



# PULSAR'S MAGNETIC FIELD DECAY DUE TO PHOTON EMISSIONS

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By  
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# Abstract

Now a days there is no clear understanding of how pulsar's magnetic field decays. This is the motivation behind the development of this particular model for pulsar field dissipation. The work will be based on previous work in which it was shown that spinning polarization charges are the most likely sources of Neutron Star (NS) magnetic field. These fields were indicated to be internal temperature dependent. Therefore, they are expected to decay as a result of cooling the NS interior. The present model for field decay is strongly linked to the long term (1-10 billion) yrs cooling of the NS core due to neutrino and photon emissions. Magnetic decay laws are formulated corresponding to each of the neutrino and photon branches of a standard NS cooling curve. So that this thesis work intends to show the decay of pulsar magnetic field due to photon emission. There after, magnetic field decays as a result of photon emission will be prominent for about 10 billion yrs. We will derive the magnetic field decay law and investigate how this law could be consistent with observations.

# Chapter 1

## Introduction

A pulsar (short for pulsating Neutron Star) is highly magnetized rotating Neutron Star (NS) that emits a beam of electromagnetic radiation. Pulsar is a NS which emits radiation that is pulsed due to miss-alignment of rotational and magnetic axis [1]. Pulsars are powered by rotational kinetic energy from their birth they show high rotational frequency. Hence pulsars are born with high rotational frequency. However, they subsequently slow down with time mainly as a result of loss of kinetic energy via the emission of high energy particles, gravitational and magnetic dipole radiations [1, 2]. In their early evolution the energy loss via quadrupole radiation is believed to be dominant over the other braking(loss) mechanisms. Without considering magnetic dipole radiation, gravitational radiation is strong decay mechanism within the first  $10^5$  yrs, after which the photon and neutrino emission become effective loss mechanisms [1].

Neutron stars (NSs) are among the most compact objects (stellar remnants) in the universe. Our knowledge of NS interiors is still uncertain and in particular, the composition and equation of state of matter at super nuclear densities in NS cores cannot be predicted with confidence [2]. It is generally believed that NSs are formed at very high interior temperature  $T > 10^{11}$  K in the core of a supernova explosion [3]. NSs are very hot at birth, this heat is radiated away mainly by neutrinos from the inner layers during the first million years or (the neutrino cooling era) and later on, the emission of

photons from the surface dominates the cooling of the star. This photon luminosity and its change with time depend on the properties of matter inside the NS and its magnetic field [3]. Observations of this radiation can thus provide important information about the state of matter above and below nuclear density as well as about the magnetic field [4]. The predominant cooling mechanism immediately after a formation is via neutrino emission, with an initial cooling timescale of seconds. After about a day the internal temperature drops to  $10^9 - 10^{10}$  K. Photon emission overtakes neutrons only when the internal temperature falls to  $\sim 10^8$  K, with corresponding surface temperature roughly two orders of magnitude smaller. Neutrino cooling dominates for at least the first  $10^3$  yrs and typically for much longer, in all standard cooling calculation performed recently [3].

At the present there is no as such a self-consistent theory for the origin of NS's magnetic fields. The current understanding is that it can either be a fossil remnant (standard picture) or it may also be generated by the thermal process soon after the formation of the NS [4]. Very recently; however, separated charges have been suggested as more likely source for NS's magnetic fields [5].

The theory of relativistic plasma diffusion as possible source for NS magnetic field is discussed in detail by [8]. In this work, the fact that pulsar fields are NS internal temperature(T) and spin frequency ( $\Omega$ ) dependent [ $B = B(\Omega, T)$ ] are shown as more suggestive possible causes of magnetic field decay which are directly related to neutrino and photon emissions as well as various pulsar breaking mechanisms.

As mentioned above, the new model for NS's magnetic fields indicates that pulsar fields are pulsar frequency ( $\Omega$ ) and internal temperature (T) dependent. Therefore, they are expected to decay as a result of cooling of the NS interior. And this is believed to be strongly linked to the long term (1-10 billion years) cooling of the NS core due to neutrino and photon emissions [8].

In the early stages of NS life (about a million years) magnetic field decay as a result of neutrino emission is dominant even though during this time is just by one order of magnitude. Studies based on simulation conducted on a limited number of low magnetic field

pulsars have shown that their magnetic field will not decay for almost 100 million years [9]. Investigations indicate that no significant magnetic decay occurs in a NS life time [10]. This raises a serious question of how magnetic moments of the so called millisecond pulsars (MSPs) in Low-Mass X-Ray Binaries (LMXBs) decay from a typical value of  $\sim 10^{30}$  G cm<sup>3</sup> down to  $10^{25-26}$  G cm<sup>3</sup> in a time window of about  $10^{7-8}$  yrs [11].

The main objective of this thesis work is to investigate how pulsar magnetic field decay during this window of time and compare with the observation of at least the seven(7) well studied pulsars and provide a generic decay law. There after, magnetic field decays as a result of photon emission will be prominent for about 10 billion years.

To analyze this we will derive the magnetic decay law by using the standard cooling equation so that magnetic decay law is formulated corresponding to photon branches of a standard NS cooling curve.

In the next chapter we are going to discuss about formation of NSs, some properties of pulsar, internal structure of NSs, possible origins of NS's magnetic fields, classification of NSs, neutrino reactions in the NSs ( $T \leq 10^9$  K) which take place in the core of NSs. We will thus consider neutrino emission from the core of NS during the predominant cooling mechanism immediately after its formation. We will also discuss neutrino emission through different process in the core of a neutron star. The emphasis is made on modified URCA process as this is the most powerful neutrino energy loss mechanism leading to the pulsar magnetic field decay. The third chapter provides the derivation of NS temperature as a function of time from which the pulsar magnetic decay laws are determined assuming photon emission processes taken to evolve initially as a black body radiation from the surface of NS. Finally result and conclusions included in Chapter four and five respectively.

# Chapter 2

## Neutron star and pulsar

### 2.1 Formation of neutron stars

The neutron, an elementary particle with neutral charge in the nucleus of atoms, was predicted by Ernest Rutherford in 1920. Twelve years later James Chadwick found experimental proof of the existence of neutrons and later received the Nobel Prize for his discovery. Only two years after this discovery, astrophysicists predicted the existence of NSs [12]. NSs are one of the most compact stars in the universe. They have mass  $M \sim 1.4 M_{\odot}$  and radius  $R \sim 10$  km and they contain matter at super nuclear densities in their cores [13]. NSs are created as a result of the gravitational collapse of the core of massive stars, with a mass  $M \geq 8 M_{\odot}$  at the end of their lifetimes [13]. Gravitational collapse will usually occur on any compact star above  $10 M_{\odot}$  and produce a black hole. Their deaths are associated with type-II supernova explosions. A type-II supernova occurs when the iron core of a super-giant star collapses to the density of an atomic nucleus [13]. At such tremendously high densities, protons and electrons fuse together to form neutrons, hence the name “neutron stars”. This shows that NSs have very high density [14]. Any star’s life is a careful balancing act; the gravity of its materials pulls inward, while the pressure from the heat and the light produced by burning of hydrogen in helium in the stars core pushes out ward. The interior of the NS is mostly neutral

matter with only traces of electrons and protons throughout the object. More than 95 % of the content of NSs is neutrons with only a few percent of protons and an equal number of electrons. It is not certainly known about the interior structure of a NS. We don't know a lot about how matter behaves at these amazingly high densities. Generally, NSs have both minimum and maximum mass limits. The maximum mass, which is of purely general relativistic origin, is still unknown, but believed to be in the range of  $1.44 - 3 M_{\odot}$ , and the minimum stable NS mass is about  $0.1 M_{\odot}$  [13].

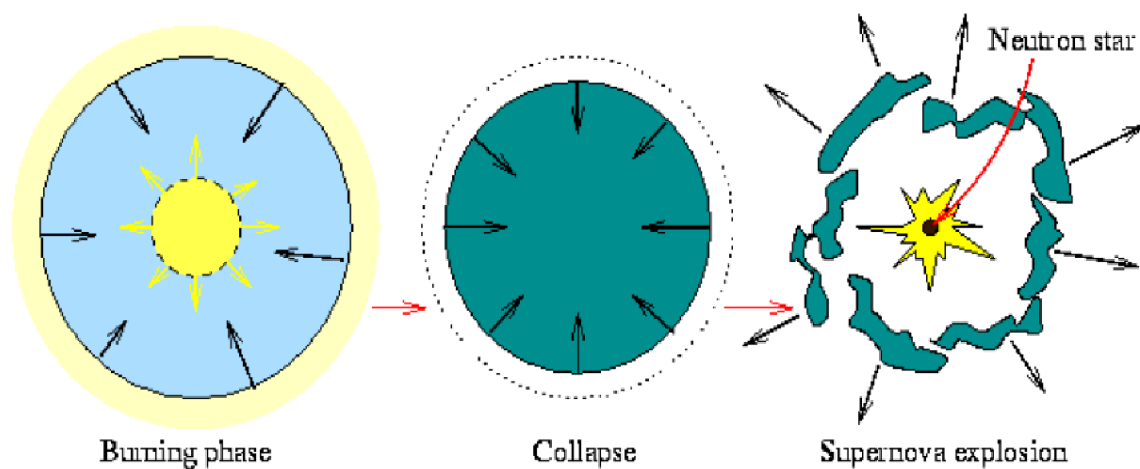


Figure 2.1: Three phases during the life of a star: virtually all its life is spent in the nuclear burning phase, following the exhaustion of the nuclear fuel it collapses and a supernova explosion leaves behind a NS.

As illustrated in Fig.2.1 during the life of a star the gravitational force is balanced by the radiation pressure created by nuclear fusion inside the star [15]. As soon as all available fuel is used up, nuclear fusion ceases and no force is present to balance gravitation any longer. As the stars core continue to collapse, the central regions get compressed to form the NS. Matter from the outer layers that are still falling in to the center hits the NS, bounces back which creates an enormous explosion when colliding with other in falling matter. This explosion produces the light which can outshine entire galaxies [15].

## 2.2 Internal composition of NS

A NS can be considered as having five major regions namely: the inner and outer cores, the crust, the envelope and the atmosphere [16]. The atmosphere and the envelope contribute a negligible amount to the over all mass of NS but the atmosphere plays an important role in shaping the emergent photon spectrum, and the envelope crucially influences the transport and release of thermal energy from the surface [16].

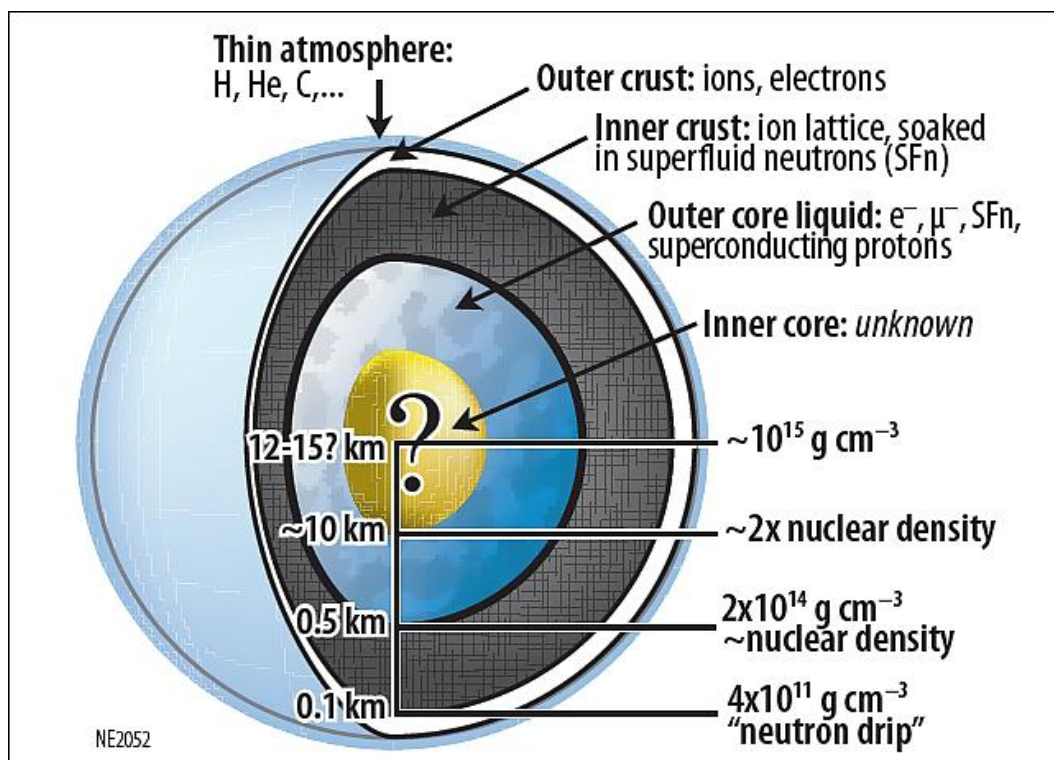


Figure 2.2: Model of internal structure of NS: NS interior composition explorer will infer the masses and radii of neutron stars to reveal the composition of matter in their interiors, at the highest stable densities allowed in nature.(image credit: NASA, NICER Team).

Fig.2.2 shows the different regions of neutron star interiors which is described as follows: the outer crust whose density lies in the range of  $(10^6 \leq \rho \leq 4 \times 10^{11} \text{ g/cm}^3)$ , is a solid region in which a Coulomb lattice of heavy Iron nuclei coexist in-equilibrium with a relativistic degenerate electron gas [17].

The inner crust : has adensity  $(4 \times 10^4 \leq \rho \leq 2 \times 10^{14} \text{ g/cm}^3)$  consists of a lattice

of neutron-rich nuclei together with a superfluid neutron gas and electron gas. Lattice of neutron-rich nuclei (electrons penetrate nuclei to combine with protons and form neutrons) with free degenerate neutrons and degenerate relativistic electrons gas [17]. Neutron fluid interior: it ranges from  $1 \text{ km} \leq r \leq 9 \text{ km}$  believed to be consists of the neutron fluid-superfluid of neutrons and superconducting protons and electrons. Its density lies in the range of  $(2 \times 10^{12} \leq \rho \leq 2 \times 10^{18}) \text{ g/cm}^3$  [17]. The core: extends out to  $\sim 1 \text{ km}$  and has a density of  $(\rho \geq 8 \times 10^{18} \text{ g/cm}^3)$ . The core may or may not exist in some NSs, and possibly a neutron-solid core with free electrons and protons. NSs could have solid cores has been suggested by several authors. Generally it is speculation that the core could be a neutron solid, quark matter or neutrons squeezed to form a pion concentrate [17]. In the high-density range the physical properties of matter are still uncertain [18]. As it can be referred from Fig.2.2 its substance is not well known.

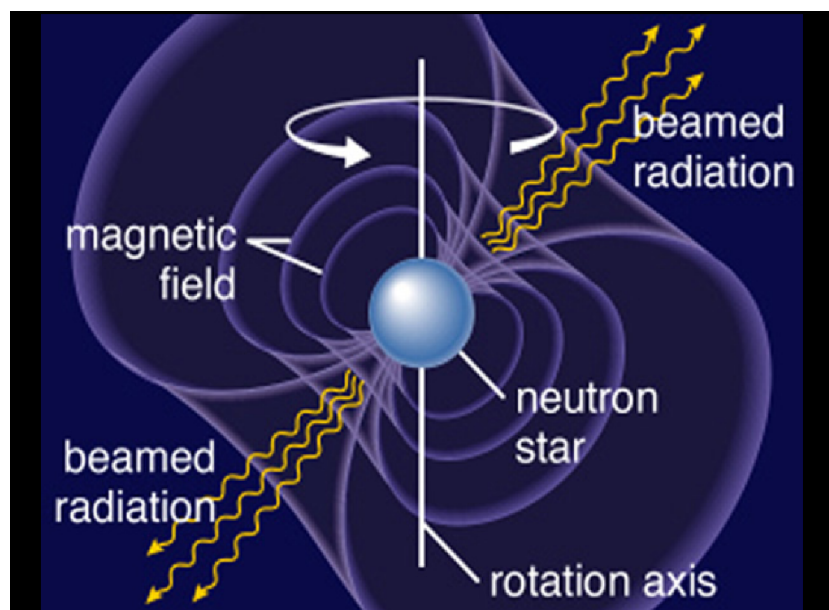


Figure 2.3: Model of rotating neutron star.

Figure 2.3 shows a model of rotating NSs around its axis of rotation. In this model strong jets of matter are believed to be emitted at the magnetic poles. When the rotation axis is not the same as the magnetic axis, the two beams will sweep out circular paths. Thus, when the Earth lies in one of those paths we will see the pulse. A pulsar is the

rotating NS emit regular pulses of electromagnetic radiation towards Earth, due to a misalignment of their rotation and magnetic axes. Pulsars radiate their energy away quite rapidly; the radiation weakens and stops in a few tens of millions of years making the NS virtually undetectable [12].

## 2.3 Possible origins of NS's magnetic fields

Nowadays only little is known about NS's magnetic fields. Most measurements of NS magnetic fields are obtained only from indirect inferences, which are put in doubt both by their inconsistency with other observational evidence and with plausible theoretical models on the physics of their surroundings [6]. Even less is known about the geometry of the magnetic field, its evolution, and its origin, which are thus still open for speculation, modelling, and possible prediction of measurable effects that might test the theoretical ideas [8]. Just recently it has been indicated that plasma density gradients inherent to NS matter could lead to large scale plasma diffusion and subsequent charge separation with excess negative charge accumulating in the crust while at the same time, almost the same amount of excess positive charge is left behind at the solid core. Surface magnetic fields are then expected to result from the spinning of these separated charges [6]. In this model, the electron and proton currents resulting from the charge separation process are modelled as;

$$n_i = -D^0(\partial_i n_0 - \Gamma_{0i}^0 n_0) + \mu n_0 g_{\beta i} F^{0\beta} \quad (2.3.1)$$

where;  $n_\alpha \equiv (n_i, n_0)$  is the four particle current and  $D^0$  represents the diffusion coefficient which is assumed to be scalar,  $n_0$  is the local plasma density,  $g_{\beta i}$  is metric tensor,  $F^{0\beta}$  electro magnetic tensor. The first term in Eqn.(2.3.1) is responsible for the electric field from which one obtains the surface charge density ( $\rho$ ), whereas the term which contains  $\Gamma_{0i}^0$  is responsible for electric field from which we obtained the charge density, this charge is the source for the non-dipolar component of the NS magnetic field [19]. There are

also different popular hypothesis about possible sources of NS magnetic fields such as: The fossil field hypothesis also called “flux conservation” is the standard theory which relates magnetic fields of the progenitor main sequence stars frozen during collapse or flux conservation. However, this model does not deliver the mechanism for the generation of magnetic multipoles which are believed to exist [20]. Additionally the fossil field hypothesis cannot generate field strength of magnitude about  $10^{16}$  G which are often observed in gamma-ray bursts (GRBs) activates. GRBs are extremely energetic explosions that have been observed in distant galaxies. They are the brightest electromagnetic events known to occur in the universe. It has also anticipated that such a very strong magnetic fields are usually needed for supernova bounce, since the energy of the shock blast normally gets dissipated half way through the in falling iron core [20]. Another model often considered for the source of NSs magnetic field is the “flux freezing.” According to proponents of this model probably, all stars at all stages of their evolution have some magnetic field due to the electronic currents circulating in their interiors [21].

## 2.4 Classification of NSs

According to their magnetic fields, NSs are classified in to two, namely, pulsars and magnetars with typical polar surface magnetic fields of  $10^{12} - 10^{13}$  G and  $10^{14} - 10^{15}$  G, respectively [22]. Magnetars are further subdivided into soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). SGRS are objects which repeatedly emit bursts of gamma-rays. Regular pulses have been observed in the persistent X-ray emission, allowing the measurement of a rotation period and period derivative where as AXPs show persistent X-ray emission, modulated at a stable, slowly lengthening period [23]. Pulsars are also subdivided into Crab pulsar (PSR B0531+21) which is a relatively young NS, Vela pulsar ( is a radio, optical, X-ray and gamma-emitting pulsar associated with the Vela Supernova Remnant), Millisecond pulsar, etc [15].

### 2.4.1 Pulsars

Pulsar was first discovered by graduate student Jocelyn Bell in 1967. She was able to isolate and identify radio sources that appeared to blink on and off. They are believed to be highly magnetized, rapidly rotating NSs [15]. Baade and Zwicky had predicted that NSs would be formed when massive stars went supernova, a claim which was extremely proved when pulsars were quickly discovered in both the Vela and Crab supernova remnants [15]. However, in the thirty subsequent years the number of convincing associations between pulsars and supernova remnants (SNRs) has only grown to perhaps six or seven [15]. A pulsar is highly magnetized rotating NS that emits a beam of electromagnetic radiation [15]. Astronomers identify pulsars as rapidly rotating, highly magnetized, extremely dense distant stars that emit beams of electromagnetic radiation in the form of x-rays or radio waves, seen here on the Earth as visible bursts or pulse of energy [13]. Ordinary radio pulsars are NSs with magnetic field  $10^{12}$  G and the spin periods between 16 milliseconds and 8.5 seconds. They are powered by slow loss of the rotational energy that the star is born with. They were named pulsar because of their rapidly pulsing nature [17].

### 2.4.2 Some properties of pulsars

As the name implies pulsars emit electromagnetic radiation in a broad frequency range from radio waves to X-rays and  $\gamma$ -rays, and pulsars pulse because they rotate [17]. The iron dominated core of a large star just before its collapse will likely have some angular momentum, even if it is very small. Conservation of angular momentum during the ensuing collapse results in the core spinning with a high angular velocity, potentially on the order of milliseconds [15]. Observationally, the average period of pulsars is on the order of one second. Pulsar generally has shorter period (higher angular velocity) at the beginning of its life and a longer period at it ages, with most of its energy dissipated due

to magnetic losses which leads to the equation [17]:

$$\dot{E} = \frac{dE}{dt} = \frac{-16\pi^4 B^2 R^6 \sin^2(\theta)}{6c^3 P^4} \text{erg/s} \quad (2.4.1)$$

where  $R$  is the neutron star radius.  $B$  is the magnetic field strength.  $c$  is the speed of light.  $\theta$  is the angle between the rotation axis and the magnetic dipole axes and  $P$  is the spin period.

Also, if the star is assumed to be a solid rotary, an equation for the rotational energy can be found as;

$$E = \frac{1}{2} I \left( \frac{2\pi}{P} \right)^2 \text{erg/s} \quad (2.4.2)$$

where  $I$  is the moment of inertia and keeping it constant.

The spin down energy can be found by taking the derivation of Eqn.(2.4.2) above gives you:

$$\dot{E} = \frac{dE}{dt} = \frac{-4\pi^2 I \dot{P}}{P^3} \text{ergs/s} \quad (2.4.3)$$

where  $\dot{P}$  is the spin down period.

For example we can approximate the energy loss for a typical crab pulsar having period:

$$P \sim 0.033 \text{ s and } \dot{P} \sim 4.22 \times 10^{-13} \text{ s s}^{-1}.$$

$$\text{Suppose that } M = 1.4 M_{\odot} \text{ and } R = 10^6 \text{ cm.}$$

$$\text{This gives; } I = 2/5 MR^2 = 1.1 \times 10^{45} \text{ gcm}^2.$$

$$\text{Hence } \dot{E} = \frac{dE}{dt} \approx -4 \times 10^{38} \text{ erg/s.}$$

$$\text{where } M_{\odot} \text{ (Solar mass)} = 1.99 \times 10^{33} \text{ g} \approx 2 \times 10^{33} \text{ g}$$

The negative sign shows that the dissipation of rotational energy. Therefore, with most of pulsars energy dissipated due to magnetic losses.

Typically, a pulsar ages are estimated by calculating the amount of energy lost during

their spin-down. consequently, the spin down age of apulsar can be formulated as:

$$\tau = \frac{P}{(n-1)\dot{P}} \left[ 1 - \left( \frac{P_0}{P} \right)^{n-1} \right] \quad (2.4.4)$$

where the period ( $P$ ) and the spin-down rate ( $\dot{P}$ ) are the two main observables acquired by pulsar timing measurements. In the standard approach, the unknown initial spin period ( $P_0$ ) of the pulsar is assumed to be much smaller ( $P_0 \ll P$ ) than the observed period. The dominant energy loss mechanism is analytically captured by the braking index, which is  $n = 3$  for pure dipole radiation, and is implicitly adapted by the characteristic age  $\tau_c$ . The age of a pulsar can then be conveniently approximated by its characteristic age [25].

$$\tau \longrightarrow \tau_c \equiv \frac{P}{2\dot{P}} \quad (2.4.5)$$

or the characteristic life time  $\tau_c$  of pulsar can be determined from Eqns.(2.4.2) and (2.4.4)

$$\tau = \frac{E}{\dot{E}} = \frac{P}{2\dot{P}} s \quad (2.4.6)$$

Now we can estimate for some normal pulsars e.g Crab pulsar (PSR B0531 + 21) having the period and spin-down period for crab pulsar respectively.  $P \sim 0.033$  s and  $\dot{P} \sim 4.22 \times 10^{-13} s s^{-1}$

Then  $\tau_c = \frac{E}{\dot{E}} = \frac{P}{2\dot{P}} s = \frac{0.033s}{2 \times 4.22 \times 10^{-13} s s^{-1}} \sim 1240$  yr where as the age from the supernova remnant  $\tau_{SNR} \sim 950$  yr.

## 2.5 Magnetars

As it stated above Magnetars (AXPs and SGRs) are a type of NS with an extremely powerful magnetic field. They are created from star's core when the star explodes as a supernova at the end of its life. Like other NSs magnetars are around 20 km in diameter and have a mass 2.3 times that of the sun. They are made of material so tightly packed

that a single tablespoon of the stuff would weigh about 10 billion tons of material on Earth. Young magnetars have magnetic fields that range from approximately  $10^{14} - 10^{15}$  Gauss and they are born spinning faster than pulsars. Magnetars are differentiated from other NSs by having ever stronger magnetic field and rotating comparatively slowly, with most magnetars completing a rotation once every one to ten seconds. The active life of magnetars is short; their strong magnetic fields decay after 10,000 yrs after which activity and strong X-ray emission cease [26].

In general we have seen that NS are created as a result of gravitational collapse of the core of massive stars, with a mass  $M \geq 8 M_{\odot}$  at the end of their life times. Their deaths are associated with type II supernova explosions [13].

## 2.6 Neutron star temperature and emissions

A NS initially loses its thermal energy through neutrino emission, but this process is taken over by surface photon radiation about  $10^5$  yr after birth. The observations of surface thermal emission from a NS have the potential to provide constraints on its inner structure, dense matter inside it and magnetic field properties [21]. Recently, the observation of millisecond pulsar J0437–4715 shows that an old neutron star after  $10^7$  yrs could have a high temperature (above  $10^5$  K), which suggests the importance of heating mechanisms in the thermal evolution of NSs. NSs begin very hot from their origin in a supernova. Their initial temperature of  $\sim 10^{11}$  K rapidly declines by a process that emits profuse neutrino radiation, the Urca process (named in 1941 after a casino in Rio de Janeiro that rapidly depleted one's money, the Cassino da Urca). The neutrinos are formed in great numbers and carry away much energy. In one day, the temperature drops to about  $10^9$  K. Interior temperature is  $10^8$  K after a few hundred years, at which time the surface has dropped to several million K [27]. Surface temperature will remain at  $\sim 10^6$  K for  $\sim 10,000$  years. At this  $T_{eff}$ , the Stefan–Boltzmann law predicts a luminosity of  $7.13 \times 10^{25}$  W, about  $\frac{1}{5}$  of solar luminosity  $L_{\odot} = 3.846 \times 10^{26}$  W. The Planck distribution

peak by Wien Displacement occurs at a wavelength of 2.9 nm, corresponding to a photon energy of 0.4 KeV, thus predominantly soft X-ray emissions. This range is best studied by space-based X-ray observatories such as the Chandra X-ray Observatory (1999–). NSs are born very hot in supernova explosions, with internal temperature  $T \sim 10^{11}$ K, but gradually cool down. It is generally believed that NSs are formed at very high interior temperatures  $T \geq 10^{11}$  K in the core of a supernova explosion. The predominant cooling mechanism immediately after formation is neutrino emission, with an initial cooling timescale of seconds. After about a day, the internal temperature drops to  $10^9 - 10^{10}$  K. Photon emission overtakes neutrinos only when the internal temperature falls to  $\sim 10^8$  K, with a corresponding surface temperature roughly two orders of magnitude smaller. Neutrino cooling dominates for at least the first  $10^3$  years, and typically for much longer, in all standard cooling calculations performed recently. These theoretical calculations provide curves of the neutron star surface temperature as a function of time, which in principle are subject to observational verification [24].

## 2.7 Neutrino reactions in the neutron stars

Neutrino is an elementary particle with no (or very little) mass and no electric charge that travels at the speed of light and carries energy away during certain types of nuclear reactions. we consider below neutrino emission from the core of neutron star during the predominant cooling mechanism immediately after its formation. We shall discuss neutrino emission through different process in the core of a neutron star. The emphasis is made on modified URCA process because powerful neutrino energy losses are produced by this process.

We shall be interested in the thermal history of a NS after it has already cooled to an interior temperature below a few times  $10^9$  K. Typically, one finds that surface temperatures fall to several times  $10^6$  K for objects approximately 300 years old, and remain in the vicinity of  $(0.5 - 2) \times 10^6$  K for at least  $10^4$  yr. Such temperatures imply potentially

detectable photon emission in the soft X-ray band,  $0.2 - 3$  KeV. Indeed, prior to the discovery of pulsars, it was believed that young NSs might first be detected as discrete X-ray sources [28]. Detailed cooling rates and cooling curves were therefore constructed in anticipation of the observations [26]. For internal temperatures below a few times  $10^9$  K, any neutrinos emitted during the cooling process escape freely from the NS, without interacting further with the NS matter. This fact, which distinguishes the low-temperature NS cooling epoch from the earlier high-temperature formation epoch, greatly simplifies the determination of the late thermal evolution [24].

At the very high temperatures  $T \geq 10^9$  K found in the cores of evolved, massive stars, the dominant mode of energy loss via neutrinos is from the so-called URCA reactions :

$$n \longrightarrow p + e^- + \bar{\nu}^- \quad ; \quad e^- + p \longrightarrow n + \nu_e \quad (2.7.1)$$

where  $\bar{\nu}_e^-$  antineutrino [24]. These reactions also dominate during core collapse. In both cases the nucleons in the hot interior are non-degenerate. However, when the nucleons become degenerate as in a NS that has cooled below  $10^9$  K, this reaction has highly suppressed. We can now demonstrate this important result. Recall that matter in the degenerate interior satisfies the  $\beta$  equilibrium condition.

$$\mu_n = \mu_p + \mu_e, \quad (2.7.2)$$

where to good approximation  $[\vartheta(\frac{KT}{\mu_n})^2]$  the chemical potential are the just the Fermi-energies. Thus

$$E_F(n) = E_F(p) + E_F(e), \quad (2.7.3)$$

where at nuclear densities

$$E_F(n) \approx m_n c^2 + \frac{P_F^2(n)}{2m_n}$$

$$E_F(p) \approx m_p c^2 + \frac{P_F^2(p)}{2m_p}$$

$$E_F(e) \approx P_F(e)c \quad (2.7.4)$$

Charge neutrality requires that

$$P_F(p) = P_F(e) \quad (2.7.5)$$

So Eqn.(3.2.3) becomes

$$\frac{P_F^2(n)}{2m_n} \approx P_F(e)c \left( 1 + \frac{P_F(p)}{2m_p c} \right) - Q, \quad (2.7.6)$$

where  $Q = (m_n - m_p)c^2 = 1.24$  MeV is small in comparison to the other terms in Eqn. (2.7.6), we see the neutron Fermi energy (minus rest mass) is very nearly equal to the electron Fermi energy :

$$E'_F(n) \equiv \frac{p_F^2(n)}{2m_n} \simeq P_F(e)c = E_F(e) \quad (2.7.7)$$

And so

$$P_F(e) = P_F(p) \ll P_F(n), \quad (2.7.8)$$

$$E_F(p) \ll E'_F(n) \quad (2.7.9)$$

Now consider the possibility of a reaction such as neutron decay, Eqn. (2.7.1). The only neutrons capable of decaying lie within  $\sim kT$  of the Fermi surface,  $E'_F(n)$ . Hence, by energy conservation, the final proton and electron must also be within  $\sim kT$  of their Fermi surfaces; the energy of the escaping neutrino must also be  $\sim kT$ .

Now, according to inequality Eqn.(2.7.8), the proton and electron must have small momenta compared to the neutron. But this is impossible: the decay cannot conserve momentum if it conserves energy.

In order for the process to work; a bystander particle (a neutron) is must be present to absorb momentum. Chiu and Salpeter therefore, proposed that “modified” URCA reactions

$$n + n \longrightarrow n + p + e^- + \nu_e^- \quad (2.7.10)$$

$$n + p + e^- \longrightarrow n + n + \nu_e \quad (2.7.11)$$

Hence the reactions Eqn.(2.7.10) & (2.7.11) cause a mass M of NS matter to loss energy at a rate given by

$$L_\nu^{URCA} = 5.3 \times 10^{39} \text{erg/s} \left( \frac{M}{M_\odot} \right) \left( \frac{\rho_{\text{nuc}}}{\rho} \right)^{\frac{1}{3}} T_9^8 \quad (2.7.12)$$

Would be important for NS cooling [35].

If the core of NS consists of quark matter then there is the possibility of significant neutrino emission via the  $\beta$  - decay of degenerate, relativistic quarks [31]. Unlike ordinary NS matter in which the simple beta decay (URCA) process described in Eqn.(2.7.1) are suppressed, the corresponding process can occur for quarks. The simplest neutrino processes occurring in quark matter are the  $\beta$ - decay reactions involving the relativistic quarks becomes:

$$d \longrightarrow u + e^- + \nu_e^- \quad , \quad u + e^- \longrightarrow d + \nu_e \quad (2.7.13)$$

, hence the rate of energy loss by neutrino emission is given by an expression of the form (Iwamoto 1980).

$$L_\nu^{quark} \simeq 1.3 \times 10^{44} \frac{\text{erg}}{\text{s}} \left( \frac{M}{M_\odot} \right) T_9^6 \quad (2.7.14)$$

Muons are also present in a NS if the Fermi energy is greater than the muon rest energy  $m_\mu c^2$ . Muon neutrinos are then produced by reactions.

$$n + n \longrightarrow n + p + \mu + \nu_\mu^- \quad (2.7.15)$$

$$n + p + \mu^- \longrightarrow n + n + \nu_\mu \quad (2.7.16)$$

These reactions are the muon-neutrino emitting reactions which occurs when ever  $\mu_e > m_\mu c^2$  ( $\rho \geq 8 \times 10^{14}$ )gcm<sup>-3</sup>. In the succeeding sections we shall calculate the cooling rate at which a neutron star loses energy due to these modified URCA reactions. In the ideal Fermi gas approximation, the following relations hold approximately for  $\rho \leq 2\rho_{nuc}$ (i.e. nonrelativistic nucleons) [3]:

$$n_n = 1.7 \times 10^{38} \left( \frac{\rho}{\rho_{nuc}} \right) \text{cm}^{-3} \quad (2.7.17)$$

$$n_e = n_p = 9.6 \times 10^{35} \left( \frac{\rho}{\rho_{nuc}} \right)^2 \text{cm}^{-3} \quad (2.7.18)$$

$$E'_F(n) = E_F(e) = 60 \left( \frac{\rho}{\rho_{nuc}} \right)^{\frac{2}{3}} \text{MeV} \quad (2.7.19)$$

$$E'_F(p) = 1.9 \left( \frac{\rho}{\rho_{nuc}} \right)^{\frac{4}{3}} \text{MeV} \quad (2.7.20)$$

$$P_F(n) = 340 \left( \frac{\rho}{\rho_{nuc}} \right)^{\frac{1}{3}} \text{MeV}/c \quad (2.7.21)$$

$$P_F(n) = P_F(p) = 60 \left( \frac{\rho}{\rho_{nuc}} \right)^{\frac{2}{3}} MeV/c \quad (2.7.22)$$

Here  $\rho_{nuc} = 2.8 \times 10^{14} \text{gcm}^{-3}$  is the standard nuclear matter density.

## 2.8 Pulsar magnetic field decay

Investigations indicate that no significant magnetic decay occurs in a NS life time [34]. This raises a serious question of how magnetic moments of the so called millisecond pulsars (MPs) in Low-Mass X-Ray Binaries (LMXBs) decay from a typical value of  $\sim 10^{30} \text{Gcm}^3$  down to  $10^{25-26} \text{Gcm}^3$  in a time window of about  $10^{7-8}$  yrs [34]. Obviously ohmic decay alone cannot be responsible for the indicated magnetic moment. In fact whether or not magnetic moments of pulsars undergo ohmic decay still an open question [9]. This problem has recently prompted a series of semi-empirical models for magnetic moment decay including mass accretion induced decay scenarios [34]. However; our work will be based on a previous work in which it was shown that spinning polarization charges are the most likely sources for NS magnetic fields. These fields were indicated to be internal temperature dependent by way of temperature dependence of the associated polarization field. Therefore; they are expected to decay as a result of cooling of the NS interior [19]. The present model for field decay is strongly linked to the long term (1-10 billion years) cooling of the NS core due to neutrino and photon emissions. In the early stage of neutron star life (about a million years) magnetic decay as a result of neutrino emission is the dominant even though during this time is just by one order of magnitude. [9] have from their simulation studies of only limited (low magnetic field pulsars) concluded that for up to 100 million years pulsar fields will not decay. Our work will show that the high magnetic field pulsars indeed decay during this window of time. Thereafter, magnetic field decays as a result of photon emission will be prominent for about 10 billion years. As stated in the introduction above pulsar is generally a fast spinning compact objects formally referred to as a NS with a radius  $\sim 10 \text{ km}$  and mass  $\simeq 1.4M_{\odot}$ . It is formed

by way of a process known as a supernova explosion. A pulsar normally spins in the range of 30-35 ms. A Theoretical model for surface magnetic field of NSs has already been developed by the author based on spinning separated charges that arise as a result of plasma diffusion process inside NS matter [19]. According to this model NS surface magnetic fields are temperature and spin frequency dependent can be related as :

$$B \propto \frac{Q(T)\Omega}{Rc} \quad (2.8.1)$$

where  $\Omega$  is the rotational frequency. This suggests that Ns surface magnetic fields decay as a result of various cooling and braking mechanisms. NSs cool as a result of neutrino and photon emissions. However, we concentrate on magnetic decay resulting from cooling sources particularly photon emissions. The contributions from braking sources such as magnetic dipole radiations and gravitational radiation to magnetic decay particularly in older pulsars (MSPs) are small as compared to that from photon emission and therefore can be neglected. A closer look at the Eqn.(2.8.1) reveals that mass accretion in (ms) pulsars could lead to magnetic field revival due to spin up (in a form of rise in  $\Omega$  ) or the transfer of angular momentum to the pulsar [32]. However; in a new model the magnetic field revival resulting from mass accretion is about two orders of magnitude smaller than the decay rate due to photon emissions [19]. According to relativistic plasma diffusion a magnetic field Eqn. (2.8.1) above can be written as:

$$B = \frac{2Q(T)\Omega}{3Rc} \quad (2.8.2)$$

where Q is magnitude of separated charges,  $\Omega =$  is the rotational frequency of neutron star, R = is radius of neutron star, and c = is speed of light. Standard calculations indicate that neutrino emissions are the dominant cooling mechanism for up to  $10^5$  yrs [33]. According to these calculations, the initial internal temperature of  $T \geq 10^{11}$  K will eventually cool down to  $T \sim 10^9$  K in a matter of eight hours (or  $10^{-3}$  yr) due to the intense neutrino cooling processes. At this temperature the system is not only

degenerate but also cool enough to form a crystalized solid crust. However, when the internal temperature falls below  $10^8$  K in time window of  $\sim 10^5$  years, photon emissions become the dominant cooling mechanism for the rest of neutron star's life [34]. So for the sake of being consistent with the original model, we have preferred to consider  $10^9$  K as the initial temperature for all our calculations.

## 2.9 Summary

In this unit we have discussed extensively about neutron star. A NS is the collapsed core of a massive star left behind after a supernova explosion. The original massive star contained between 8 and 20 times the mass of our Sun, that is, 8-20  $M_{\odot}$ . Depending up on the mass of the core of dying star, the remnant is a compact star which is a white dwarf ( $M \lesssim 1.44 M_{\odot}$ ), a NS ( $\sim 1.44 < M \lesssim 3 M_{\odot}$ ) or a black holes ( $M \gtrsim 3 M_{\odot}$ ). This shows more massive stars collapse into black holes. Pulsars are a special category of spinning neutron stars, discovered in 1967 by Jocelyn Bell, an astronomy graduate student working with Prof. Antony Hewish at Cambridge University in England. Pulsars derive their name from “pulsating radio sources” because they were first observed at radio wave frequencies. All pulsars are NSs, but (so far as we know ) not all NSs are pulsars, because not all NSs radiate light (such as radio waves or X-rays) with such steady pulses. Pulsars are divided into two main categories, isolated pulsars and binary pulsars. Isolated pulsars (which include most radio pulsars) produce radiation primarily through their rotation, as they gradually slow down and cool off. Their light is generated by electrons caught in the pulsar's strong magnetic field, concentrated and emitted near the magnetic poles. There are different popular hypothesis about possible sources of neutron star magnetic fields such as the fossil field hypothesis also called ”flux conservation”, “flux freezing” and spinning of separated charges. Magnetars are a NSs with huge magnetic storms (or the highest magnetic fields). Those huge fields are believed to form either via alph-dynamo soon after birth or as a result of fossil fields from a every magnetic progenitor star. NSs

are born very hot in supernova explosions, with internal temperature  $T \geq 10^{11} K$  but gradually cool down. The cooling of neutron star can be realized via two channels: By neutrino emission from the entire stellar body, the neutrino cooling stage (neutrino luminosity  $L_\nu \gg L_\gamma$  lasts for  $t \leq 10^5$  years); the cooling is produced by neutrino emission from the stellar interior (mainly from the core) and during the photon cooling stage ( $L_\gamma \gg L_\nu$ ,  $t \geq 10^5$  years) the star cools via photon emission from the surface and the evolution of the internal temperature is governed by the radiation from the stellar surface, and hence it is sensitive to properties of the outer parts of the star by transport of heat from the internal layers to the surface resulting in the thermal emission of photons. It is generally believed that NSs are formed at very high interior temperatures ( $T \geq 10^{11}$ ) K in the core of a supernova explosion. The predominant cooling mechanism immediately after formation is neutrino emission, with an initial cooling timescale of seconds. After about a day, the internal temperature drops to  $10^9 - 10^{10}$  K. Photon emission overtakes neutrinos only when the internal temperature falls to  $\sim 10^8$  K with a corresponding surface temperature roughly two orders of magnitude smaller.

# Chapter 3

## Cooling rate and magnetic field decay laws

### 3.1 Introduction

As we have been discussed in chapter two, when the reaction takes place in the core of NS the thermal energy loss through the neutrino emission in different ways. This thermal energy can be expressed in the following section by describing the temperature as a function of time in different reactions which take place during the cooling process of NSs not only in its interior but also on the surface. Based on this discussion the theoretical results are compared with observations of thermal radiation from NSs.

Under this chapter we are going to derive separately the temperature of a NS as a function of time  $T(t)$  for some reactions and derive the magnetic decay law corresponding to this cooling rates.

### 3.2 Cooling rates

The thermal energy of the star resides almost exclusively in degenerate fermions (neutrons or quarks). Neglecting interactions, the heat capacity of  $N$  such particles of mass  $m$  and

relativity parameter  $\chi = \frac{P_f}{mc}$  is

$$C_\nu = Nc_\nu \equiv \frac{dU}{dT}/N, V = \frac{\pi^2}{\chi^2} (\chi^2 + 1) \left( Nk \right) \left( \frac{kT}{mc^2} \right) \quad (3.2.1)$$

where  $c_\nu$  is the specific heat per particle. Now integrating Eqn.(3.2.1) you will find the total thermal energy U for N particles. (Note that the quantity  $\chi$  remains constant to the least order), which gives

$$U \simeq \frac{\pi^2}{2\chi^2} (\chi^2 + 1)^{\frac{1}{2}} k \left( \frac{kN}{mc^2} T^2 \right) \quad (3.2.2)$$

The total thermal energy  $U_n$  for a normal NS of mass M, density  $\rho$  and temperature T is

$$U_n \simeq \frac{\pi^2}{2\chi^2} (\chi^2 + 1)^{\frac{1}{2}} \left( \frac{Nk^2}{m_n c^2} \right) T^2 \quad (3.2.3)$$

Assuming that  $\chi \ll 1$ , we get

$$U_n \simeq \frac{\pi^2}{2\chi^2} \left( \frac{Nk^2}{m_n c^2} \right) T^2 \quad (3.2.4)$$

But  $N = n_n V$ , where  $V = \frac{M}{\rho}$  is the volume of the NS and using Eqns. (2.7.17) & (2.7.21) we get:

$$U_n \simeq \frac{\pi^2 n_n m_n k^2}{2P_F^2(n)} \left( \frac{M}{\rho} \right) T^2 \quad (3.2.5)$$

$$U_n \simeq \pi^2 \left[ 1.7 \times 10^{38} \left( \frac{\rho}{\rho_{nuc}} \right) \text{cm}^{-3} \right] m_n k^2 \left( \frac{M}{\rho} \right) T^2 \quad (3.2.6)$$

Where  $m_n = 1.6749 \times 10^{-27}$  Kg is the neutron mass  $c = 2.9979 \times 10^8$  m/s is the speed of light in vacuum.  $k = 1.3806 \times 10^{-23}$  J/K Boltzmann's constant. By substituting the values which describe above into Eqn.(3.2.6) and multiplying it by  $\left( \frac{M_\odot}{M} \right)$  and  $\left( \frac{\rho_{nuc}}{\rho} \right)$

we obtain

$$U_n \simeq 6 \times 10^{47} \text{erg} \left( \frac{M}{M_\odot} \right) \left( \frac{\rho}{\rho_{\text{nuc}}} \right)^{\frac{-2}{3}} T_9^2 \quad (3.2.7)$$

Similarly, we can follow the same procedure to calculate the thermal energy by quark neutrino emissions.

$$U_q = \simeq 9 \times 10^{47} \text{erg} \left( \frac{M}{M_\odot} \right) \left( \frac{n}{n_{\text{nuc}}} \right)^{\frac{-1}{3}} T_9^2 \quad (3.2.8)$$

The temperature  $T$  appearing in Eqns.(3.2.1) to (3.2.8) is the interior temperature and  $T_9$  is the temperature in units of  $10^9$  K. NS interiors are to good approximation isothermal, because of the high thermal conductivity of the degenerate electron gas. It is only in the low-density, nondegenerate, outermost layer that an appreciable temperature gradient exists [35].

The Cooling Equation is

$$\frac{dU}{dT} = C \frac{dT}{dt} = - \left( L_\nu + L_\gamma \right) \quad (3.2.9)$$

Where  $L_\nu$  is the total neutrino luminosity and  $L_\gamma$  is the photon luminosity [3]. Assuming black body photon emission from the surface at an effective surface temperature  $T_e$  we have

$$L_\gamma = 4\pi R^2 \sigma T_e^4 = 7 \times 10^{36} \text{erg/s} \left( \frac{R}{10\text{km}} \right)^2 T_{e,7}^4, \quad (3.2.10)$$

where  $\sigma$  is the Stefan-Boltzmann constant and  $T_{e,7}$  is temperature in units of  $10^7$  K [3]. Inserting the appropriate luminosities into Eqn.(3.2.9) and integrating gives the time for the star to cool from an initial interior temperature  $T_i$  to a final temperature  $T_f$ . The

cooling time during neutrino emission in the modified URCA process is calculated from

$$\frac{dU_n}{dt} = -L_\nu^{URCA}, \quad (3.2.11)$$

where  $L_\nu^{URCA} = 5.3 \times 10^{39} \text{ erg/s} \left(\frac{M}{M_\odot}\right) \left(\frac{\rho_{nuc}}{\rho}\right)^{\frac{1}{3}} T_9^8$  from Eqn.(2.7.12) above and we have

$$U_n \simeq 6 \times 10^{47} \text{ erg} \left(\frac{M}{M_\odot}\right) \left(\frac{\rho}{\rho_{nuc}}\right)^{\frac{-2}{3}} T_9^2$$

So differentiating  $U_n$  with respect to temperature (T) we get :  $\frac{dU_n}{dT} = 12 \times 10^{47} \text{ erg} \left(\frac{M}{M_\odot}\right) \left(\frac{\rho_{nuc}}{\rho}\right)^{\frac{-2}{3}} T_9$

$$dU_n = 1.2 \times 10^{48} \text{ erg} \left(\frac{M}{M_\odot}\right) \left(\frac{\rho_{nuc}}{\rho}\right)^{\frac{-2}{3}} T_9 dT \quad (3.2.12)$$

Substituting into Eqn.(3.2.11) then,  $dt = - \frac{1.2 \times 10^{48} \text{ erg} \left(\frac{M}{M_\odot}\right) \left(\frac{\rho_{nuc}}{\rho}\right)^{\frac{2}{3}} T_9 dT}{5.3 \times 10^{39} \frac{\text{erg}}{\text{s}} \left(\frac{M}{M_\odot}\right) \left(\frac{\rho_{nuc}}{\rho}\right)^{\frac{1}{3}} T_9^8}$

After we simplify this equation and integrate it as follow

$$\int_{t(i)}^{t(f)} dt = - 2.3 \times 10^8 \text{ sec} \left(\frac{\rho_{nuc}}{\rho}\right)^{\frac{1}{3}} \int_{T(i)}^{T(f)} \frac{dT}{T_9^7}$$

$$\Delta t \simeq 1.2 \text{ yr} \left(\frac{\rho_{nuc}}{\rho}\right)^{\frac{1}{3}} \left(T_{9(f)}^{-6} - T_{9(i)}^{-6}\right) \quad (3.2.13)$$

Therefore, the temperature of NS as a function of time for modified URCA reaction becomes

$$T_f^{URCA}(t) = 10^9 K \left[ \frac{0.83t}{\text{yr}} \left(\frac{\rho}{\rho_{nuc}}\right)^{\frac{1}{3}} + 10^{-12} \right]^{\frac{-1}{6}} \quad (3.2.14)$$

From Eqn.(2.7.14) we have  $L_\nu^{quark} \simeq 1.3 \times 10^{44} \frac{\text{ergs}}{\text{s}} \left(\frac{M}{M_\odot}\right) T_9^6$  and using Eqn.(3.2.8) the

cooling time of NS during neutrino emission in quark beta decay is calculated as follows:

$$\frac{dU_q}{dt} = -L_\nu^{quark} \quad (3.2.15)$$

Let us derivate  $U_q$  with respect to temperature ( $T$ )

$$dU_q = 1.8 \times 10^{48} \text{ erg} \left( \frac{M}{M_\odot} \right) \left( \frac{n_{nuc}}{n} \right)^{\frac{-1}{3}} T_9 dT \quad (3.2.16)$$

Substituting Eqn.(3.2.16) into Eqn. (3.2.15).

$$dt = -1.38 \times 10^{34} \text{ sec} \left( \frac{n_{nuc}}{n} \right)^{\frac{1}{3}} T_9^6 T_9 dT$$

$$\int_{t(i)}^{t(f)} dt = -1.38 \times 10^4 \text{ sec} \left( \frac{n_{nuc}}{n} \right)^{\frac{1}{3}} \int_{T(i)}^{T(f)} T_9^{-5} dT$$

Hence;

$$\Delta t(quark) \simeq 1hr \left( \frac{n_{nuc}}{n} \right)^{\frac{1}{3}} \left( T_{9(f)}^{-4} - T_{9(i)}^{-4} \right) \quad (3.2.17)$$

Therefore, the temperature of a NS as a function of time for quark beta decay can be expressed :

$$T_f^{quark}(t) = 10^9 K \left[ \frac{t}{hr} \left( \frac{n}{n_{nuc}} \right)^{\frac{1}{3}} + 10^{-8} \right]^{\frac{1}{4}} \quad (3.2.18)$$

Detailed calculation by Tsuruta and Malone indicate that in general the surface and interior temperature of a NS are related by:

$$\frac{T_e}{T} \sim 10^{-2} \alpha \quad 0.1 \lesssim \alpha \lesssim 1 \quad (3.2.19)$$

where  $T_e$  and  $T$  are effective temperature(surface temperature) and internal temperature respectively, both are measured in degrees K [3].

Now if photon emission is ever dominant energy loss mechanism, then Eqns.(3.2.7), (3.2.10) and (3.2.19) gives

$$\Delta t(\text{photons}) = 1.9 \times 10^3 yr \alpha^{-2} \left( \frac{M}{M_{\odot}} \right)^{\frac{1}{3}} \left( T_{e,7(f)}^{-2} - T_{e,7(i)}^{-2} \right) \quad (3.2.20)$$

where the relation  $M = \left( \frac{4\pi\rho R^3}{3} \right)$  has been used to eliminate R and we assumed that  $\alpha \simeq$  constant for short time intervals [3]. Therefore, the temperature of a NS as a function of time for photon emission can be expressed:

$$T_{e(f)}^{photon}(t) = 10^7 K \left[ 0.5 \times 10^{-3} t \alpha^2 yr^{-1} \left( \frac{M_{\odot}}{M} \right)^{\frac{1}{3}} + 10^{-4} \alpha^{-2} \right]^{\frac{-1}{2}} \quad (3.2.21)$$

### 3.3 Magnetic field decay due to photon emission

Here we will derive an expression for the magnetic decay as a result of photon emission as a function of time ( $t$ ). As we tried to mention in the previous sections NSs are born in supernova explosions at very high internal temperature greater than  $10^{11}$  K and eventually cool down to various cooling mechanisms. Standard calculations indicate that neutrino emission is the dominant cooling mechanism for the first  $10^5$  years [28]. However, when the internal temperature falls below  $10^8$  K in a time Window of  $\sim 10^5$  yrs photon emission becomes dominant cooling mechanism for the rest of neutron star's life [36].

The corresponding photon luminosity becomes:

$$L_{\gamma} = 4\pi R^2 \sigma T_{es}^4 g_{00}^{-1}, \quad (3.3.1)$$

where  $T_{es}$  is the observable overall effective surface temperature related to the internal temperature T approximately by (Tsuruta, 1979). That means photon emission overtakes neutrino only when the internal temperature falls to about  $10^8$  K with surface temperature

of about  $10^6$  K the temperature interrelated as;

$$T_{es} = \left(10T\right)^{\frac{2}{3}} \quad (3.3.2)$$

The magnetic field beyond this particular point in time can be estimated from the relation (ignoring the contribution from braking/spinup process which under normal conditions are expected to be minimal) [8]. The decay rate is given by

$$\left(\frac{dB}{dt}\right)_{\Omega} = \left(\frac{\partial B}{\partial T}\right)_{\Omega} \times \frac{dT_7}{dt}, \quad (3.3.3)$$

where  $\left(\frac{\partial B}{\partial T}\right)_{\Omega}$  and  $\frac{dT}{dt}$  are obtained from our model and standard cooling equations respectively as follows.

According to our new model NS surface magnetic fields are temperature and spin frequency dependent Eqn.(2.8.1). Using Gauss's law we can calculate (-/+ ) charge as follows

$$\oint_S \vec{E} \cdot d\vec{a} = \frac{Q}{\epsilon_0} \quad (3.3.4)$$

where  $\epsilon_0 = 8.85 \times 10^{-12} \frac{C^2}{Nm^2}$ .

The magnitude of  $\vec{E}$  is constant over the Gaussian surface,

$$\int_S \vec{E} \cdot d\vec{a} = |E| \int_S da = |E|4\pi^2 r^2 \quad (3.3.5)$$

$$\frac{Q}{\epsilon_0} = |E(r)|4\pi^2 r^2 \quad (3.3.6)$$

$$Q = 4\pi^2 \epsilon_0 r^2 |E(r)| \quad (3.3.7)$$

where  $E(r)$  is the electric field due to the space charge created as a result of the diffusion process is approximated as [19].

$$E(r) \sim \frac{1}{\rho_{\text{nuc}}} \left( \frac{m_p^*}{m_e^*} \right) \left( \frac{k_\beta T}{|e|} \right) \frac{\partial \rho(r)}{\partial r} \quad (3.3.8)$$

where  $m_p^*$  and  $m_e^*$  are effective electron and proton masses respectively,  $|e|$  is the absolute magnitude of the electron charge,  $\rho_{\text{nuc}}$  is nuclear density  $\rho(r)$  is the rest mass density of NS matter. Substituting Eqn.(3.3.8) in to Eqn.(3.3.7) we obtain:

$$Q = 4\pi^2 \epsilon_0 r^2 \frac{1}{\rho_{\text{nuc}}} \left( \frac{m_p^*}{m_e^*} \right) \left( \frac{k_\beta T}{|e|} \right) \frac{\partial \rho(r)}{\partial r} \quad (3.3.9)$$

where  $\rho(r)$  is given by [37].

$$\rho(r) = \frac{3}{56\pi G r^2} \quad (3.3.10)$$

where  $G$  is universal gravitational constant. Derivating Eqn.(3.3.10) with respect to  $r$  one can obtain

$$\frac{\partial \rho(r)}{\partial r} = \frac{-6}{56\pi G r^3} \quad (3.3.11)$$

Then Eqn.(3.3.9) becomes

$$Q(T) = \frac{-3}{7} \left( \frac{\epsilon_0}{\rho_{\text{nuc}} r G} \right) \left( \frac{m_p^*}{m_e^*} \right)^2 \frac{k_\beta T}{|e|} \quad (3.3.12)$$

Now we consider the dipolar magnetic field [8,19]. Which is given by:

$$B = \frac{-2}{3} \frac{Q(T)}{Rc} \Omega \quad (3.3.13)$$

Therefore, by substituting Eqn.(3.3.12) in to Eqn.(3.3.13) we obtain

$$B = \frac{2}{7} \left( \frac{\epsilon_0}{\rho_{\text{nuc}} G} \right) \left( \frac{m_p^*}{m_e^*} \right)^2 \frac{k_\beta T \Omega}{|e| R^2 c} \quad (3.3.14)$$

where  $r = R$ . Derivating Eqn.(3.3.14) with respect to temperature keeping angular frequency constant we obtain the following expression

$$\left( \frac{\partial B}{\partial T} \right)_\Omega = \frac{2}{7} \left( \frac{\epsilon_0}{\rho_{\text{nuc}} G} \right) \left( \frac{m_p^*}{m_e^*} \right)^2 \frac{k_\beta \Omega}{|e| R^2 c} \quad (3.3.15)$$

The cooling rate due to photon emission can be calculated from

$$\frac{dT}{dt} = - \frac{1}{q} \int g_{00}^{-1} n \varepsilon_\gamma dV_P, \quad (3.3.16)$$

where  $dV_P$  is the proper volume element,  $g_{00}$  is the metric tensor,  $n$  is baryon density,  $q$  is heat capacity and  $\varepsilon_\gamma$  is the total photon emissivity per baryon.

From Post-Newtonian approximation we have the following facts.

$$g_{00} = -1 + \frac{2}{g_{00}} + \frac{4}{g_{00}} + \dots \quad (3.3.17)$$

$$g_{ij} = \delta_{ij} + \frac{2}{g_{ij}} + \frac{4}{g_{ij}} + \dots \quad (3.3.18)$$

$$g_{i0} = \frac{3}{g_{i0}} + \frac{5}{g_{i0}} + \dots \quad (3.3.19)$$

The inverse of metric tensor is defined by the equations:

$$g^{i\mu} g_{0\mu} = g^{i0} g_{00} + g^{ij} g_{j0} = 0 \quad (3.3.20)$$

$$g^{0\mu}g_{0\mu} = g^{00}g_{00} + g^{0i}g_{0i} = 1 \quad (3.3.21)$$

$$g^{i\mu}g_{j\mu} = g^{i0}g_{j0} + g^{ik}g_{jk} = \delta_{ij} \quad (3.3.22)$$

We expected that

$$g^{00} = -1 + g_{00}^2 + g_{00}^4 + \dots \quad (3.3.23)$$

$$g^{ij} = \delta_{ij} + g_{ij}^2 + g_{ij}^4 + \dots \quad (3.3.24)$$

$$g^{i0} = g_{i0}^3 + g_{i0}^5 + \dots \quad (3.3.25)$$

Inserting these expansions in to defining Eqns.(3.3.20 to 3.3.22) we obtain:

$$g_{00}^2 = g_{00}$$

$$g_{ij}^2 = -g_{ij}$$

$$g_{i0}^3 = g_{i0}$$

So that we can kept only the first term of Eqn.(3.3.17) above by vanishing the other terms. That means,  $g_{00} = -1$ . Therefore; we can have:

$$g_{00}^{-1} = \frac{1}{g_{00}} = -1 \quad (3.3.26)$$

Therefore, Eqn.(3.3.16) can be reuced as

$$\frac{dT}{dt} = -\frac{1}{q} \int n\varepsilon_{\gamma} dV_P, \quad (3.3.27)$$

The integral stands for photon luminosity  $L_\gamma$  and the heat capacity  $q$  is given by

$$q = \int n C_\nu dV_p, \quad (3.3.28)$$

where  $C_\nu$  is the specific heat per baryon. Eqns.(3.3.16) and (3.3.28) provide the cooling law due to photon emissions in the time window of  $\sim 10^5$  yrs as [33] . The cooling equation as Shapiro and Teukolsky [3].

$$\frac{dU}{dt} = C_\nu \frac{dT}{dt} = -\left(L_\nu + L_\gamma\right), \quad (3.3.29)$$

where  $U$  is the total thermal energy for a NS,  $L_\nu$  is the total neutrino luminosity (energy transported by neutrinos per unit time) and  $L_\gamma$  is the photon luminosity (energy transported by photons per unit time) [3]. Assuming blackbody photon emission from the surface at an effective surface temperature  $T_e$ , we have [3].

$$L_\gamma = 4\pi R^2 \sigma T_{e,7}^4 = 7 \times 10^{36} \text{erg/s} \left(\frac{R}{10\text{km}}\right)^2 T_{e,7}^4, \quad (3.3.30)$$

where  $\sigma$  is the Stefan-Boltzmann constant and  $T_{e,7}$ , is the temperature in units of  $10^7$  K. Tsuruta and Malone indicate that in general the surface and interior temperature of a NS are related by Eqn (3.2.19) or in terms of mass of NS can be related as [3].

$$\frac{T_e}{T} \simeq 1 \times 10^{-2} T_9^{-\frac{1}{8}} \left(\frac{M}{M_\odot}\right)^{\frac{1}{4}} \left(\frac{R}{10\text{km}}\right)^{-\frac{1}{2}}, \quad (3.3.31)$$

and we have also the total thermal energy  $U_n$  for a NS of mass  $M$ , density  $\rho$  and temperature  $T$  is

$$U_n \simeq 6 \times 10^{47} \text{erg} \left(\frac{M}{M_\odot}\right) \left(\frac{\rho}{\rho_{\text{nuc}}}\right)^{-\frac{2}{3}} T_9^2 \quad (3.3.32)$$

During the photon cooling stage ( $L_\gamma \gg L_\nu$ ) for  $t \geq 10^5$  yrs; the cooling is produced by photon emission from the surface of NS. Thus, the photon luminosity during these

process can be calculated from

$$\frac{dU}{dt} = -L_{\gamma}^{\text{URCA}}. \quad (3.3.33)$$

Substituting Eqns.(3.3.30), (3.3.31) and (3.3.32) in to Eqn.(3.3.33) after some simplification one can obtain

$$\frac{dT_7}{dt} = -5 \times 10^{-5} \text{yr}^{-1} \left( \frac{M}{M_{\odot}} \right)^{-\frac{1}{3}} \left( T_7^{\frac{5}{3}} \right), \quad (3.3.34)$$

where  $T_7 = T \times 10^{-7}$ ,  $M = \text{mass of NS}$ ,  $M_{\odot} = \text{solar mass}$ . By integrating the above Eqn.(3.3.34) we can relate temperature  $T$  and time  $t$  as follows:

$$t - t_0 = 3 \times 10^4 \left( \frac{M}{M_{\odot}} \right)^{\frac{1}{3}} \left[ \frac{1}{T_{f,7}^{\frac{2}{3}}} - \frac{1}{T_{i,7}^{\frac{2}{3}}} \right] \text{yr}. \quad (3.3.35)$$

From Eqn.(3.3.35) we can write temperature  $T_7$  in terms of time  $t$  (in years) as follows:

$$T_7 = \left[ 3 \times 10^{-5} \text{yr}^{-1} \left( \frac{M}{M_{\odot}} \right)^{-\frac{1}{3}} t + T_{i,7}^{-\frac{2}{3}} \right]^{-\frac{3}{2}} \quad (3.3.36)$$

Now inserting Eqn.(3.3.15) and Eqn.(3.3.34) in to Eqn.(3.3.3) above we obtain

$$\left( \frac{dB}{dt} \right)_{\Omega} = \frac{2}{7} \left( \frac{\epsilon_0}{\rho_{\text{nuc}} G} \right) \left( \frac{m_p^*}{m_e^*} \right)^2 \frac{k_{\beta} \Omega}{|e| R^2 c} \frac{dT_7}{dt}, \quad (3.3.37)$$

this implies that

$$\left( \frac{dB}{dt} \right)_{\Omega} = B^0 \frac{dT_7}{dt}, \quad (3.3.38)$$

where  $B^0 = \frac{2}{7} \left( \frac{\epsilon_0}{\rho_{\text{nuc}} G} \right) \left( \frac{m_p^*}{m_e^*} \right)^2 \frac{k_{\beta} \Omega}{|e| R^2 c}$

Thus, integrating Eqn.(3.3.38) both sides we obtain the magnetic field decay law due to

photon emissions as a function of time becomes:

$$B(t) = B_2^{(0)} \left[ 1.47 \times 10^{13} \left( \frac{M}{M_\odot} \right)^{\frac{1}{2}} \left( \frac{K}{T^0} \right) \right] \left( \frac{t}{\text{yr}} \right)^{-\frac{3}{2}}, \quad (3.3.39)$$

where  $B^{(0)} = B(t \sim 10^5 \text{ yrs})$

$T^{(0)} = T(t \sim 10^5 \text{ yrs})$

# Chapter 4

## Result and discussions

Under this chapter we are going to plot some graphs based on derived equations in the previous section. In addition to these we will interpret, describe and compare our theoretical results with related research conducted as well as observations.

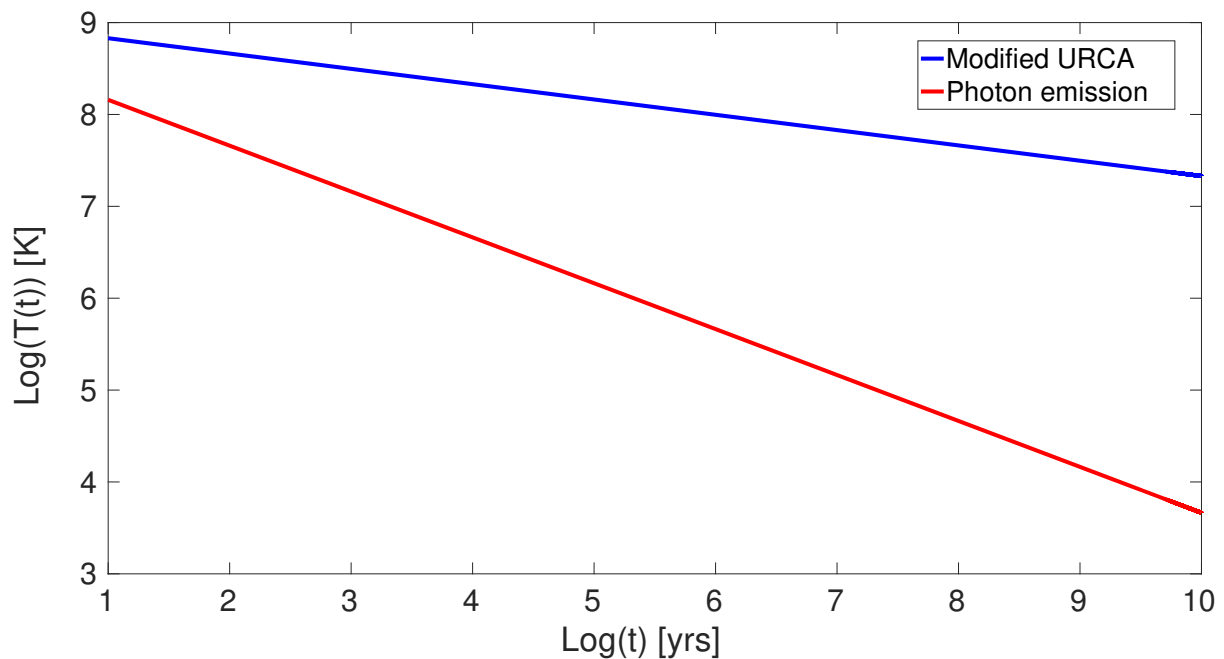


Figure 4.1: Schematic neutron star cooling curves of interior temperature versus time for two processes.

Figure 4.1 shows the cooling process plotted as a function of time for NS with  $M = 1.4 M_{\odot}$  and  $\alpha$  is very small  $\approx 1$  based on Eqns.(3.2.14) and (3.2.21). As seen from the

graph the red line (photon emissions) is more steeper than the blue line(modified URCA) process. This shows the most effective cooling process at any time will be the lowest  $T(t)$  in another word photon emissions is dominant energy loss mechanism than neutrino emissions in the modified URCA process. As we can see from the graph, as the time increases the internal temperature of neutron star declines so that the cooling process will be effective.

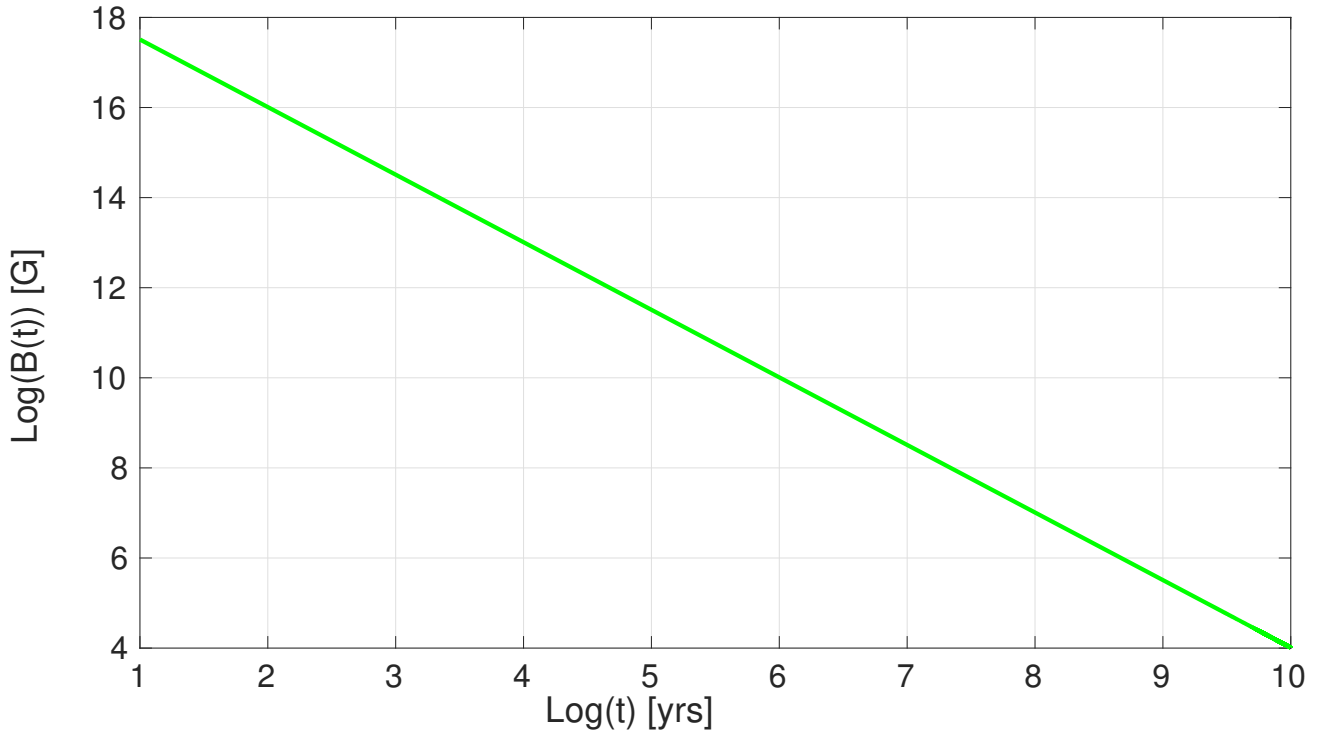


Figure 4.2: Pulsar magnetic field decay curve due to photon emissions.

Figure 4.2 this graph shows the pulsar magnetic field versus decaying time based on the Eqn.(3.3.39) for  $10^1 \leq t \leq 10^{10}$  yrs. As we can see from the graph as the time increases the magnetic field of pulsars fall down. Which is in good agreement with widely accepted theoretical model.

Table below shows lists of the parameters of the detected high-energy gamma-ray known pulsars including the surface magnetic fields ( $B_s$ ), surface temperature ( $T_s$ ), the spin period ( $P$ ), characteristics age ( $\tau_c$ ) and spin down energy loss rate ( $\dot{E}$ ) [38].

Based on data collected in table 1 below and using equation (3.3.39) we can plot the

Name of PSR	$B_0(10^{12} \text{ G})$	$T_s(10^6 \text{ K})$	P(ms)	$\tau_c(\text{kyr})$	$\dot{E}(\text{ergs/s})$
Crab pulsar	7.6	1.6	33.4	1.3	$4.5 \times 10^{38}$
Geminga	1.6	0.52	237.1	340	$3.3 \times 10^{34}$
Vela pulsar	3.3	1.55	89.3	11	$6.9 \times 10^{36}$
PSR B1509-58	31	1.8	150	1.5	$1.8 \times 10^{37}$
PSR B1055-52	9.7	0.69	197.1	530	$3.0 \times 10^{34}$
PSR B1706-44	3.1	2	102.4	17	$3.4 \times 10^6$
PSR B1951+32	8.2	0.78	39.5	110	$3.7 \times 10^{36}$

Table 4.1: the seven well known gamma-ray pulsars.

seven known high-energy gamma ray pulsars for  $10^1 \leq t \leq 10^{10}$  yrs as follows:

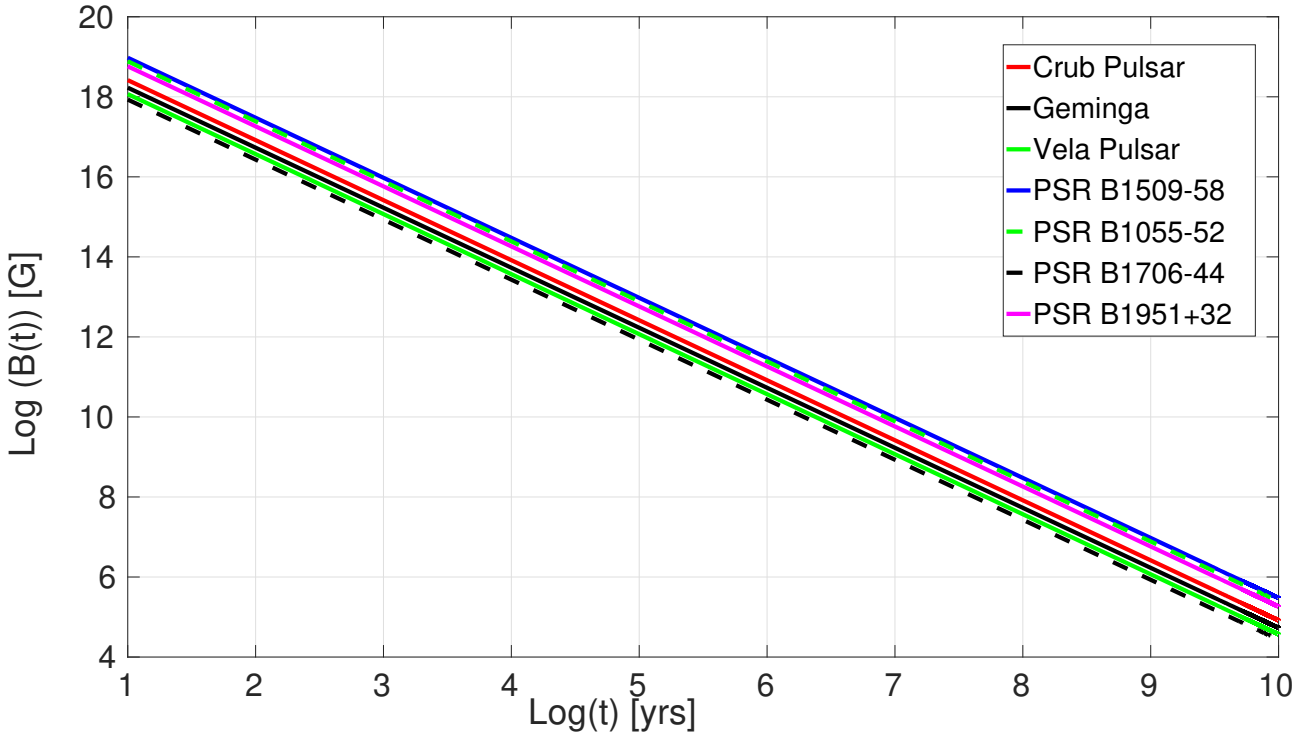


Figure 4.3: Surface magnetic field as function of time, with different initial magnetic field strengths for seven well known pulsar's.

Figure 4.3 graphical comparison of the seven well known pulsars, this is to confirm that how much theoretical pulsar magnetic field decay fits with the observations. As we can see from the graph their decay almost very close to each other because of their initial surface magnetic field and surface temperatures are nearly the same.

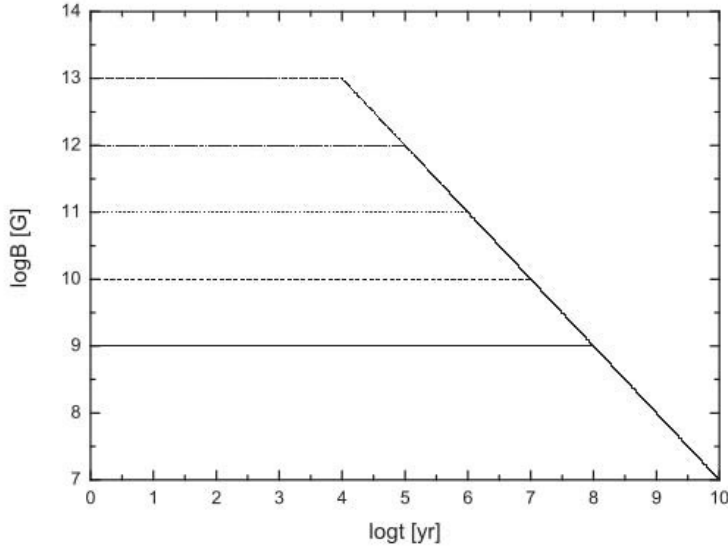


Figure 4.4: Surface magnetic field as function of time, with different initial magnetic field strengths  $B_0 = 10^9$  G represents solid line,  $B_0 = 10^{10}$  G represents dashedline,  $B_0 = 10^{11}$  G dotted line,  $B_0 = 10^{12}$  G represents dashed dotted line &  $B_0 = 10^{13}$  G represents dashed-dot-dotted line.(Taken from <http://www.raa-journal.org>)

Figure 4.4 shows the evolution of the surface magnetic field with different initial magnetic field strengths and the corresponding beginning times for decay. Since the cooling of neutron star is a process that follows a long time scale, the time scales for oscillation is on the order of yrs. The magnetic fields of the star are about  $10^8$  G at  $10^9$  yrs which agrees with observations of old millisecond pulsars. However, the decay of the magnetic field results in the older NSs having different surface temperatre with almost same magnetic field strengths, which will change our understanding of cooling millisecond pulsars [42]. Depending on the existing observations, if the magnetic field does not decay millisecond pulsars may have lower magnetic field strength at their birth. The magnetic field decays to about  $10^{7-8}$  G depending on the initial magnetic field. For a typical NS of  $R = 10$  km, surface magnetic field of this strength generate a magnetic moments of about  $10^{25-26}$  Gcm<sup>3</sup>. This particular value is what magnetic moments of most MSPs in LMXBs are known to crowd around [40]. Our finding is not only in good agreement with widely accepted scenario for MSPs that they are recycled old NS [41] but most importantly it also shows that our model for NS magnetic fields successfully addresses

the issue of how magnetic moments of MSPs decay from a typical value of  $10^{30} \text{ Gcm}^3$  down to  $10^{25-26} \text{ Gcm}^3$  in time span of  $10^{7-8}$  yrs [11]. Finally if we compare the slope for  $t \leq 10^5$  and  $t \geq 10^5$  from figure 4.4 it is clear that the photon branch of the cooling curve has a slope much steeper than that of the neutrino emission branch.

# Chapter 5

## Conclusion

This thesis work demonstrates some of the facts about NS which is formed at a very high temperature in the core of a supernova explosion caused by the death of a massive star that run out its nuclear fuel. During these process inward pressure due to gravity forces inverse beta decay ( $p + e \longrightarrow n + \nu_e$ ) to occur at higher densities  $\geq 10^{13} \text{ kgm}^{-3}$ . At densities  $\geq 10^{17} \text{ kgm}^{-3}$  the nuclei suddenly fall apart into a gas with more than 80 % neutrons. The neutrons so formed are degenerate and provide the degenerate gas pressure required to balance the inward pull of gravity and form a NS. From this point of view, this pressure allows the formation of a stable NS which is composed mainly of neutrons.

The emission of neutrinos take place in the core of NSs during the predominant cooling stage immediately after its formation. When the NS cools thermal energy losses through the emission of neutrino in the core and photon on the surface of NS. As we have seen from Eqns.(3.2.14) and (3.2.21) the most effective cooling process at  $t \leq 10^5$  yrs will be the neutrino emission during the modified URCA reaction and the photon emission overtakes the neutrino on the NS when  $t \geq 10^5$  yrs. That means, after the formation of NS the the surface temperature of NS is decrease rapidly than interior temperature during different reactions take place in the core of NS. These shows that the energy loss by neutrino emission depends on the interior temperature  $T$ , but the rate at which photons are emitted from the surface is governed by the effective temperature  $T_e$ .

In this thesis work we considered spinning separated charges are most likely sources for NS magnetic field. In such model the NS surface magnetic fields are not identified as dipolar but also shown to be temperature (T) and spin frequency ( $\Omega$ ) dependent as we derived in Eqns.(3.3.14) and (3.3.39).

In this work, we assume the magnetic field is decaying due a simple power-law, whereas the exponential decay are also discussed by some other reserchers (Igoshev & Popov 2013). The magnetic field follows an exponential decay that decreases slowly at the beginning but damps very quickly at the end. A higher magnetic field at the beginning leads to the fast extraction of rotational energy, but at the late stage, most of the rotational energy is converted into heat, and the magnetic field is so small [42].

The decay law given in Eqn.(3.3.39) and figure 4.3 are already indicated to provide results which are in good agreement with observations of the seven well known pulsars (Crab, PSR B1509-58, Vela, PSR B1706-44, PSR B1951 +32, Geminga and PSR B1055-52) because their surface magnetic field ranges from  $1.6 \times 10^{12}$  G -  $9.7 \times 10^{12}$  G. From figure 4.4 it is clear that the photon branch ( $t \geq 10^5$ ) of the cooling curve has a slope much steeper than that of the neutrino emissin branch ( $t \leq 10^5$ ). Therefore, we can conclude that the high magnetic field pulsars indeed decay during this window of time. There after, magnetic field decays as a result of photon emission will be prominent for about 10 billion years.

These cooling timescales were determined assuming that the neutrons and protons comprises a normal fluid how ever superfluidity would modify the results in two different ways. The specific heat capacity increases discontinuously as the temperature falls below the transition temperature, and then decreases exponentially at lower temperatures. So immediately above the transition temperature the cooling timescale increases, while at lower temperatures it decreases. Second, neutrino production processes are suppressed in a superfluid, thus increasing the cooling timescale [3]. Therefore, presenting the superfluid state of the nucleons and considering the corresponding parameters of pulsars, a more realistic cooling model can be compared with observations. This is our future goal.

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