrons and ions along magnetic field lines as well as across magnetic field lines induced instantly static electric field and fast propagating shock waves. The propagating shock wave instantly compresses the magnetic field and high conductivity plasma in fraction of seconds at small local region. Inside the compacted plasma, at small local region, the magnetic field lines are highly twisted. In this case, the magnetic curvature radius is very smaller than the characteristic scale length of local system. Annihilation and formation of magnetic field inside the compacted or collapsed local region is the expected process that leads to sudden change in entropy (i.e., change behaviors of physical quantities). The compacted magnetized particles absorb energy from shock wave and magnetic field due to non-linear behavior of particle wave interaction process. The shocked particles are accelerated and emitted radiations in all kinds of spectrum. The energy conversion process due to shock wave at the small local region is so complex, it needs a further research. However, it is clear that the source of particle acceleration during conversion of energy is non-linear behavior of particle-field interaction, particle-particle interaction and field-field interaction process.

It is clearly explained that in chapter 3, section 3.8, the evolution of magnetized PVR is determined by the intense imploding electron jet and strong force free pre-existed magnetic field. Thus, the SWIF-2SAR model is developed based on the idea of particles kinematic theory associated with fluid dynamics, evolution of local electric field and magnetic field (i.e., Maxwell's equations). However, based on SWIF-2SAR model, the fast propagating non-variable shock wave generates instantly static electric field, we called it electrostatic shock wave, see section 3.8. In some specific case, the shock wave induced steep electrostatic potential in connection with gradient of magnetic field across moving shock wave accelerates charged particles in steady state situation, see section 3.8, Eq.(3.41a). Electrons distribution inside magnetized PVR is controlled by strength of magnetic field before shock passage.

During stellar (solar) explosive events, all kinds of electromagnetic wave spectrums are observed using ground based and space installed telescopes above the Earth atmosphere. Those observational evidences are strongly supported by SWIF model, see chapter 1, section 1.1 – 1.3

and chapter 2 and chapter 3. The comparison between SWIF-1SQR model and SWIF-2SAR model is clearly explained in chapter 5. We relate the theoretical SWIF model with some old flare models and modern space experiments results. The quantities which can be predicted by SWIF model is agreeably with space experimental value; see section 5.7 chapter 5. Plasma materials are accelerated and emit radiation behind of shock wave, see table-2 and table-4 in chapter 5, in specific analytical calculation. The enhancement of pre-existed magnetic field in to SWIF-1SQR model integrated with fast magnetic reconnection (FMR) provides additional stored energy. The topological change of magnetic field lines are initiated by fast propagating shock surfaces through rare dense of high conductivity plasma. Based on the SWIF model incorporated with FMR theory, explosive events are occurred everywhere on stellar atmosphere. Moreover, the impulse explosive events are probably occurred at strong force free pre-existed magnetic field region (i.e., modeled by SWIF-2SAR). While micro flares and Nano flare are also probably occurred at weak negligible pre-existed magnetic field region (i.e., modeled by SWIF-1SQR). In this scenario, the old theory, slow magnetic reconnection theory (SMR) is replaced by fast magnetic reconnection (FMR) theory, due to enhancement of fast propagating shock theory.

The SWIF model is testable and preferable to describe the nature of stellar explosive events. Necessary formulas have been articulated here and basic idea of the SWIF model also has been explained well. However, it needs a further advanced studying to simulate in spherical or cylindrical coordinates so as to explain the nature of physical phenomena. We believe the SWIF model strongly supports the coronal heating mechanism in-connection with stellar (solar) daily activities. In future work, I have stiff interest to study deeply on flare formation in connection with magnetic reversal, stellar activities, and coronal heating mechanism. The SWIF model predicts the mechanism of explosive events such as flares and CMEs from both quiet region and active region. The main cause of flares and CMEs is proposed as the complex nature of completely ionized plasma in-connection with particle-field interaction principle that brings intense electron over-voltage at high conductivity rare dense medium. The non-linear effects of particle-wave interaction process is considered as the agent of strong charge separation process leads to develop unknown potential (i.e., VSP through high conductivity plasma) that generates a strong stream of electron flow (i.e., lightning, electron discharge). As FMR is carried on force free magnetic flux tubes, intense flares and CMEs are created at stellar (solar) atmosphere.

Appendix:

1. Maxwell's equation

In MKS unit, which is the default unit we use in this thesis

$$\vec{\nabla} \cdot \vec{D} = \rho \quad \text{Gauss's law for electric field} \quad (\text{A1})$$

$$\vec{\nabla} \cdot \vec{H} = 0 \quad \text{Gausses's law for magnetic field} \quad (\text{A2})$$

$$\vec{\nabla} \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad \text{Amper's law} \quad (\text{A3})$$

$$\vec{\nabla} \times \vec{B} = \mu_0 \vec{J} + \mu_0 \frac{\partial \vec{D}}{\partial t} \quad \text{Farad's law} \quad (\text{A4})$$

Where,

$$\vec{H} = \mu_0 \vec{B} \quad \text{and} \quad \vec{D} = \epsilon_0 \vec{E}$$

$$\vec{D} \quad \text{Electric displacement (C/m}^2\text{)}, \quad \vec{E} \quad \text{electric displacement (V/m)}$$

$$\vec{B} \quad \text{Magnetic field (T or V.s/m}^2\text{)}, \quad \vec{H} \quad \text{magnetic field intensity (A/m)}$$

$$\rho \quad \text{Volume charge density (C/m}^3\text{)}, \quad \vec{J} \quad \text{current density (A/m}^2\text{)}$$

$$\mu_0 = 4\pi \times 10^{-7} \text{ (H/m)} \quad \text{and} \quad \epsilon_0 = (1/36\pi) \times 10^{-9} \text{ (F/m)}, \quad \text{permeability and permittivity of free space}$$

In CGS unit for reference:

$$\vec{\nabla} \cdot \vec{D} = 4\pi\rho \quad \text{Gauss's law for electric field} \quad (\text{A5})$$

$$\vec{\nabla} \cdot \vec{H} = 0 \quad \text{Gausses's law for magnetic field} \quad (\text{A6})$$

$$\vec{\nabla} \times \vec{E} = -\frac{1}{c} \frac{\partial \vec{B}}{\partial t} \quad \text{Amper's law} \quad (\text{A7})$$

$$\vec{\nabla} \times \vec{B} = \frac{4\pi}{c} \vec{J} + \frac{1}{c} \frac{\partial \vec{D}}{\partial t} \quad \text{Farad's law} \quad (\text{A8})$$

2. Explicit form of vector operation

Let $\hat{e}_1$, $\hat{e}_2$ and $\hat{e}_3$ be orthogonal unit vectors associated with the coordinate directions specified in the headings on the left, and A_1 , A_2 and A_3 be the corresponding components of $\vec{A}$. Then

a. Cylindrical coordinate (r, φ, z)

$$\vec{\nabla}\psi = \hat{e}_1 \frac{\partial \psi}{\partial r} + \hat{e}_2 \frac{1}{r} \frac{\partial \psi}{\partial \varphi} + \hat{e}_3 \frac{\partial \psi}{\partial z} \quad (\text{A9})$$

$$\vec{\nabla} \cdot \vec{A} = \frac{1}{r} \frac{\partial}{\partial r} (r A_1) + \frac{1}{r} \frac{\partial A_2}{\partial \varphi} + \frac{\partial A_3}{\partial z} \quad (\text{A10})$$

$$\vec{\nabla} \times \vec{A} = \hat{e}_1 \left(\frac{1}{r} \frac{\partial A_3}{\partial \varphi} - \frac{\partial A_2}{\partial z} \right) + \hat{e}_2 \left(\frac{\partial A_1}{\partial z} - \frac{\partial A_3}{\partial r} \right) + \hat{e}_3 \frac{1}{r} \left(\frac{\partial}{\partial r} (r A_2) - \frac{\partial A_1}{\partial \varphi} \right) \quad (\text{A11})$$

$$\vec{\nabla}^2 \psi = \frac{1}{r} \frac{\partial}{\partial r} \left(r \frac{\partial \psi}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 \psi}{\partial \varphi^2} + \frac{\partial^2 \psi}{\partial z^2} \quad (\text{A12})$$

$$(\vec{\nabla}^2 \vec{A})_r = \vec{\nabla}^2 A_1 - \frac{1}{r^2} A_1 - \frac{2}{r^2} \frac{\partial A_3}{\partial \varphi} \quad (\text{A13})$$

$$(\vec{\nabla}^2 \vec{A})_\varphi = \vec{\nabla}^2 A_3 - \frac{1}{r^2} A_3 + \frac{2}{r^2} \frac{\partial A_1}{\partial \varphi} \quad (\text{A14})$$

$$(\vec{\nabla}^2 \vec{A})_z = \vec{\nabla}^2 A_3 \quad (\text{A15})$$

$$(\vec{A} \cdot \vec{\nabla}) \vec{B} = \hat{e}_1 \left(A_1 \frac{\partial B_1}{\partial r} + \frac{A_3}{r} \frac{\partial B_1}{\partial \varphi} + A_3 \frac{\partial B_1}{\partial z} - \frac{A_3 B_3}{r} \right) + \hat{e}_2 \left(A_1 \frac{\partial B_3}{\partial r} + \frac{A_3}{r} \frac{\partial B_3}{\partial \varphi} + A_3 \frac{\partial B_3}{\partial z} + \frac{A_3 B_3}{r} \right) + \hat{e}_3 \left(A_1 \frac{\partial B_3}{\partial r} + \frac{A_3}{r} \frac{\partial B_3}{\partial \varphi} + A_3 \frac{\partial B_3}{\partial z} \right) \quad (\text{A16})$$

b. Spherical coordinate (r, θ, φ)

$$\vec{\nabla} \psi = \hat{e}_1 \frac{\partial \psi}{\partial r} + \hat{e}_2 \frac{1}{r} \frac{\partial \psi}{\partial \theta} + \hat{e}_3 \frac{1}{r \sin \theta} \frac{\partial \psi}{\partial \varphi} \quad (\text{A17})$$

$$\vec{\nabla} \cdot \vec{A} = \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 A_1) + \frac{1}{r \sin \theta} \frac{\partial}{\partial \theta} (\sin \theta A_2) + \frac{1}{r \sin \theta} \frac{\partial A_3}{\partial \varphi} \quad (\text{A18})$$

$$\vec{\nabla} \times \vec{A} = \frac{\hat{e}_1}{r \sin \theta} \left(\frac{\partial}{\partial \varphi} (\sin \theta A_3) - \frac{\partial A_2}{\partial \theta} \right) + \hat{e}_2 \left(\frac{1}{r \sin \theta} \frac{\partial A_1}{\partial \varphi} - \frac{\partial}{\partial r} (r A_3) \right) + \frac{\hat{e}_3}{r} \left(\frac{\partial}{\partial r} (r A_2) - \frac{\partial A_1}{\partial \theta} \right) \quad (\text{A19})$$

$$\vec{\nabla}^2 \psi = \frac{1}{r} \frac{\partial^2}{\partial r^2} (r \psi) + \frac{1}{r^2 \sin \theta} \frac{\partial}{\partial \theta} \left(\sin \theta \frac{\partial \psi}{\partial \theta} \right) + \frac{1}{r^2 \sin \theta} \frac{\partial^2 \psi}{\partial \varphi^2} \quad (\text{A20})$$

$$(\vec{\nabla}^2 \vec{A})_r = \vec{\nabla}^2 A_1 - \frac{1}{r^2} A_1 - \frac{2}{r^2} \frac{\partial A_2}{\partial \theta} - \frac{2 \cos \theta}{r^2 \sin \theta} A_2 - \frac{2}{r^2} \frac{\partial A_3}{\partial \varphi} \quad (\text{A21})$$

$$(\vec{\nabla}^2 \vec{A})_\theta = \vec{\nabla}^2 A_2 - \frac{1}{r^2 \sin^2 \theta} A_2 + \frac{2}{r^2} \frac{\partial A_1}{\partial \theta} - \frac{2 \cos \theta}{r^2 \sin^2 \theta} A_2 - \frac{2}{r^2} \frac{\partial A_3}{\partial \varphi} \quad (\text{A22})$$

$$(\vec{\nabla}^2 \vec{A})_\varphi = \vec{\nabla}^2 A_3 - \frac{1}{r^2 \sin^2 \theta} A_3 + \frac{2}{r^2 \sin \theta} \frac{\partial A_1}{\partial \varphi} + \frac{2 \cos \theta}{r^2 \sin^2 \theta} \frac{\partial A_2}{\partial \varphi} \quad (\text{A23})$$

$$(\vec{A} \cdot \vec{\nabla}) \vec{B} = \hat{e}_1 \left(A_1 \frac{\partial B_1}{\partial r} + \frac{A_2}{r} \frac{\partial B_1}{\partial \theta} + \frac{A_3}{r \sin \theta} \frac{\partial B_1}{\partial \varphi} - \frac{A_2 B_2 + A_3 B_3}{r} \right) + \hat{e}_2 \left(A_1 \frac{\partial B_2}{\partial r} + \frac{A_2}{r} \frac{\partial B_2}{\partial \theta} + \frac{A_3}{r \sin \theta} \frac{\partial B_2}{\partial \varphi} - \frac{A_3 B_3}{r} \cot \theta \right) + \hat{e}_3 \left(A_1 \frac{\partial B_3}{\partial r} + \frac{A_2}{r} \frac{\partial B_3}{\partial \theta} + \frac{A_3}{r \sin \theta} \frac{\partial B_3}{\partial \varphi} + \frac{A_3 B_1}{r} + \frac{A_3 B_3}{r} \cot \theta \right) \quad (\text{A24})$$

Bibliography

1. Krupp, E.C., 2003. *Echoes of the ancient skies: The astronomy of lost civilizations*. Courier Corporation.
2. Lockyer, J.N., 2006. *The dawn of astronomy: a study of temple worship and mythology of the ancient Egyptians*. Courier Dover Publications.
3. Muller, P.M. and Stephenson, F.R., 1975. The accelerations of the Earth and Moon from early astronomical observations. In *Growth Rhythms and the History of the Earth's Rotation* (pp. 459-533).
4. Galilei, G. and Scheiner, C., 2010. *On sunspots*. University of Chicago Press.
5. Dear, P., 1987. Jesuit mathematical science and the reconstitution of experience in the early seventeenth century. *Studies in History and Philosophy of Science Part A*, 18(2), pp.133-175.
6. Débarbat, S., The French Savants, and the Earth–Sun Distance.
7. Newton, I., 1999. *The Principia: mathematical principles of natural philosophy*. Univ of California Press.
8. Arlt, R., 2011. The sunspot observations by Samuel Heinrich Schwabe. *Astronomische Nachrichten*, 332(8), pp.805-814.
9. Wilson, R.M., 1998. A comparison of Wolf's reconstructed record of annual sunspot number with schwabe's observed record of 'clusters of spots' for the interval of 1826–1868. *Solar Physics*, 182(1), pp.217-230.
10. Izenman, A.J., 1985. JR Wolf and the Zürich sunspot relative numbers. *The Mathematical Intelligencer*, 7(1), pp.27-33.
11. Rüdiger, G., 1989. *Differential rotation and stellar convection: Sun and solar-type stars* (Vol. 5). Taylor & Francis.
12. Cliver, E.W., 2006. The 1859 space weather event: Then and now. *Advances in Space Research*, 38(2), pp.119-129.
13. Hentschel, K., 2002. *Mapping the spectrum: Techniques of visual representation in research and teaching*. Oxford University Press on Demand.
14. Malville, J.M., 2014. THE ECLIPSE EXPEDITIONS OF THE LICK OBSERVATORY AND THE DAWN OF ASTROPHYSICS. *Mediterranean Archaeology & Archaeometry*, 14(3).
15. Hale, G.E., 1908. On the probable existence of a magnetic field in sun-spots. *The astrophysical journal*, 28, p.315.
16. English, N., 2017. Empire of the Sun. In *Space Telescopes* (pp. 187-245). Springer, Cham.
17. Lyot, B. and Marshall, R.K., 1933. The study of the solar corona without an eclipse. *Journal of the Royal Astronomical Society of Canada*, 27, p.225.
18. Mainzer, A., Bauer, J., Grav, T., Masiero, J., Cutri, R.M., Dailey, J., Eisenhardt, P., McMillan, R.S., Wright, E., Walker, R. and Jedicke, R., 2011. Preliminary results from NEOWISE: an enhancement to the wide-field infrared survey explorer for solar system science. *The Astrophysical Journal*, 731(1), p.53.
19. Bruner Jr, E.C., Chipman, E.G., Lites, B.W., Rottman, G.J., Shine, R.A., Athay, R.G. and White, O.R., 1976. Preliminary results from the Orbiting Solar Observatory 8-Transition-zone dynamics over a sunspot. *The Astrophysical Journal*, 210, pp.L97-L101.
20. Acton, L.C.A., Culhane, J.L., Gabriel, A.H., Bentley, R.D., Bowles, J.A., Firth, J.G., Finch, M.L., Gilbreth, C.W., Guttridge, P., Hayes, R.W. and Joki, E.G., 1980. The soft X-ray polychromator for the Solar Maximum Mission. *Solar Physics*, 65(1), pp.53-71.
21. Willson, R.C. and Hudson, H.S., 1988. Solar luminosity variations in solar cycle 21. *Nature*, 332(6167), p.810.

22. Ogawara, Y., Acton, L.W., Bentley, R.D., Bruner, M.E., Culhane, J.L., Hiei, E., Hirayama, T., Hudson, H.S., Kosugi, T., Lemen, J.R. and Strong, K.T., 1992. The status of YOHKOH in orbit-An introduction to the initial scientific results. *Publications of the Astronomical Society of Japan*, 44, pp.L41-L44.
23. Acton, L., Bruner, M., Lemen, J., Tsuneta, S., Ogawara, Y., Nishimura, J., Bentley, R., Culhane, L., Canfield, R., Hudson, H. and Doschek, G., 1992. The Yohkoh mission for high-energy solar physics. *Science*, 258(5082), pp.618-625.
24. De Pontieu, B., McIntosh, S.W., Carlsson, M., Hansteen, V.H., Tarbell, T.D., Schrijver, C.J., Shine, R.A., Tsuneta, S., Katsukawa, Y., Ichimoto, K. and Suematsu, Y., 2007. Chromospheric Alfvénic waves strong enough to power the solar wind. *science*, 318(5856), pp.1574-1577.
25. Malherbe, J.M. and Priest, E.R., 1983. Current sheet models for solar prominences. I Magnetohydrostatics of support and evolution through quasi-static models. *Astronomy and Astrophysics*, 123, pp.80-88.
26. Keller, C.U., Schüssler, M., Vögler, A. and Zakharov, V., 2004. On the origin of solar faculae. *The Astrophysical Journal Letters*, 607(1), p.L59.
27. Spruit, H.C., 1981. Motion of magnetic flux tubes in the solar convection zone and chromosphere. *Astronomy and Astrophysics*, 98, pp.155-160.
28. Behannon, K.W. and Ness, N.F., 1966. Magnetic storms in the earth's magnetic tail. *Journal of Geophysical Research*, 71(9), pp.2327-2351.
29. Frank, L.A., Craven, J.D., Burch, J.L. and Winningham, J.D., 1982. Polar views of the Earth's aurora with Dynamics Explorer. *Geophysical Research Letters*, 9(9), pp.1001-1004.
30. Brekke, A. and Egeland, A., 1994. The Northern Lights. *Grøndahl & Dreyer, Oslo*.
31. Snyder, A.L., Akasofu, S.I. and Davis, T.N., 1974. Auroral substorms observed from above the north polar region by a satellite. *Journal of Geophysical Research*, 79(10), pp.1393-1402.
32. Schwenn, R., Dal Lago, A., Huttunen, E. and Gonzalez, W.D., 2005, March. The association of coronal mass ejections with their effects near the Earth. In *Annales Geophysicae* (Vol. 23, No. 3, pp. 1033-1059).
33. Kim, R.S., Cho, K.S., Moon, Y.J., Kim, Y.H., Yi, Y., Dryer, M., Bong, S.C. and Park, Y.D., 2005. Forecast evaluation of the coronal mass ejection (CME) geoeffectiveness using halo CMEs from 1997 to 2003. *Journal of Geophysical Research: Space Physics*, 110(A11).
34. Almeida, J.S., 1997. Physical properties of the solar magnetic photosphere under the MISMA hypothesis. I. Description of the inversion procedure. *The Astrophysical Journal*, 491(2), p.993.
35. Roddier, F., 1981. V the effects of atmospheric turbulence in optical astronomy. *Progress in optics*, 19, pp.281-376.
36. Claverie, A., Isaak, G.R., McLeod, C.P., Van der Raay, H.B. and Cortes, T.R., 1979. Solar structure from global studies of the 5-minute oscillation. *Nature*, 282(5739), pp.591-594.
37. Athay, R.G. and White, O.R., 1979. Chromospheric oscillations observed with OSO 8. IV-Power and phase spectra for C IV. *The Astrophysical Journal*, 229, pp.1147-1162.
38. Ayres, T.R., 1979. Chromospheric scaling laws, width-luminosity correlations, and the Wilson-Bappu effect. *The Astrophysical Journal*, 228, pp.509-520.
39. Withbroe, G.L. and Noyes, R.W., 1977. Mass and energy flow in the solar chromosphere and corona. *Annual review of astronomy and astrophysics*, 15(1), pp.363-387.

40. Athay, R.G. and Holzer, T.E., 1982. The role of spicules in heating the solar atmosphere. *The Astrophysical Journal*, 255, pp.743-752.
41. Hirayama, T., 1985. Modern observations of solar prominences. *Solar physics*, 100(1), pp.415-434.
42. Nordlund, Å., 1985. Solar convection. *Solar Physics*, 100(1-2), pp.209-235.
43. Phillips, K.J., Feldman, U. and Landi, E., 2008. *Ultraviolet and X-ray Spectroscopy of the Solar Atmosphere* (Vol. 44). Cambridge: Cambridge University Press.
44. Rottman, G.J., 1988. Observations of solar UV and EUV variability. *Advances in Space Research*, 8(7), pp.53-66.
45. Thekaekara, M.P., 1973. Solar energy outside the earth's atmosphere. *Solar energy*, 14(2), pp.109-127.
46. Friedman, H., 1963. Ultraviolet and X Rays from the Sun. *Annual Review of Astronomy and Astrophysics*, 1(1), pp.59-96.
47. Labitzke, K. and Van Loon, H., 1988. Associations between the 11-year solar cycle, the QBO and the atmosphere. Part I: the troposphere and stratosphere in the northern hemisphere in winter. *Journal of Atmospheric and Terrestrial Physics*, 50(3), pp.197-206.
48. Gurman, J.B., 1987. NASA's solar maximum mission: A look at a new Sun.
49. Aschwanden, M., 2006. *Physics of the solar corona: an introduction with problems and solutions*. Springer Science & Business Media.
50. Fishman, G.J., Bhat, P.N., Mallozzi, R., Horack, J.M., Koshut, T., Kouveliotou, C., Pendleton, G.N., Meegan, C.A., Wilson, R.B., Paciesas, W.S. and Goodman, S.J., 1994. Discovery of intense gamma-ray flashes of atmospheric origin. *Science-AAAS-Weekly Paper Edition-including Guide to Scientific Information*, 264(5163), pp.1313-1316.
51. Peres, G., Orlando, S., Reale, F., Rosner, R. and Hudson, H., 2000. The Sun as an X-ray star. II. Using the Yohkoh/Soft X-ray telescope-derived solar emission measure versus temperature to interpret stellar X-ray observations. *The Astrophysical Journal*, 528(1), p.537.
52. Dennis, B. and Milligan, R., 2010. Solar Satellites. *Scholarpedia*, 5(7), p.6139.
53. Cowling, T.G., 1933. The magnetic field of sunspots. *Monthly Notices of the Royal Astronomical Society*, 94, pp.39-48.
54. Willson, R.C. and Hudson, H.S., 1991. The Sun's luminosity over a complete solar cycle. *Nature*, 351(6321), pp.42-44.
55. Galsgaard, K. and Nordlund, Å., 1996. Heating and activity of the solar corona: 1. Boundary shearing of an initially homogeneous magnetic field. *Journal of Geophysical Research: Space Physics*, 101(A6), pp.13445-13460.
56. Krucker, S., Battaglia, M., Cargill, P.J., Fletcher, L., Hudson, H.S., MacKinnon, A.L., Masuda, S., Sui, L., Tomczak, M., Veronig, A.L. and Vlahos, L., 2008. Hard X-ray emission from the solar corona. *The Astronomy and Astrophysics Review*, 16(3-4), pp.155-208.
57. Lean, J., 1991. Variations in the Sun's radiative output. *Reviews of Geophysics*, 29(4), pp.505-535.
58. Thompson, B.J., Plunkett, S.P., Gurman, J.B., Newmark, J.S., St Cyr, O.C. and Michels, D., 1998. SOHO/EIT observations of an Earth-directed coronal mass ejection on May 12, 1997. *Geophysical Research Letters*, 25(14), pp.2465-2468.
59. Hoflin, P., 1991. Asphericity effects in scattering dominated photospheres. *Astronomy and astrophysics*, 246,p.481.
60. Grace, C.H., 2010. *Astronomy: Selected Topics*. Trafford Publishing.

61. Bruner Jr, E.C., 1978. Dynamics of the solar transition zone. *The Astrophysical Journal*, 226, pp.1140-1146.
62. Doyle, J.G., O'shea, E., Erdélyi, R., Dere, K.P., Socker, D.G. and Keenan, F.P., 1997. Nonthermal velocities in the solar transition zone and corona. *Solar Physics*, 173(2), pp.243-258.
63. De Pontieu, B., Erdélyi, R. and James, S.P., 2004. Solar chromospheric spicules from the leakage of photospheric oscillations and flows. *Nature*, 430(6999), pp.536-539.
64. Mathew, S.K., Zakharov, V. and Solanki, S.K., 2009. Stray light correction and contrast analysis of Hinode broad-band images. *Astronomy & Astrophysics*, 501(3), pp.L19-L22.
65. Howard, R., 1959. Observations of Solar Magnetic Fields. *The Astrophysical Journal*, 130, p.193.
66. Lin, H. and Rimmele, T., 1999. The granular magnetic fields of the quiet Sun. *The Astrophysical Journal*, 514(1), p.448.
67. Bahng, J. and Schwarzschild, M., 1961. Lifetime of Solar Granules. *The Astrophysical Journal*, 134, p.312.
68. Deardorff, J.W., 1970. Convective velocity and temperature scales for the unstable planetary boundary layer and for Rayleigh convection. *Journal of the atmospheric sciences*, 27(8), pp.1211-1213.
69. Stein, R.F. and Nordlund, Å., 1989. Topology of convection beneath the solar surface. *The Astrophysical Journal*, 342, pp.L95-L98.
70. Rosenthal, C.S., Christensen-Dalsgaard, J., Nordlund, A., Stein, R.F. and Trampedach, R., 1998. Convective contributions to the frequencies of solar oscillations. *arXiv preprint astro-ph/9803206*.
71. Roudier, T. and Muller, R., 1986. Structure of the solar granulation. *Solar Physics*, 107(1), pp.11-26.
72. Schwarzschild, M., 1975. On the scale of photospheric convection in red giants and supergiants. *The Astrophysical Journal*, 195, pp.137-144.
73. Schwarzschild, M., 1961. Convection in Stars. *The Astrophysical Journal*, 134, p.1.
74. Brandt, P.N., Scharmer, G.B., Ferguson, S., Shine, R.A. and Tarbell, T.D., 1988. Vortex flow in the solar photosphere. *Nature*, 335(6187), pp.238-240.
75. Vilmer, N., Kane, S.R. and Trotter, G., 1982. Impulsive and gradual hard X-ray sources in a solar flare. *Astronomy and Astrophysics*, 108, pp.306-313.
76. Priest, E.R., 2012. *Solar magnetohydrodynamics* (Vol. 21). Springer Science & Business Media.
77. Kale, V.S., A Review: Sunspots, Solar Wind, Solar Flares and Solar Radio Burst.
78. Parker, E., 1970. The origin of solar magnetic fields. *Annual Review of Astronomy and Astrophysics*, 8(1), pp.1-30.
79. Lin, R.P. and Hudson, H.S., 1976. Non-thermal processes in large solar flares. *Solar Physics*, 50(1), pp.153-178.
80. Schlichenmaier, R., Bruls, J.H.M.J. and Schüssler, M., 1999. Radiative cooling of a hot flux tube in the solar photosphere. *Astronomy and Astrophysics*, 349, pp.961-973.
81. Cheung, M.C.M., Schüssler, M. and Moreno-Insertis, F., 2007. The origin of the reversed granulation in the solar photosphere. *Astronomy & Astrophysics*, 461(3), pp.1163-1171.
82. Nesis, A., Hammer, R., Hanslmeier, A., Schleicher, H., Sigwarth, M. and Staiger, J., 1997. Dynamics of the solar granulation. IV. Granular shear flow. *Astronomy and Astrophysics*, 326, pp.851-859.
83. Bray, R.J., Loughhead, R.E. and Durrant, C.J., 1984. *The solar granulation* (Vol. 270). Cambridge: Cambridge University Press.

84. Archontis, V., Moreno-Insertis, F., Galsgaard, K., Hood, A. and O'Shea, E., 2004. Emergence of magnetic flux from the convection zone into the corona. *Astronomy & Astrophysics*, 426(3), pp.1047-1063.
85. Avrami, M., 1941. Granulation, phase change, and microstructure kinetics of phase change. III. *The Journal of chemical physics*, 9(2), pp.177-184.
86. Dravins, D., 1982. Photospheric spectrum line asymmetries and wavelength shifts. *Annual Review of Astronomy and Astrophysics*, 20(1), pp.61-8.
87. Lajeunesse, E., Mangeney-Castelnau, A. and Vilotte, J.P., 2004. Spreading of a granular mass on a horizontal plane. *Physics of Fluids*, 16(7), pp.2371-2381.
88. MiDi, G.D.R., 2004. On dense granular flows. *European Physical Journal E--Soft Matter*, 14(4).
89. Rieutord, M. and Rincon, F., 2010. The Sun's supergranulation. *Living Reviews in Solar Physics*, 7(1), p.2.
90. Tanenbaum, A.S., Wilcox, J.M., Franzier, E.N. and Howard, R., 1969. Solar velocity fields: 5-min oscillations and supergranulation. *Solar Physics*, 9(2), pp.328-342.
91. DeRosa, M.L. and Toomre, J., 2004. Evolution of solar supergranulation. *The Astrophysical Journal*, 616(2), p.1242.
92. Solov'ev, A.A. and Kirichek, E.A., 2008. Sunspot as an isolated magnetic structure: Stability and oscillations. *Astrophysical Bulletin*, 63(2), pp.169-180.
93. Costa, A., García, B. and Moreno, R., Solar Spectrum and Sunspots.
94. Babcock, H.W., 1961. The Topology of the Sun's Magnetic Field and the 22-YEAR Cycle. *The Astrophysical Journal*, 133, p.572.
95. Bradshaw, S.J. and Hartigan, P., 2014. On sunspot and starspot lifetimes. *The Astrophysical Journal*, 795(1), p.79.
96. Bouvier, J., Covino, E., Kovo, O., Martin, E.L., Matthews, J.M., Terranegra, L. and Beck, S.C., 1995. COYOTES II: SPOT properties and the origin of photometric period variations in T Tauri stars. *Astronomy and Astrophysics*, 299, p.89.
97. Silva, A.V., 2003. Method for spot detection on solar-like stars. *The Astrophysical Journal Letters*, 585(2), p.L147.
98. Iizuka, S., Saeki, K., Sato, N. and Hatta, Y., 1979. Buneman instability, pierce instability, and double-layer formation in a collisionless plasma. *Physical Review Letters*, 43(19), p.1404.
99. Moore, T.E., Gallagher, D.L., Horwitz, J.L. and Comfort, R.H., 1987. MHD wave breaking in the outer plasmasphere. *Geophysical Research Letters*, 14(10), pp.1007-1010.
100. Fontenla, J.M., Avrett, E.H. and Loeser, R., 1990. Energy balance in the solar transition region. I- Hydrostatic thermal models with ambipolar diffusion. *The Astrophysical Journal*, 355, pp.700-718.
101. Babel, J. and Michaud, G., 1991. Ambipolar diffusion of hydrogen in the atmosphere of AP stars. *Astronomy and Astrophysics*, 248, pp.155-165.
102. Cheung, M.C. and Cameron, R.H., 2012. Magnetohydrodynamics of the weakly ionized solar photosphere. *The Astrophysical Journal*, 750(1), p.6.
103. Pandey, B.P., Vranjes, J. and Krishan, V., 2008. Waves in the solar photosphere. *Monthly Notices of the Royal Astronomical Society*, 386(3), pp.1635-1643.
104. Lanz, T., Artru, M.C., Le Dourneuf, M. and Hubeny, I., 1996. Photoionization resonances of SiII in stellar spectra. *Astronomy and Astrophysics*, 309, pp.218-226.

105. Rudawy, P. and Heinzl, P., 1992. Hydrogen photoionization rates for chromospheric and prominence plasmas. *Solar physics*, 138(1), pp.123-131.
106. Van Regemorter, H., 1962. Rate of Collisional Excitation in Stellar Atmospheres. *The Astrophysical Journal*, 136, p.906.
107. Vernazza, J.E., Avrett, E.H. and Loeser, R.U.D.O.L.F., 1976. Structure of the solar chromosphere. II-The underlying photosphere and temperature-minimum region. *The Astrophysical Journal Supplement Series*, 30, pp.1-60.
108. Grossmann-Doerth, U., 1994. Height of formation of solar photospheric spectral lines. *Astronomy and Astrophysics*, 285, pp.1012-1018.
109. Foukal, P.V., 1976. The pressure and energy balance of the cool corona over sunspots. *The Astrophysical Journal*, 210, pp.575-581.
110. Christensen-Dalsgaard, J., Dappen, W., Ajukov, S.V. and Anderson, E.R., 1996. The current state of solar modeling. *Science*, 272(5266), p.1286.
111. Weaver, T.A., Zimmerman, G.B. and Woosley, S.E., 1978. Presupernova evolution of massive stars. *The Astrophysical Journal*, 225, pp.1021-1029.
112. Gray, D.F., 2005. *The observation and analysis of stellar photospheres*. Cambridge University Press.
113. Iqbal, M., 2012. *An introduction to solar radiation*. Elsevier.
114. Allen, C.W., 1975. Quiet and Active Solar Emission of Fe xv 284 Å Radiation. *Monthly Notices of the Royal Astronomical Society*, 172(1), pp.159-173.
115. Burns, J.A., Lamy, P.L. and Soter, S., 1979. Radiation forces on small particles in the solar system. *Icarus*, 40(1), pp.1-48.
116. Liu, B.Y. and Jordan, R.C., 1960. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Solar energy*, 4(3), pp.1-19.
117. Nakajima, T. and King, M.D., 1990. Determination of the optical thickness and effective particle radius of clouds from reflected solar radiation measurements. Part I: Theory. *Journal of the atmospheric sciences*, 47(15), pp.1878-1893.
118. Hinteregger, H.E., Hall, L.A. and Schmidtke, G., 1965. Solar XUV radiation and neutral particle distribution in July 1963 thermosphere. In *Space Research Conference* (p. 1175).
119. Akasofu, S.I. and Chapman, S., 1972. Solar-terrestrial physics.
120. Liou, K.N., 2002. *An introduction to atmospheric radiation* (Vol. 84). Academic press.
121. McLean, D.J. and Labrum, N.R., 1985. Solar radiophysics: Studies of emission from the sun at metre wavelengths.
122. Kerker, M., 2016. *The scattering of light and other electromagnetic radiation*. Elsevier.
123. Kodama, R., Norreys, P.A., Mima, K., Dangor, A.E., Evans, R.G., Fujita, H., Kitagawa, Y., Krushelnick, K., Miyakoshi, T., Miyanaga, N. and Norimatsu, T., 2001. Fast heating of ultrahigh-density plasma as a step towards laser fusion ignition. *Nature*, 412(6849), pp.798-802.
124. Koyama, H. and Inutsuka, S.I., 2000. Molecular cloud formation in shock-compressed layers. *The Astrophysical Journal*, 532(2), p.980.
125. Whitham, G.B., 2011. *Linear and nonlinear waves* (Vol. 42). John Wiley & Sons.
126. Shugaev, F.V. and Shtemenko, L.S., 1998. *Propagation and reflection of shock waves* (Vol. 49). World Scientific.
127. Sachs, R.G., 1946. Some properties of very intense shock waves. *Physical Review*, 69(9-10), p.514.

128. Merzkirch, W.F., 1970. Mach's contribution to the development of gas dynamics. In *Ernst Mach: Physicist and Philosopher* (pp. 42-59). Springer Netherlands
129. Anderson, J.D., 2000. *Hypersonic and high temperature gas dynamics*. Aiaa.
130. NELEGION, L.P. and GRIMSHAW, J.F., 1980. The Diffraction of the Blast Wave Emerging from a Conical Nozzle Driven by Compressed Gas. *I*^{III}.
131. Sheeley Jr, N.R., Nash, A.G. and Wang, Y.M., 1987. The origin of rigidly rotating magnetic field patterns on the sun. *The Astrophysical Journal*, 319, pp.481-502.
132. Gilman, P.A. and Fox, P.A., 1997. Joint instability of latitudinal differential rotation and toroidal magnetic fields below the solar convection zone. *The Astrophysical Journal*, 484(1), p.439.
133. Reinhold, T. and Reiners, A., 2013. A fast and reliable method to measure stellar differential rotation from photometric data. *arXiv preprint arXiv:1306.2176*.
134. Schröter, E.H., 1985. The solar differential rotation: present status of observations. *Solar physics*, 100(1), pp.141-169.
135. Thompson, M.J., Toomre, J., Anderson, E.R., Antia, H.M., Berthomieu, G., Burtonclay, D., Chitre, S.M., Christensen-Dalsgaard, J., Corbard, T., DeRosa, M. and Genovese, C.R., 1996. Differential rotation and dynamics of the solar interior. *Science*, 272(5266), pp.1300-130.
136. Dziembowski, W.A. and Goode, P.R., 1992. Effects of differential rotation on stellar oscillations-A second-order theory. *The Astrophysical Journal*, 394, pp.670-687.
137. Küker, M. and Stix, M., 2001. Differential rotation of the present and the pre-main-sequence Sun. *Astronomy & Astrophysics*, 366(2), pp.668-675.
138. Thompson, M.J., Toomre, J., Anderson, E.R. and Antia, H.M., 1996. Differential rotation and dynamics of the solar interior. *Science*, 272(5266), p.1300.
139. Schou, J., Antia, H.M., Basu, S., Bogart, R.S., Bush, R.I., Chitre, S.M., Christensen-Dalsgaard, J., Di Mauro, M.P., Dziembowski, W.A., Eff-Darwich, A. and Gough, D.O., 1998. Helioseismic studies of differential rotation in the solar envelope by the solar oscillations investigation using the Michelson Doppler Imager. *The Astrophysical Journal*, 505(1), p.390.
140. Lemen, J.R., Akin, D.J., Boerner, P.F., Chou, C., Drake, J.F., Duncan, D.W., Edwards, C.G., Friedlaender, F.M., Heyman, G.F., Hurlburt, N.E. and Katz, N.L., 2011. The atmospheric imaging assembly (AIA) on the solar dynamics observatory (SDO). In *The Solar Dynamics Observatory* (pp. 17-40). Springer US.
141. Brookes, J.R., Isaak, G.R. and Van der Raay, H.B., 1976. Observation of free oscillations of the Sun. *Nature*, 259(5539), pp.92-95.
142. Appourchaux, T., Michel, E., Auvergne, M., Baglin, A., Toutain, T., Baudin, F., Benomar, O., Chaplin, W.J., Deheuvels, S., Samadi, R. and Verner, G.A., 2008. CoRoT sounds the stars: p-mode parameters of Sun-like oscillations on HD 49933. *Astronomy & Astrophysics*, 488(2), pp.705-714.
143. Spergel, D.N. and Press, W.H., 1985. Effect of hypothetical, weakly interacting, massive particles on energy transport in the solar interior. *The Astrophysical Journal*, 294, pp.663-673.
144. Gilliland, R.L., Faulkner, J., Press, W.H. and Spergel, D.N., 1986. Solar models with energy transport by weakly interacting particles. *The Astrophysical Journal*, 306, pp.703-709.

145. Silk, J., Olive, K. and Srednicki, M., 1985. The photino, the sun, and high-energy neutrinos. *Physical Review Letters*, 55(2), p.257.
146. De Loore, C., 1970. Convection regions and coronas of sun and stars. *Astrophysics and Space Science*, 6, pp.60-100.
147. Zhao, J. and Kosovichev, A.G., 2004. Torsional oscillation, meridional flows, and vorticity inferred in the upper convection zone of the sun by time-distance helioseismology. *The Astrophysical Journal*, 603(2), p.776.
148. Thomas, R.N., 1977. What is a stellar atmosphere. *Memorie della Societa Astronomica Italiana*, 48, pp.339-356.
149. Dere, K.P., Bartoe, J.D. and Brueckner, G.E., 1989. Explosive events in the solar transition zone. *Solar physics*, 123(1), pp.41-68.
150. Evans, J.W. and Michard, R., 1962. Observational Study of Macroscopic Inhomogeneities in the Solar Atmosphere. III. Vertical Oscillatory Motions in the Solar Photosphere. *The Astrophysical Journal*, 136, p.493.
151. Noyes, R.W. and Hall, D.N., 1972. Thermal oscillations in the high solar photosphere. *The Astrophysical Journal*, 176, p.L89.
152. Hoflich, P., 1991. Asphericity effects in scattering dominated photospheres. *Astronomy and Astrophysics*, 246, p.481.
153. Giannios, D., 2006. Prompt emission spectra from the photosphere of a GRB. *Astronomy & Astrophysics*, 457(3), pp.763-770.
154. Finkelstein, A.M., 1984. Weak localization and coulomb interaction in disordered systems. *Zeitschrift für Physik B Condensed Matter*, 56(3), pp.189-196.
155. November, L.J. and Simon, G.W., 1988. Precise proper-motion measurement of solar granulation. *The Astrophysical Journal*, 333, pp.427-442.
156. Ayres, T.R., 1981. Thermal bifurcation in the solar outer atmosphere. *The Astrophysical Journal*, 244, pp.1064-1071.
157. Barbosa, D.D., 1979. Stochastic acceleration of solar flare protons. *The Astrophysical Journal*, 233, pp.383-394.
158. Melrose, D.B., 1980. The emission mechanisms for solar radio bursts. *Space Science Reviews*, 26(1), pp.3-38.
159. Lydon, T.J., Fox, P.A. and Sofia, S., 1992. A formulation of convection for stellar structure and evolution calculations without the mixing-length theory approximations. I-Application to the sun. *The Astrophysical Journal*, 397, pp.701-716.
160. Shibata, K. and Magara, T., 2011. Solar flares: magnetohydrodynamic processes. *Living Reviews in Solar Physics*, 8(1), p.6.
161. Démoulin, P. and Berger, M.A., 2003. Magnetic energy and helicity fluxes at the photospheric level. *Solar Physics*, 215(2), pp.203-215.
162. Centeno, R., Socas-Navarro, H., Lites, B., Kubo, M., Frank, Z., Shine, R., Tarbell, T., Ichimoto, K., Tsuneta, S., Katsukawa, Y. and Suematsu, Y., 2007. Emergence of small-scale magnetic loops in the quiet-Sun internetwork. *The Astrophysical Journal Letters*, 666(2), p.L137.
163. Fleck, B., 1995. The SOHO mission. *Coronal Magnetic Energy Releases*, pp.233-244.
164. Ofman, L. and Wang, T.J., 2008. Hinode observations of transverse waves with flows in coronal loops. *Astronomy & Astrophysics*, 482(2), pp.L9-L12.
165. De Pontieu, B., McIntosh, S.W., Carlsson, M., Hansteen, V.H., Tarbell, T.D., Boerner, P., Martinez-Sykora, J. and Schrijver, C.J., 2011. The origins of hot plasma in the solar corona. *Science*, 331(6013), pp.55-58.

166. Twarog, B.A., 1980. The chemical evolution of the solar neighborhood. II-The age-metallicity relation and the history of star formation in the galactic disk. *The Astrophysical Journal*, 242, pp.242-259.
167. Duvall, T.L., 1982. A dispersion law for solar oscillations. *nature*, 300(5889), pp.242-243.
168. Messina, S. and Guinan, E.F., 2003. Magnetic activity of six young solar analogues II. Surface Differential Rotation from long-term photometry. *Astronomy & Astrophysics*, 409(3), pp.1017-1030.
169. Barnes, J.R., Cameron, A.C., Donati, J.F., James, D.J., Marsden, S.C. and Petit, P., 2005. The dependence of differential rotation on temperature and rotation. *Monthly Notices of the Royal Astronomical Society: Letters*, 357(1), pp.L1-L5.
170. Pesnell, W.D., 2015. *Solar dynamics observatory (SDO)* (pp. 179-196). Springer International Publishing.
171. Pneuman, G.W. and Kopp, R.A., 1971. Gas-magnetic field interactions in the solar corona. *Solar Physics*, 18(2), pp.258-270.
172. Banaszkiewicz, M., Axford, W.I. and McKenzie, J.F., 1998. An analytic solar magnetic field model. *Astronomy and Astrophysics*, 337, pp.940-944.
173. Tsyganenko, N.A., 1989. A magnetospheric magnetic field model with a warped tail current sheet. *Planetary and Space Science*, 37(1), pp.5-20.
174. Isenberg, P.A. and Forbes, T.G., 2007. A three-dimensional line-tied magnetic field model for solar eruptions. *The Astrophysical Journal*, 670(2), p.1453.
175. Duvall Jr, T.L., Jefferies, S.M., Harvey, J.W., Osaki, Y. and Pomerantz, M.A., 1993. Asymmetries of solar oscillation line profiles. *The Astrophysical Journal*, 410, pp.829-836.
176. Ulrich, R.K., 1970. The five-minute oscillations on the solar surface. *The Astrophysical Journal*, 162, p.993.
177. Libbrecht, K.G. and Woodard, M.F., 1990. Solar-cycle effects on solar oscillation frequencies. *Nature*, 345(6278), p.779.
178. Lites, B.W., Rutten, R.J. and Kalkofen, W., 1993. Dynamics of the solar chromosphere. I-Long-period network oscillations. *The Astrophysical Journal*, 414, pp.345-356.
179. Bedding, T.R. and Kjeldsen, H., 2003. Solar-like oscillations. *Publications of the Astronomical Society of Australia*, 20(2), pp.203-212.
180. Duvall, T.L. and Harvey, J.W., 1984. Rotational frequency splitting of solar oscillations. *Nature*, 310(5972), pp.19-22.
181. Libbrecht, K.G., Woodard, M.F. and Kaufman, J.M., 1990. Frequencies of solar oscillations. *The Astrophysical Journal Supplement Series*, 74, pp.1129-1149.
182. Kumar, P. and Goldreich, P., 1989. Nonlinear interactions among solar acoustic modes. *The Astrophysical Journal*, 342, pp.558-575.
183. Bougeret, J.L. and Steinberg, J.L., 1977. A new scattering process above solar active regions-Propagation in a fibrous medium. *Astronomy and Astrophysics*, 61, pp.777-783.
184. Gray, D.F. and Hatzes, A.P., 1997. Non-radial oscillation in the solar-temperature star 51 Pegasi. *The Astrophysical Journal*, 490(1), p.412.
185. Howard, R., 1978. The rotation of the Sun. *Reviews of Geophysics*, 16(4), pp.721-732.

186. Kosovichev, A.G., 2009, September. Solar oscillations. In *AIP Conference Proceedings* (Vol. 1170, No. 1, pp. 547-559). AIP.
187. Reznikova, V.E., Shibasaki, K., Sych, R.A. and Nakariakov, V.M., 2012. Three-minute oscillations above sunspot umbra observed with the Solar Dynamics Observatory/Atmospheric Imaging Assembly and Nobeyama Radioheliograph. *The Astrophysical Journal*, 746(2), p.119.
188. Abdelatif, T.E., Lites, B.W. and Thomas, J.H., 1986. The interaction of solar p-modes with a sunspot. I- Observations. *The Astrophysical Journal*, 311, pp.1015-1024.
189. Schwarzschild, M., 1948. On Noise Arising from the Solar Granulation. *The Astrophysical Journal*, 107, p..
190. Nesis, A., Hammer, R. and Mattig, W., 1990. The upper boundary of the solar convection zone- Hydrodynamical aspects. In *Cool Stars, Stellar Systems, and the Sun* (Vol. 9, pp. 113-115).
191. Brueckner, G.E. and Bartoe, J.D., 1983. Observations of high-energy jets in the corona above the quiet sun, the heating of the corona, and the acceleration of the solar wind. *The Astrophysical Journal*, 272, pp.329-348.
192. Alfvén, H., 1977. Electric currents in cosmic plasmas. *Reviews of Geophysics*, 15(3), pp.271-284.
193. Wedemeyer-Böhm, S., Scullion, E., Steiner, O., van der Voort, L.R., de La Cruz Rodriguez, J., Fedun, V. and Erdélyi, R., 2012. Magnetic tornadoes as energy channels into the solar corona. *Nature*, 486(7404), pp.505-508.
194. Shelyag, S., Keys, P., Mathioudakis, M. and Keenan, F.P., 2011. Vorticity in the solar photosphere. *Astronomy & Astrophysics*, 526, p.A5.
195. Parker, E.N., 1963. Kinematical Hydromagnetic Theory and its Application to the Low Solar Photosphere. *The Astrophysical Journal*, 138, p.55.
196. Choudhuri, A.R., Auffret, H. and Priest, E.R., 1993. Implications of rapid footpoint motions of photospheric flux tubes for coronal heating. *Solar physics*, 143(1), pp.49-68.
197. Zwaan, C., 1985. The emergence of magnetic flux. In *Progress in Solar Physics* (pp. 397-414). Springer Netherlands.
198. Ponomarenko, Y.B., 1972. Mechanism for the Formation of Sunspots. *Soviet Astronomy*, 16, p.116.
199. Leighton, R.B., 1964. Transport of Magnetic Fields on the Sun. *The Astrophysical Journal*, 140, p.1.
200. Caspi, A. and Lin, R.P., 2010. RHESSI line and continuum observations of super-hot flare plasma. *The Astrophysical Journal Letters*, 725(2), p.L161.
201. Charles, C. and Boswell, R., 2003. Current-free double-layer formation in a high-density helicon discharge. *Applied Physics Letters*, 82(9), pp.1356-1358.
202. Lieberman, M.A., Charles, C. and Boswell, R.W., 2006. A theory for formation of a low pressure, current-free double layer. *Journal of Physics D: Applied Physics*, 39(15), p.3294.
203. Hafemeister, D., 2014. Nuclear Weapons. In *Physics of Societal Issues* (pp. 1-41). Springer New York.
204. Karzas, W.J. and Latter, R., 1965. Detection of the electromagnetic radiation from nuclear explosions in space. *Physical Review*, 137(5B), p.B1369.
205. Glasstone, S. and Dolan, P.J., 1977. *Effects of nuclear weapons* (No. TID-28061). Department of Defense, Washington, DC (USA); Department of Energy, Washington, DC (USA).
206. Kinney, G.F. and Graham, K.J., 2013. *Explosive shocks in air*. Springer Science & Business Media.

207. Ulmschneider, P., 1970. On frequency and strength of shock waves in the solar atmosphere. *Solar Physics*, 12(3), pp.403-415.
208. Stein, R.F. and Leibacher, J., 1974. Waves in the solar atmosphere. *Annual review of astronomy and astrophysics*, 12(1), pp.407-435.
209. Courant, R. and Friedrichs, K.O., 1999. *Supersonic flow and shock waves* (Vol. 21). Springer Science & Business Media.
210. Babinsky, H. and Harvey, J.K. eds., 2011. *Shock wave-boundary-layer interactions* (Vol. 32). Cambridge University Press.
211. Hoshino, M., 2008. Wakefield acceleration by radiation pressure in relativistic shock waves. *The Astrophysical Journal*, 672(2), p.940.
212. Labitzke, K., 1987. Sunspots, the QBO, and the stratospheric temperature in the north polar region. *Geophysical Research Letters*, 14(5), pp.535-537.
213. Schussler, M., Caligari, P., Ferriz-Mas, A. and Moreno-Insertis, F., 1994. Instability and eruption of magnetic flux tubes in the solar convection zone. *Astronomy and Astrophysics*, 281, pp.L69-L72.
214. Lin, H., 1995. On the distribution of the solar magnetic fields. *The Astrophysical Journal*, 446, p.421.
215. Gurevich, A.V., Milikh, G.M. and Roussel-Dupre, R., 1992. Runaway electron mechanism of air breakdown and preconditioning during a thunderstorm. *Physics Letters A*, 165(5-6), pp.463-468.
216. Dreicer, H., 1959. Electron and ion runaway in a fully ionized gas. I. *Physical Review*, 115(2), p.238.
217. Dreicer, H., 1960. Electron and ion runaway in a fully ionized gas. II. *Physical review*, 117(2), p.329.
218. Reiners, A. and Schmitt, J.H., 2002. On the feasibility of the detection of differential rotation in stellar absorption profiles. *Astronomy & Astrophysics*, 384(1), pp.155-162.
219. Weber, M. and Strassmeier, K.G., 2001. Doppler imaging of stellar surface structure-XV. A possible detection of differential rotation and local meridional flows on the rapidly-rotating giant HD 218153= KU Pegasi. *Astronomy & Astrophysics*, 373(3), pp.974-986.
220. Ilonidis, S., Zhao, J. and Kosovichev, A., 2011. Detection of emerging sunspot regions in the solar interior. *Science*, 333(6045), pp.993-996.
221. Scharmer, G.B., Henriques, V.M., Kiselman, D. and de la Cruz Rodríguez, J., 2011. Detection of convective downflows in a sunspot Penumbra. *Science*, 333(6040), pp.316-319.
222. Streefkerk, B.M., Pols, L.C. and ten Bosch, L., 1998. Automatic detection of prominence (as defined by listeners' judgements) in read aloud dutch sentences. In *ICSLP*.
223. Donahue, R.A. and Baliunas, S.L., 1992. Evidence of differential surface rotation in the solar-type star HD 114710. *The Astrophysical Journal*, 393, pp.L63-L66.
224. Spiegel, E.A. and Zahn, J.P., 1992. The solar tachocline. *Astronomy and Astrophysics*, 265, pp.106-114.
225. Leighton, R.B., 1969. A magneto-kinematic model of the solar cycle. *The Astrophysical Journal*, 156, p.1.
226. Dikpati, M. and Charbonneau, P., 1999. A Babcock-Leighton flux transport dynamo with solar-like differential rotation. *The Astrophysical Journal*, 518(1), p.508.
227. Stenflo, J.O., 2013. *Solar magnetic fields: polarized radiation diagnostics* (Vol. 189). Springer Science & Business Media.

228. Chae, J., 2001. Observational determination of the rate of magnetic helicity transport through the solar surface via the horizontal motion of field line footpoints. *The Astrophysical Journal Letters*, 560(1), p.L95.
229. Altschuler, M.D. and Newkirk, G., 1969. Magnetic fields and the structure of the solar corona. *Solar Physics*, 9(1), pp.131-149.
230. Howard, R. and Labonte, B.J., 1981. Surface magnetic fields during the solar activity cycle. *Solar Physics*, 74(1), pp.131-145.
231. Lu, E.T. and Hamilton, R.J., 1991. Avalanches and the distribution of solar flares. *The astrophysical journal*, 380, pp.L89-L92.
232. Van Ballegooijen, A.A. and Martens, P.C.H., 1989. Formation and eruption of solar prominences. *The Astrophysical Journal*, 343, pp.971-984.
233. Burkepile, J.T., Hundhausen, A.J., Stanger, A.L., St Cyr, O.C. and Seiden, J.A., 2004. Role of projection effects on solar coronal mass ejection properties: 1. A study of CMEs associated with limb activity. *Journal of Geophysical Research: Space Physics*, 109(A3).
234. HANAOKA, Y., 2013. plasma with the velocities of about 1000 km s.⁻¹. These ejection phenomena are considered as X-ray jets observed by Yohkoh (eg Shibata et al., 1992). *Magnetodynamic Phenomena in the Solar Atmosphere: Prototypes of Stellar Magnetic Activity*, 207, p.207.
235. Simnett, G.M., Tappin, S.J., Plunkett, S.P., Bedford, D.K., Eyles, C.J., Cyr, O.S., Howard, R.A., Brueckner, G.E., Michels, D.J., Moses, J.D. and Socker, D., 1997. LASCO observations of disconnected magnetic structures out to beyond 28 solar radii during coronal mass ejections. *Solar Physics*, 175(2), pp.685-698.
236. Li, X., Morgan, H., Leonard, D. and Jeska, L., 2012. A solar tornado observed by AIA/SDO: Rotational flow and evolution of magnetic helicity in a prominence and cavity. *The Astrophysical Journal Letters*, 752(2), p.L22.
237. Kebede, L.W., 2013. The Role of Magnetic Fields in Gamma-Ray Bursts from SNeII. *International Journal of Astronomy and Astrophysics*, 3(04), p.500.
238. Goodson, A.P., Winglee, R.M. and Böhm, K.H., 1997. Time-dependent accretion by magnetic young stellar objects as a launching mechanism for stellar jets. *The Astrophysical Journal*, 489(1), p.199.
239. Hasegawa, A. and Chen, L., 1976. Kinetic processes in plasma heating by resonant mode conversion of Alfvén wave. *The Physics of Fluids*, 19(12), pp.1924-1934.
240. Frieman, E.A. and Chen, L., 1982. Nonlinear gyrokinetic equations for low-frequency electromagnetic waves in general plasma equilibria. *The Physics of Fluids*, 25(3), pp.502-508.
241. Grec, G., Fossat, E. and Pomerantz, M., 1980. Solar oscillations-Full disk observations from the geographic South Pole. *Nature*, 288, pp.541-544.
242. Scherrer, P.H., Bogart, R.S., Bush, R.I., Hoeksema, J.A., Kosovichev, A.G., Schou, J., Rosenberg, W., Springer, L., Tarbell, T.D., Wolfson, C.J. and Zayer, I., 1995. The solar oscillations investigation-Michelson Doppler imager. *Solar Physics*, 162(1-2), pp.129-188.
243. Tang, D.L., Sun, A.P., Qiu, X.M. and Chu, P.K., 2003. Interaction of electromagnetic waves with a magnetized nonuniform plasma slab. *IEEE Transactions on Plasma Science*, 31(3), pp.405-410.

244. Tortosa-Andreu, A. and Moreno-Insertis, F., 2009. Magnetic flux emergence into the solar photosphere and chromosphere. *Astronomy & Astrophysics*, 507(2), pp.949-967.
245. Arber, T.D., Haynes, M. and Leake, J.E., 2007. Emergence of a flux tube through a partially ionized solar atmosphere. *The Astrophysical Journal*, 666(1), p.541.
246. Khodachenko, M.L. and Zaitsev, V.V., 2002. Formation of intensive magnetic flux tubes in a converging flow of partially ionized solar photospheric plasma. *Astrophysics and space science*, 279(4), pp.389-410.
247. Stenzel, R.L., Ionita, C. and Schrittwieser, R., 2008. Dynamics of fireballs. *Plasma Sources Science and Technology*, 17(3), p.035006.
248. Bale, S.D., Kellogg, P.J., Larsen, D.E., Lin, R.P., Goetz, K. and Lepping, R.P., 1998. Bipolar electrostatic structures in the shock transition region: Evidence of electron phase space holes. *Geophysical research letters*, 25(15), pp.2929-2932.
249. Scholer, M., 1985. *Collisionless shock waves in space* (No. EUR--9708 (V. 2)).
250. Mann, G. and Klassen, A., 2005. Electron beams generated by shock waves in the solar corona. *Astronomy & Astrophysics*, 441(1), pp.319-326.
251. Maehara, H., Shibayama, T., Notsu, S., Notsu, Y., Nagao, T., Kusaba, S., Honda, S., Nogami, D. and Shibata, K., 2012. Superflares on solar-type stars. *Nature*, 485(7399), p.478.
252. Sturrock, P.A., 1966. Model of the high-energy phase of solar flares. *Nature*, 211(5050), p.695.
253. Cross, R., 1988. *An introduction to Alfvén waves*. CRC Press.
254. Török, T. and Kliem, B., 2003. The evolution of twisting coronal magnetic flux tubes. *Astronomy & Astrophysics*, 406(3), pp.1043-1059.
255. Schlichenmaier, R., Jahn, K. and Schmidt, H.U., 1998. Magnetic flux tubes evolving in sunspots. A model for the penumbral fine structure and the Evershed flow. *Astronomy and Astrophysics*, 337, pp.897-910.
256. Hale, G.E., Ellerman, F., Nicholson, S.B. and Joy, A.H., 1919. The magnetic polarity of sun-spots. *The Astrophysical Journal*, 49, p.153.
257. Li, K.J., Yun, H.S. and Gu, X.M., 2001. Latitude migration of sunspot groups. *The Astronomical Journal*, 122(4), p.2115.
258. Parker, E.N., 1955. The Formation of Sunspots from the Solar Toroidal Field. *The astrophysical journal*, 121, p.491.
259. Kopp, G. and Rabin, D., 1992. A relation between magnetic field strength and temperature in sunspots. *Solar physics*, 141(2), pp.253-265.
260. Parker, E.N., 1979. Sunspots and the physics of magnetic flux tubes. I-The general nature of the sunspot. II-Aerodynamic drag. *The Astrophysical Journal*, 230, pp.905-923.
261. Roberts, B. and Webb, A.R., 1978. Vertical motions in an intense magnetic flux tube. *Solar Physics*, 56(1), pp.5-35.
262. Poedts, S., Goossens, M. and Kerner, W., 1989. Numerical simulation of coronal heating by resonant absorption of Alfvén waves. *Solar physics*, 123(1), pp.83-115.
263. Jess, D.B., Mathioudakis, M., Erdélyi, R., Crockett, P.J., Keenan, F.P. and Christian, D.J., 2009. Alfvén waves in the lower solar atmosphere. *Science*, 323(5921), pp.1582-1585.
264. Mathioudakis, M., Jess, D.B. and Erdélyi, R., 2013. Alfvén waves in the solar atmosphere. *Space Science Reviews*, 175(1-4), pp.1-27.

265. Alfvén, H. and Carlqvist, P., 1967. Currents in the solar atmosphere and a theory of solar flares. *Solar Physics*, 1(2), pp.220-228.
266. Sweet, P.A., 1958. The production of high energy particles in solar flares. *Il Nuovo Cimento (1955-1965)*, 8, pp.188-196.
267. Shibata, K., Ishido, Y., Acton, L.O.R.E.N.W., Strong, K.E.I.T.H.T., Hirayama, T., Uchida, Y., Mcallister, A.L.A.N.H., Matsumoto, R., Tsuneta, S., Shimizu, T. and Hara, H., 1993, January. Observations of X-ray jets using Yohkoh soft X-ray telescope. In *International Astronomical Union Colloquium* (Vol. 141, pp. 343-346). Cambridge University Press.
268. Tsuneta, S. and Naito, T., 1998. Fermi acceleration at the fast shock in a solar flare and the impulsive loop-top hard X-ray source. *The Astrophysical Journal Letters*, 495(1), p.L67.
269. Lynch, B.J., Fast, P.L., Harris, M. and Truhlar, D.G., 2000. Adiabatic connection for kinetics. *The Journal of Physical Chemistry A*, 104(21), pp.4811-4.
270. Somov, B.V. and Kosugi, T., 1997. Collisionless reconnection and high-energy particle acceleration in solar flares. *The Astrophysical Journal*, 485(2), p.859.
271. Spruit, H.C. and Roberts, B., 1983. Magnetic flux tubes on the Sun. *Nature*, 304(5925), pp.401-406.
272. Rae, I.C. and Roberts, B., 1982. Pulse propagation in a magnetic flux tube. *The Astrophysical Journal*, 256, pp.761-767.
273. Heyvaerts, J., Priest, E.R. and Rust, D.M., 1977. An emerging flux model for the solar flare phenomenon. *The Astrophysical Journal*, 216, pp.123-137.
274. Linton, M.G., Dahlburg, R.B., Fisher, G.H. and Longcope, D.W., 1998. Nonlinear Evolution of Kink-unstable Magnetic Flux Tubes and Solar δ -Spot Active Regions. *The Astrophysical Journal*, 507(1), p.404.
275. Birn, J., Drake, J.F., Shay, M.A., Rogers, B.N., Denton, R.E., Hesse, M., Kuznetsova, M., Ma, Z.W., Bhattacharjee, A., Otto, A. and Pritchett, P.L., 2001. Geospace Environmental Modeling (GEM) magnetic reconnection challenge. *Journal of Geophysical Research: Space Physics*, 106(A3), pp.3715-3719.
276. Southwood, D., 2015. From the Carrington Storm to the Dungey Magnetosphere. In *Magnetospheric Plasma Physics: The Impact of Jim Dungey's Research* (pp. 253-271). Springer, Cham.
277. Lang, K.R., 1980. Gas Processes. In *Astrophysical Formulae* (pp. 221-327). Springer Berlin Heidelberg.
278. Hayashi, T. and Sato, T., 1978. Magnetic reconnection: Acceleration, heating, and shock formation. *Journal of Geophysical Research: Space Physics*, 83(A1), pp.217-220.
279. Pneuman, G.W., 1983. The formation of solar prominences by magnetic reconnection and condensation. *Solar physics*, 88(1), pp.219-239.
280. Zwaan, C., 1987. Elements and patterns in the solar magnetic field. *Annual review of Astronomy and Astrophysics*, 25(1), pp.83-111.
281. Shibata, K., Nozawa, S., Matsumoto, R., Sterling, A.C. and Tajima, T., 1990. Emergence of solar magnetic flux from the convection zone into the photosphere and chromosphere. *The Astrophysical Journal*, 351, pp.L25-L28.
282. Rust, D.M. and Kumar, A., 1996. Evidence for helically kinked magnetic flux ropes in solar eruptions. *The Astrophysical Journal Letters*, 464(2), p.L199.

283. Anderson, K.A. and Winckler, J.R., 1962. Solar flare X-ray burst on September 28, 1961. *Journal of Geophysical Research*, 67(11), pp.4103-4117.
284. Yokoyama, T., Akita, K., Morimoto, T., Inoue, K. and Newmark, J., 2001. Clear evidence of reconnection inflow of a solar flare. *The Astrophysical Journal Letters*, 546(1), p.L69.
285. Raouafi, N.E., Mancuso, S., Solanki, S.K., Inhester, B., Mierla, M., Stenborg, G., Delaboudiniere, J.P. and Benna, C., 2004. Shock wave driven by an expanding system of loops. *Astronomy & Astrophysics*, 424(3), pp.1039-1048.
286. Zaslavskii, G.M. and Chirikov, B.V., 1965, May. Fermi acceleration mechanism in the one-dimensional case. In *Soviet Physics Doklady* (Vol. 9, p. 989).
287. Moore, R.L., Sterling, A.C., Hudson, H.S. and Lemen, J.R., 2001. Onset of the magnetic explosion in solar flares and coronal mass ejections. *The Astrophysical Journal*, 552(2), p.833.
288. Kahler, S.W., 1992. Solar flares and coronal mass ejections. *Annual Review of Astronomy and Astrophysics*, 30(1), pp.113-141.
289. Török, T. and Kliem, B., 2005. Confined and ejective eruptions of kink-unstable flux ropes. *The Astrophysical Journal Letters*, 630(1), p.L97.
290. Aulanier, G., Démoulin, P., Schrijver, C.J., Janvier, M., Pariat, E. and Schmieder, B., 2013. The standard flare model in three dimensions-II. Upper limit on solar flare energy. *Astronomy & Astrophysics*, 549, p.A66.
291. Biskamp, D., 1996. Magnetic reconnection in plasmas. *Astrophysics and Space Science*, 242(1-2), pp.165-207.
292. Kane, S.R., Chupp, E.L., Forrest, D.J., Share, G.H. and Rieger, E., 1986. Rapid acceleration of energetic particles in the 1982 February 8 solar flare. *The Astrophysical Journal*, 300, pp.L95-L98.
293. Fermi, E., 1949. On the origin of the cosmic radiation. *Physical Review*, 75(8), p.1169.
294. Ji, H., Terry, S., Yamada, M., Kulsrud, R., Kuritsyn, A. and Ren, Y., 2004. Electromagnetic fluctuations during fast reconnection in a laboratory plasma. *Physical review letters*, 92(11), p.115001.
295. Drummond, W.E. and Rosenbluth, M.N., 1963. Cyclotron radiation from a hot plasma. *The Physics of Fluids*, 6(2), pp.276-283.
296. Hundhausen, A., 1999. Coronal mass ejections. In *The Many Faces of the Sun* (pp. 143-200). Springer, New York, NY.
297. Kahler, S., 1987. Coronal mass ejections. *Reviews of Geophysics*, 25(3), pp.663-675.
298. Wagner, W.J., 1984. Coronal mass ejections. *Annual review of astronomy and astrophysics*, 22(1), pp.267-289.
299. Kaiser, M.L., Kucera, T.A., Davila, J.M., Cyr, O.S., Guhathakurta, M. and Christian, E., 2008. The STEREO mission: An introduction. *Space Science Reviews*, 136(1-4), pp.5-16.
300. Frazin, R.A. and Kamalabadi, F., 2005. Rotational tomography for 3D reconstruction of the white-light and EUV corona in the post-SOHO era. *Solar Physics*, 228(1), pp.219-237.
301. Cremades, H. and Bothmer, V., 2004. On the three-dimensional configuration of coronal mass ejections. *Astronomy & Astrophysics*, 422(1), pp.307-322.
302. Hamidi, Z.S., Abidin, Z.Z., Ibrahim, Z.A., Shariff, N.N.M. and Monstein, C., 2013, May. Observations of coronal mass ejections (CMEs) at low frequency radio region on 15th April 2012. In *AIP Conference Proceedings* (Vol. 1528, No. 1, pp. 55-60). AIP.

303. Carlowicz, M.J. and Lopez, R.E., 2002. *Storms from the sun: The emerging science of space weather*. Joseph Henry Press.
304. Bone, N., 2007. *Aurora: Observing and Recording Nature's Spectacular Light Show*. Springer Science & Business Media.
305. Cyr, O.S. and Webb, D.F., 1991. Activity associated with coronal mass ejections at solar minimum: SMM observations from 1984–1986. *Solar physics*, 136(2), pp.379-394.
306. Cane, H.V. and Richardson, I.G., 2003. Interplanetary coronal mass ejections in the near-Earth solar wind during 1996–2002. *Journal of Geophysical Research: Space Physics*, 108(A4).
307. Richardson, I.G., Cliver, E.W. and Cane, H.V., 2001. Sources of geomagnetic storms for solar minimum and maximum conditions during 1972–2000. *Geophysical Research Letters*, 28(13), pp.2569-2572.
308. Penn, M.J. and Livingston, W., 2010. Long-term evolution of sunspot magnetic fields. *Proceedings of the International Astronomical Union*, 6(S273), pp.126-133.
309. Webb, D.F., Mizuno, D.R., Buffington, A., Cooke, M.P., Eyles, C.J., Fry, C.D., Gentile, L.C., Hick, P.P., Holladay, P.E., Howard, T.A. and Hewitt, J.G., 2006. Solar Mass Ejection Imager (SMEI) observations of coronal mass ejections (CMEs) in the heliosphere. *Journal of Geophysical Research: Space Physics*, 111(A12).
310. Tsuneta, S., Hara, H., Shimizu, T., Acton, L.W., Strong, K.T., Hudson, H.S. and Ogawara, Y., 1992. Observation of a solar flare at the limb with the YOHKOH Soft X-ray Telescope. *Publications of the Astronomical Society of Japan*, 44, pp.L63-L69.
311. De Jager, C., 1959. Structure and dynamics of the solar atmosphere. In *Astrophysics III: The Solar System/Astrophysik III: Das Sonnensystem* (pp. 80-362). Springer Berlin Heidelberg.
312. Hoekzema, N.M., Brandt, P.N. and Rutten, R.J., 1998. Small-scale topology of solar atmosphere dynamics. III. Granular persistence and photospheric wave amplitudes. *Astronomy and astrophysics*, 333, pp.322-332.
313. Gaizauskas, V., Harvey, K.L., Harvey, J.W. and Zwaan, C., 1983. Large-scale patterns formed by solar active regions during the ascending phase of cycle 21. *The Astrophysical Journal*, 265, pp.1056-1065.
314. Harvey, K.L. and Zwaan, C., 1993. Properties and emergence patterns of bipolar active regions. *Solar physics*, 148(1), pp.85-118.
315. Kellermann, K.I., 2005. Grote Reber (1911–2002). In *The new astronomy: Opening the electromagnetic window and expanding our view of planet earth* (pp. 43-70). Springer, Dordrecht.
316. Zhang, Y., Tan, B., Karlický, M., Mészárosóvá, H., Huang, J., Tan, C. and Simões, P.J., 2015. Solar radio bursts with spectral fine structures in preflares. *The Astrophysical Journal*, 799(1), p.30.
317. Wild, J.P., 1964. Radio observations of solar flares. *NASA Special Publication*, 50, p.161.
318. Rieger, E., Gan, W.Q. and Marschhäuser, H., 1998. Gamma-ray line versus continuum emission of electron-dominated episodes during solar flares. *Solar Physics*, 183(1), pp.123-132.
319. Yoshida, T. and Tsuneta, S., 1996. Temperature structure of solar active regions. *The Astrophysical Journal*, 459, p.342.

320. Wang, Y.M., Sheeley, N.R. and Andrews, M.D., 2002. Polarity reversal of the solar magnetic field during cycle 23. *Journal of Geophysical Research: Space Physics*, 107(A12).
321. Vecchio, A., Laurenza, M., Meduri, D., Carbone, V. and Storini, M., 2012. The dynamics of the solar magnetic field: polarity reversals, butterfly diagram, and quasi-biennial oscillations. *The Astrophysical Journal*, 749(1), p.27.
322. McClymont, A.N. and Canfield, R.C., 1986. The solar flare extreme ultraviolet to hard X-ray ratio. *The Astrophysical Journal*, 305, pp.936-946.
323. Parker, E., 1972. Topological dissipation and the small-scale fields in turbulent gases. *The Astrophysical Journal*, 174, p.499.
324. Winebarger, A.R., Warren, H.P., Schmelz, J.T., Cirtain, J., Mulu-Moore, F., Golub, L. and Kobayashi, K., 2012. Defining the “blind spot” of Hinode EIS and XRT temperature measurements. *The Astrophysical Journal Letters*, 746(2), p.L17.
325. Brosius, J.W., Daw, A.N. and Rabin, D.M., 2014. Pervasive faint Fe XIX emission from a solar active region observed with EUNIS-13: evidence for nanoflare heating. *The Astrophysical Journal*, 790(2), p.112.
326. Narayan, R. and Piran, T., 2012. Variability in blazars: clues from PKS 2155– 304. *Monthly Notices of the Royal Astronomical Society*, 420(1), pp.604-612.
327. Priest, E. and Forbes, T., 2007. Magnetic reconnection. *Magnetic Reconnection*, by Eric Priest, Terry Forbes, Cambridge, UK: Cambridge University Press, 2007.
328. Masuda, S., Kosugi, T., Hara, H., Tsuneta, S. and Ogawara, Y., 1994. A loop-top hard X-ray source in a compact solar flare as evidence for magnetic reconnection. *Nature*, 371(6497), p.49.
329. Gopalswamy, N., Nitta, N., Akiyama, S., Mäkelä, P. and Yashiro, S., 2011. Coronal magnetic field measurement from EUV images made by the solar dynamics observatory. *The Astrophysical Journal*, 744(1), p.72.].
330. Gopalswamy, Nat. "Coronal mass ejections and solar radio emissions." (2011): 325-342.