



**ELECTRON ACCELERATION MECHANISM  
AND THE DIFFUSED RADIO EMISSION IN  
GALAXY CLUSTERS**

**By**

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**This Work is Dedicated**  
**to**  
**Ahmed Jemal Essa**

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## Abbreviations

<b>ACT</b>	Atacama Cosmology Telescope
<b>AGN</b>	Active Galactic Nuclei
<b>cD</b>	Central Dominant
<b>DSA</b>	Diffusive Shock Acceleration
<b>EGRS</b>	Extended Giant Radio Survey
<b>GMRT</b>	Giant Meterwave Radio Telescope
<b>ICM</b>	Intracluster Medium
<b>MACS</b>	Massive Cluster Survey
<b>MeerKAT</b>	South African MeerKAT Radio Telescope
<b>MHD</b>	Magnetohydrodynamic
<b>MWA</b>	Murchison Widefield Array
<b>NRAO</b>	National Radio Astronomy Observatory
<b>NVSS</b>	National Radio Astronomy Very Large Array Sky Survey
<b>SALT</b>	Southern African Large Telescope
<b>VLA</b>	Very Large Array
<b>WENSS</b>	The Westerbork Northern Sky Survey
<b>WSRT</b>	Westerbork Synthesis Radio Telescope
<b>XMM-Newton</b>	X-ray Multi-Mirror Newton Satellite

## Physical Constants

Speed of Light	$C = 2.99792458 \times 10^8 \text{ ms}^{-2}$
Universal Gravitational Constant	$G = 6.67 \times 10^{-11} \text{ Nm}^2 \text{ kg}^{-2}$
Mega parsec	$\text{Mpc} = 3.08568025 \times 10^{24} \text{ cm}$
Planck luminosity	$L_0 = 10^{59} \text{ egr/s}$
Mass of the Sun	$M_{\odot} = 1.99 \times 10^{33} \text{ g}$
Kilo parsec	$\text{kpc} = 3.08568025 \times 10^{21} \text{ cm}$
luminosity of the Sun	$L_{\odot} = 3.839 \times 10^{33} \text{ erg/s}$

## Symbols

$f_{GW}$	Gravitational Wave frequency in Hz
$L$	Total radiated luminosity in erg/s
$\rho_{crit}$	Critical energy density in $eV/cm^3$
$D_l$	Luminosity distance of the from the source to Earth in Mpc
$S_{GW}$	Power spectral density in unit of egr/sHz

## **Abstract**

The study of electron acceleration mechanisms in galaxy clusters is crucial for understanding the origin of diffused radio emission, which provides insights into the physical processes occurring in these massive cosmic structures. As massive structures in the Universe, galaxy clusters are sites of astrophysical processes that facilitate the acceleration of relativistic electrons. The diffuse radio emission, characterized by its synchrotron radiation. Our understanding of galaxy clusters, with implications for the broader study of cosmic evolution and large-scale structure formation is one of the fascinating topics Astrophysics. The extended diffuse radio emission in clusters are referred to as halos, relics and mini halos. The numbers of these sources grown in recent years making them to discuss their properties and different models for their origin. The origin of these diffuse source tightly connected to the process that leads to the cluster formation themselves.

# Galaxy Clusters and Search for Diffuse Source

## 1.1 Introduction

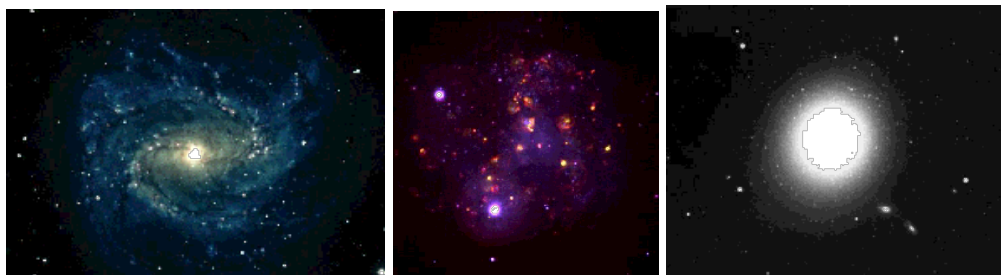
Galaxy clusters are an element of the large-scale structure of the Universe, one of a continuous range of objects; galaxies, groups, clusters, superclusters, large-scale structure. Galaxies tend to gather into groups and clusters.[6]. The Universe is filled with rich tapestry of structures, from individual stars and vast cosmic webs of matter and energy. Among the most intriguing and important of these structures are galaxy clusters and diffuse source. These largest known structures in Universe, play important role in our understanding of large scale structure of the Universe.

The large-scale structure which are still in the process of formation. Excessively dense regions such as clusters and filaments keep accreting matter. Gas streams out of cosmic voids on to the sheets and filaments. When the newly accreted gas collides with the denser gas within these structures, shock fronts arise and dissipating the kinetic energy. In sheet and filaments the gas follows the gravitational potential towards the clusters of galaxies. Eventually, the gas collides with the ICM with a few  $1000 \text{ km s}^{-1}$  and gets heated to temperatures of  $10^7 \sim 10^8 \text{ K}$ [7]. A significant fraction of the gas accretion on to clusters is in the form of groups and clusters. The mergers of rich clusters are the most energetic events after the big bang[8].

Galaxy clusters are the largest multi-functional spaces for cosmic material galaxies, dark matter, hot thermal baryonic plasma, non-thermal and relativistic plasma, black holes, magnetic fields and cosmic rays. In this sense they can be considered as the largest multi-disciplinary laboratories in the Universe[9]. Where we can proficiently study some of interesting aspects of the astrophysics of large-scale structures, the nature of dark matter, the origin and distribution of cosmic rays, the impact of magnetic fields, the impact of black holes, the inter play between

thermal and non-thermal phenomena. As such, galaxy clusters are environments for the production of high energy emission from the cluster diffuse medium [10]. An increasing number of clusters of galaxies is known to have large-scale diffuse radio sources whose origin is not associated to the activity of AGN in cluster galaxies but to the ICM. These sources are classified as radio halos, relics and mini-halos according to their location with respect to the cluster center. Radio halos show a regular emission around the cluster center and relics are not located at the cluster center and in most cases are in peripheral cluster regions and have an irregular, circular or elongated shape.

Clusters contains up to several thousands of galaxies. In 1920's Edwin Hubble went on to observe and classify extragalactic sources establishing the basic properties of what are now known as galaxies and providing the first accurate insight into the large-scale structure of the universe. Hubble developed a classification scheme which is still used to separate the main classes of galaxies elliptical, spiral and irregular galaxies [2].



**Figure 1.1:** *Left:* Spiral galaxy NGC4535, known as the ‘Southern Pinwheel’. *Middle:* Irregular Spiral galaxy IC4182. *Right:* Giant elliptical galaxy NGC4486 in the Virgo cluster Images from <http://www.noao.edu/>

Left, Spiral galaxies are one of the most common galaxy types in the Universe, consisting of a central bulge, a rotating disk of gas and stars, and spiral arms that wind outward from the center.

middle, Irregular galaxies are a class of galaxies that lack the distinct spiral arms or elliptical shapes of other major galaxy types. They often exhibit an asymmetric, disorganized appearance, with star-forming regions and dense concentrations of young, luminous stars scattered throughout the galactic body.

right, Giant elliptical galaxies are massive, spheroidal stellar systems that lack the distinct spiral arms or disk structures of other galaxy types. They are typically

found at the centers of galaxy clusters and are dominated by older, red stars. Individual galaxy like milky way don't like isolated environment and often exist in groups of thousands bounded together by gravity. Galaxy clusters can be observed at multiple wave-lengths such as x-ray, optical and radio observations, where different wavelength show different parts of galaxy clusters.

The optical observation shows individual galaxy where the radio and x-ray show us the intracluster medium which the gas between individual galaxy. ICM consists of proton, electron and magnetic field. Because there is magnetic field and sometimes high energetic electrons we see what we call synchrotron emission, which is basically electrons spiraling along magnetic field lines and produces photons.

The ejected photons actually observed at radio wave lengths and it is what we observe as diffuse emission. Studying about the distribution of galaxies tell us almost everything we know about the large-scale structure of the Universe. Galaxies are not distributed evenly throughout the Universe, rather they are located in gravitationally bound aggregations, called clusters. Galaxy classification depend on many ways like location, morphology, mass and rich or poor, which depend on the number of galaxies they contain. A typical poor cluster such as the Local group which contains the Milky Way contains  $10 \sim 100$  galaxies, whereas a much richer cluster such as Coma can contain  $\sim 1000$  galaxies.

### 1.1.1 The local Group Clusters and Poor Clusters

The local group and poor clusters are related topics in cosmology and galaxy formation. The Local Group refers to the group of galaxies that includes the Milky Way and Andromeda galaxies, as well as about 50 other smaller galaxies. It is a relatively small, gravitationally bound collection of galaxies located in the Milky Way's neighborhood within the Virgo Supercluster. Poor clusters, on the other hand, are groups of galaxies that are less dense and less massive than the more well-known galaxy clusters. They typically contain anywhere from a few to hundred member galaxies, compared to the hundreds or thousands of galaxies found in rich galaxy clusters.

Overall, the local group and poor clusters are related in that the Local group is considered a prime example of a poor cluster and the study of the Local Group informs our understanding of the formation and evolution of similar galaxy groups and poor clusters in the Universe. The milky way belongs to a very small cluster

called local group. Most of the local group galaxies are faint, small dwarf and ragged. The poor clusters contains dozen or So galaxies, morphologicaly they are irregular and high proportion of spiral galaxies [11].

### 1.1.2 Rich Clusters

Rich clusters,also known as massive galaxy clusters, are the largest gravitationally bound structures in the Universe, containing hundreds to thousands of galaxies. Rich clusters are important laboratories for studying galaxy evolution, the formation of large-scale structure, and the distribution of dark matter and dark energy in the Universe. They are key targets for cosmological research and provide insights into the processes that shape the structure of the cosmos. In rich clusters,the number density of galaxies is low at the border or margin of the cluster and increases smoothly towards a central peak. large number of galaxies orbiting around the central region in a rich cluster means that there are frequent gravitonal interaction in this region. During these interactions there is dynamical friction between the gas of the galaxies. This dynamical friction deforms the shape of the galaxies and can remove away their outer regions. On a larger-scale the ICM is heated. These processes may result in spiral galaxies being converted into elliptical galaxies, which could explain the population bias in the type of galaxies elliptical.

Another effect of collisions between galaxies is the formation of a giant elliptical galaxy, the cD in the centre of the cluster. So both are moving under the influence of the deep gravitational potential well at the centre of the cluster. Large galaxies orbiting the centre gradually move towards this potential well and may eventually merge with other galaxies creating a single giant elliptical galaxy which then attracts more galaxies and hence becomes more massive. This model of ‘galaxy cannibalism’ is one of several which explain the observed properties of rich clusters. The model of galaxy cannibalism means gaint elliptical galaxy tends to be near cluster centre and spirals tend to be on fringes of cluster. Rich clusters contains large amount of  $10^{12} \sim 10^{15} M_{\odot}$  [12].

### 1.1.3 Abell Cluster Types

The Abell Type classifications reflect the regularity of the cluster morphology. Abell clusters are the most conspicuous groupings of galaxies identified by George Abell

on the plates of the first photographic survey made with the SCHMIDT TELESCOPE at Mount Palomar in the 1950's. Sometimes, the term Abell clusters is used as a synonym of nearby, optically selected galaxy clusters.

George Abell constructed a catalogue containing 2712 of the richest such groupings in the northern sky, which was later extended to the southern sky. Abell cluster types are the total sample of around 4076 cluster candidates over the whole sky has revolutionized the study of the large-scale structure in the Universe. The Abell catalogue has formed the basis for the first quantitative studies of the densest component of the large-scale structure in the local Universe[13].

#### 1.1.4 Bautz-Morgan Cluster Types

The Bautz-Morgan classifications gives the degree to which the brightest galaxy stands out against the general cluster background. It defines three main types: I, II, and III. Intermediate types (I-II, II-III) are also allowed. A type I cluster is dominated by a bright, large, supermassive cD galaxy, for example Abell 2029 and Abell 2199. A type II cluster contains elliptical galaxies whose brightness relative to the cluster is intermediate to that of type I and type III. The Coma cluster is an example of a type II. A type III cluster has no remarkable members, such as the Virgo Cluster[14].

## 1.2 General Objective

Review the mechanisms of electron acceleration and the properties of diffuse radio emission in galaxy clusters.

### 1.2.1 Specific Objectives

- i. Review the origins of diffuse radio emission in galaxy clusters.
- ii. Highlighting the relevant physical processes.
- iii. Discuss classification of diffuse radio emission.

Chapter 1 of the project provides an introduction to galaxy clusters and multiwavelength observations. It highlights the presence of diffuse radio emissions in galaxy clusters and the importance of understanding the electron acceleration mechanisms responsible for these emissions. In chapter 2, diffuse radio emission, namely radio halos, radio relics and radio mini-halos will be introduced. Again review their properties as

well as the classification diffuse radio emission discussed in chapter 3, models for origin of diffuse source acceleration mechanisms in chapter 4 and finally summary and conclusion in chapter 5.

## 1.3 Multiwavelength Observations of Galaxy Clusters

Clusters can be observed in different wavelengths, each revealing only part of their properties. Moreover, some observations need confirmation in other wavelengths to assess their reliability. Having multi-wavelength observations and expertise allows to provide confirmation galaxy, gas or dark matter properties of new candidate clusters and confirmed clusters[15].

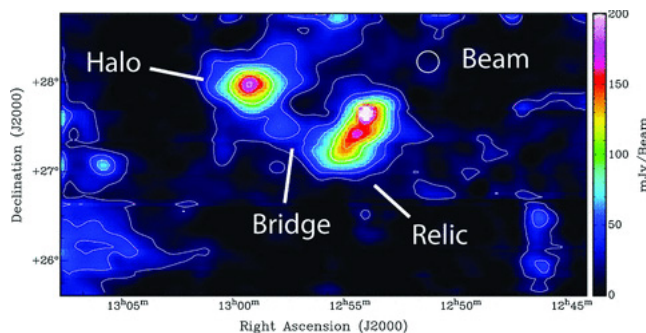
Multiwavelength studies have been extremely important in understanding the nature of clusters of galaxies. The information together from radio, X-ray and optical studies are of great significance to get an overall picture of clusters of galaxies and one method used is to overlay images observed at different wavelengths. For example an optical image showing individual galaxies which become visible as point sources may be overlaid with radio contours to show the full extent of the sources. Alternatively, a radio image of a cluster could be overlaid with smoothed X-ray contours to show how the radio sources are the same with respect to the density of the hot ICM. Observations at radio, X-ray and optical wavelengths gives absolutely needed information about context of studying clusters of galaxies [16].

### 1.3.1 Radio Observations

Radio emission from clusters is predominantly synchrotron emission from individual galaxies within the cluster. Synchrotron radiation is the result of highly relativistic electrons being accelerated as they spiral around magnetic field lines. The radiation is strongly beamed into a forward cone in the direction the electrons are travelling. This is the main process of emission from non-thermal plasmas.

Diffuse radio emission from galaxy clusters was discovered in Coma and then confirmed the extended synchrotron radio emission was due to the presence of relativistic electrons Lorentz factor  $\gamma \gg 1000$  and magnetic fields in the intracluster volume. Radio observations thus provided the first direct evidence of the presence of a non-thermal intracluster component. Statistical studies of the intracluster

radio emission could start only in the 90's with the advent of continuum radio surveys such as the NVSS [17]. The coma cluster is classic example of merging systems which hosts both gaint radio halo and peripheral relics(1253+275). These large-scale features have been found in around 50 clusters. Even if the origin of relativistic electrons are still debating topic all of these systems appear to have recenlty undergone at least some merger or accretion[1].



**Figure 1.2:** Image of radio halo and relic of the Coma cluster taken from. This is a GBT total intensity image with all NVSS emission [1]

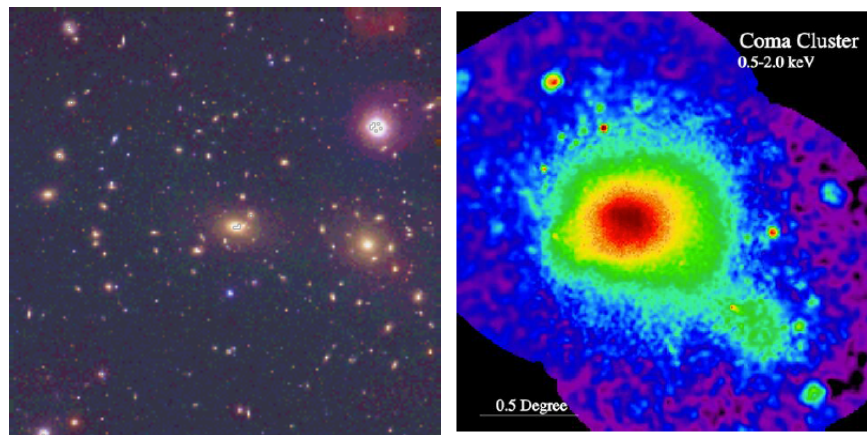
1. Halo: A diffuse, extended region of emission or brightness surrounding a central object.
2. Beam: A more concentrated, brighter region or feature within the image.
3. Bridge: A connecting structure or elongated feature linking different regions.
4. Relic: A distinct, isolated region of emission or brightness within the overall map.

### 1.3.2 X-ray Observations

X-ray emission comes predominantly from Bremsstrahlung or free-free emission in the ICM. Bremsstrahlung occurs when electrons travel through a hot ionized gas. The electrons are accelerated in the Coulomb fields of the ions, converting kinetic energy into radiation. This is the main emission process from thermal plasmas. X-ray emission is directly related to the physical parameters of the clusters and gives information about dynamics of the ICM and also the structure and evolution of clusters on a large scale. X-ray surveys are less susceptible to observational bias than optical surveys and the signal to noise ratio of detections is generally higher. The main cluster parameters that can be directly seen or determined from X-ray observations are luminosity, temperature and the mass within a given radius.

### 1.3.3 Optical Observations

Galaxy clusters were discovered as overdense region in the sky. The first statistically complete sample of galaxy clusters based on image plates obtained by the Palomar Observatory Sky Survey. For many years catalogs of clusters were performed using only optical observations [18]. Most observations have been carried out at optical wavelengths and it was in accordance with optical information (galaxy density within a given radius) that defined clusters. Optical studies are still the main source of information about the type and distribution of galaxies within a cluster.



**Figure 1.3:** *Left:* Optical image of the central part of the Coma cluster galaxy NGC4889; *Right:* X-ray image of the bright galaxy NGC4874 (ROSAT) of Coma (from <http://chandra.harvard.edu/photo/2002/0150/more.html>)

An optical image of the Coma cluster, one of the most well-studied galaxy clusters in the Universe. The Coma cluster one of the nearest and richest collections of galaxies. Some key features observed in this optical image of the Coma Cluster.

1. **High Galaxy Density:** The image shows a dense concentration of hundreds of individual galaxies packed tightly together. This high galaxy density is a defining characteristic of rich galaxy clusters like the Coma cluster.
2. **Variety of Galaxy Morphologies:** The image reveals a mix of spiral, elliptical, and irregular galaxy shapes and structures. This diversity reflects the different stages of galaxy evolution present within the cluster.
3. **Diffuse Intracluster Light:** In addition to the discrete galaxy sources, there

appears to be a faint, diffuse glow or halo of light surrounding the cluster. This intracluster light is thought to arise from stars that have been stripped from their host galaxies and now orbit freely within the cluster's gravitational potential.

4. **Bright Core Region:** The central region of the Coma Cluster appears particularly bright and concentrated, likely due to the presence of a high density of giant elliptical galaxies in the core. The Coma cluster is an important target for astronomers studying the properties of galaxy clusters, their formation and evolution, as well as the distribution of dark matter within these massive structures. The optical image provides a comprehensive view of the cluster's rich galaxy population and the complex interplay between the cluster's components. The image on the right appears to be an X-ray observation of the Coma Cluster of galaxies. The central, reddish-orange region in the image represents the core of the Coma Cluster, where the X-ray emission is the strongest. This intense X-ray emission is primarily due to the hot, diffuse gas present in the ICM the space between the individual galaxies within the cluster. The surrounding blue and green areas indicate regions of lower X-ray intensity, gradually decreasing outwards from the cluster's core. These fainter regions likely correspond to the less dense, cooler gas and plasma present in the outer parts of the Coma Cluster.

## **1.4 Radio Instruments used to Detect Diffuse source**

GMRT, MeerKAT and VLA are some of the radio instruments which are used to detect diffuse source. These instruments create images which are used to analyse different diffuse radio sources. However these are not the only instruments that are used to detect different diffuse radio source. Multiwavelength telescope like ACT( which is at microwave wavelength), Chandra (x-ray telescope), SALT (optical telescope) and XMM-newton (x-ray telescope) are telescopes can be used to follow interesting objects found in galaxy clusters. Collisions between galaxy clusters froms enourmouns amount of energy. These energy is injected to ICM and the gas as a result exceting and energzing electrons which then results diffuse emission. Having multi-wavelength observations of these objects tells us diffuse emission is related to major acitivity in galaxy clusters [19].

## 1.5 The Origin of Diffuse Sources

The origin of diffuse sources has remained a mystery since the discovery of the first and now canonical example in the Coma cluster, mainly due to the few number of relics that have been observed. The main models put forward to clarify the origin and evolution of diffuse sources along with some physical arguments for or against them.

The first model for diffuse sources suggested that diffuse sources from synchrotron emission from relativistic electrons originating from a single host galaxy. The electrons are emitted from the radio galaxy (a strong radio source, often with large radio lobes and jets) and disperse over time until they occupy the large volumes now observed. The problem with this model is that by the time the electrons have travelled the distance required from the source galaxy, they would have radiated away most of their energy.

The secondary electron model to overcome the problem of energy loss. In this model collisions between relativistic protons from radio galaxies and the protons in the intracluster medium produce secondary electrons. These electrons emit synchrotron radiation which forms the diffuse source. The secondary electron model is an improvement because protons lose less energy to synchrotron radiation than electrons do and so could travel much further from their host galaxy than electrons could. The major argument against this model is that we would expect to observe more diffuse sources since protons have a long lifetime.

The third model is the galactic wake model. Galactic wakes are resulted as a galaxy moves through the ICM. Bow and tail shocks are created by the movement and a turbulent wake forms. This results in an intracluster magnetic field being generated and relativistic electrons being accelerated. The aim of this model is to overcome the problem of the electrons having to travel such a large distance in a relatively short time. It opens up the possibility that the electrons are already spread over a large area and then are re-accelerated by the galactic wake. Although this model resolves the problems of the previous two, it appears that galactic wakes do not have enough energy to power the diffuse source and so this is not a completely satisfactory explanation [20]

### 1.5.1 The Merger Assumption and the Role of Cooling Flows

It is the merger hypothesis that provides the most plausible explanation for the presence of diffuse sources, although it has not been extensively tested. The merger hypothesis suggests that interactions between two clusters during a merger, may produce shocks which can re-accelerate relativistic electrons and amplify the magnetic field within the clusters.

Evidence supporting the merger hypothesis is that there has been no cooling flow detected in any of the clusters observed to contain diffuse sources. cooling flows are disrupted during a cluster merger, so the absence of a cooling flow suggests a recent cluster merger. However, mergers can not be the only contributing factor in the formation of diffuse sources, since cluster mergers are quite common, whereas diffuse sources are quite rare.

The role of cooling flows or the absence of them in creating diffuse sources is discussed by comparing Coma, which has a large diffuse source and no cooling flow, with the Perseus cluster, which has a mini-halo and does have a cooling flow. Mini-halos are much smaller than other diffuse sources and are confined to the cluster core, usually centred on the dominant galaxy. The magnetic field strength and the cluster kinetic energy density are highest at the cluster centre. In the absence of a cooling flow, the magnetic field will diffuse outwards and possibly produce a large scale diffuse source as in Coma. However, if a cooling flow is present, it will impede the diffusion of the magnetic field, resulting in a mini-halo confined to the cluster core as in persus [21].

### 1.5.2 A New Model for the Origin of Diffuse Sources

Although the merger hypothesis is currently accepted as the most seemingly worthy of approval model, a new points out that the correlation between the presence of a diffuse source and a cluster merger does not conclusively show that mergers cause diffuse sources. Instead it is proposed that this correlation could be a selection effect. Mergers disrupt the cooling flows in clusters and clusters without a cooling flow are less likely to have a central dominant radio source. This means that a low surface brightness diffuse source would be easier to detect in such a cluster than in a cluster with higher levels of radio emission. Hence diffuse sources could actually be present in most clusters but are not observed due to the difficulties in

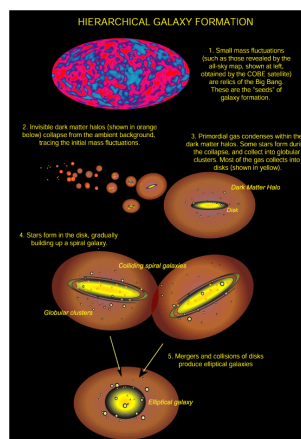
achieving the high dynamic range required and the fact that they have a relatively short lifetime.

The later proposed new model for the origin of diffuse sources in which merger activity and thermal electrons both contribute to the formation of diffuse sources. In this model, the relativistic particles mandatory for synchrotron emission originate from the high energy tail of the ICM thermal electron distribution. X-ray observations show that rich clusters are dense enough for the acceleration of thermal electrons to relativistic speeds to take place a process that has previously been ruled out as a possible mechanism [22].

## 1.6 Summary

Galaxy clusters are some of the heavy objects in the universe and their classification can be based on location (field, groups, clusters), morphology, mass and colours. Galaxies contain 100's to 1000's and are moving in an orbit decided by gravitational potential mostly from dark matter. Galaxies also contain diffuse gas which is very hot. A number of galaxy clusters are known to contain large scale diffuse sources which have no obvious connection with individual galaxies.

Hierarchical formation of galaxies according to the currently accepted cosmological



**Figure 1.4:** Schematic illustration of the formation of galaxies in the hierarchical formation paradigm [2]

model. The image is divided into several steps that illustrate the key stages of galaxy formation,

1. Small mass fluctuations: The image notes that these are the "seeds" of galaxy formation, likely referring to the tiny density variations in the early universe

revealed by the cosmic microwave background.

2. Invisible dark matter halos, These are shown in orange and represent the collapse of dark matter structures that provide the gravitational scaffolding for galaxy formation.

3. Primordial gas condenses: Within the dark matter halos, primordial gas collapses and collects into globular clusters, which are shown in yellow.

4. Stars form in disks: As the gas continues to collapse, it forms rotating disks in which stars gradually build up, eventually forming spiral galaxies.

5. Mergers and collisions: The final stage depicts the mergers and collisions of galactic disks, which can produce larger elliptical galaxies.

## Diffuse Radio Emissions

### 2.1 Introduction

Studies at radio wavelengths allow the investigation of important components of clusters of galaxies. The most spectacular aspect of cluster radio emission is described, by the large-scale diffuse radio sources, which cannot be seemingly associated with any individual galaxy. These sources indicate the existence of relativistic particles and magnetic fields in the cluster volume, thus the presence of non-thermal processes in the hot gas between clusters. The knowledge of the properties of these sources has increased in recent years due to higher sensitivity radio images and to the development of theoretical models. The importance of these sources is that they are large-scale features, which are related to other cluster properties in the optical and X-ray domain and are thus directly connected to the cluster history and evolution [23].

#### 2.1.1 Radio Emission

The radio emission bring out the presence of cosmic rays and magnetic fields ICM. We classify diffuse non-thermal radio sources into radio halos, cluster radio shocks (relics) and mini-halos sources since the detection of radio radiation from the Coma cluster. There has been growing evidence for the existence of large-scale diffuse radio sources associated to clusters of galaxies, which cannot be obviously associated with any individual galaxy. These diffuse radio sources have been associated with synchrotron radiation from a population of relativistic electrons with Energy  $\geq 1$  GeV. Observations of nearby galaxy clusters that show it's potential for detecting the different phenomena responsible of clusters emission [24].

### 2.1.2 Thermal and Non-Thermal Emission

Free charged particles can be accelerated by electrostatic or magnetic force, where gravitational acceleration being negligible by resemblance. Electrostatic bremsstrahlung is the magnetic braking radiation or synchrotron radiation. Thermal emission is produced by a source whose emitting particles are in local thermodynamic equilibrium. Most astronomical sources of electrostatic bremsstrahlung are thermal. The relativistic electrons in most astronomical sources are magnetobremstrahlung have power-law energy distributions and not local thermodynamic equilibrium, synchrotron sources are called non-thermal sources [25].

## 2.2 The Detection of Diffuse Source

The instrument best suited to detect cluster diffuse radio sources should provide a compromise between high sensitivity to surface brightness and high angular resolution. Moreover, diffuse emission is generally characterized by steep radio spectra, the observations should be carried out at low frequencies  $\leq 1.4$  GHz. VLA at 1.4 GHz has been demonstrated to be a very good instrument to detect and study radio halos, owing to its superb sensitivity. However, it should be noted, as a caveat, the Coma radio halo is not detected by WSRT and VLA observations at 1.4 GHz because of the missing short spacings [19].

## 2.3 Diffuse Synchrotron Emission

The properties of large-scale radio halos and relics are poorly known, because of the now existing or in progress observational limits. Due to synchrotron and inverse Compton losses, the typical life time of the relativistic electrons in the ICM is relatively short  $\sim 10^8$  yrs, making it challenging for the electrons to diffuse over a Mpc scale region within their radiative lifetime. The expected diffusion velocity of the electron population is indeed of the order of the Alfvén speed,  $\sim 100$  km/s. Because diffuse sources extend across the cluster volume their electrons cannot have been edged in or re-accelerated in some localized points of the cluster, such as an active galaxy or a shock, but they need in situ re-acceleration. Several suggestions for the mechanism transferring energy into the relativistic electron population and for the origin of relativistic electrons themselves have been made. Current models for radio emission can be grouped in to two main classes involving primary and secondary model [26].

## 2.4 Diffuse Synchrotron Emission from ICM

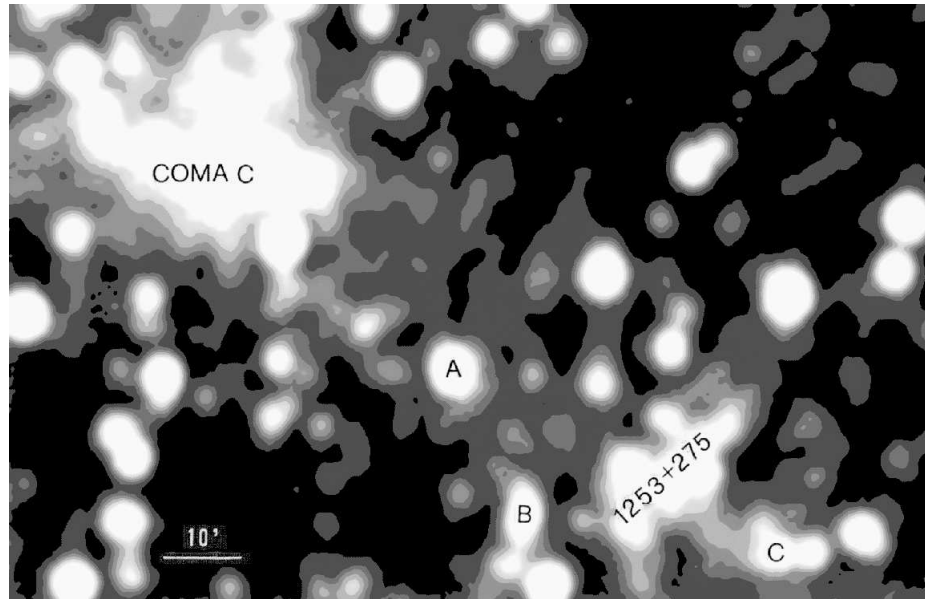
The detectable radio emission from extragalactic sources in and around galaxy clusters is mainly of synchrotron origin. Therefore it is a direct probe of processes that have strongly influence the actions and conduct on the generation and evolution of relativistic particles and magnetic fields in the galaxies themselves and in the diffuse media surrounding them.

Cluster wide non-thermal radio emission has been a topic of study for nearly half a century since it's discovery in the Coma cluster. Over the last few decades, a large number of galaxy clusters were imaged at radio wavelengths (20–200 cm) using a variety of synthesis radio telescopes like VLA, WSRT and GMRT. A large variety in the size, morphology and spectrum of these sources has been based on the properties of the radio sources and the host cluster, the sources have been classified into three classes radio halos, radio mini-halos and radio relics [5].

## 2.5 ICM and Past Studies of Diffuse source

The space between galaxies in galaxy clusters is filled with a hot and diffuse gas. The galaxy clusters grow through infall of matter and merging events, creating shocks and turbulence in the ICM, which heats up the it to tens of millions of Kelvin. A theory of infall of material into clusters of galaxies is developed and applied to the Coma cluster. It is suggested that the infall phenomenon is responsible for the growth of cluster galaxies.

The distinct regions labeled 'COMA C', 'A', and 'B', as well as a numerical label '1253+275' in the bottom right corner. A complex, mottled pattern of varying shades of gray, with brighter regions and darker regions interspersed. Since the real infall pattern to clusters should be aspherical and correlated with the surrounding large-scale structure the shock radii and the shock velocities are expected to differ from these estimates. They might be regarded as average quantities, where from a single cluster can easily deviate. Inserting the X-ray temperature of the Coma cluster of 8.2 keV [3]



**Figure 2.1:** Westerbork Synthesis Radio Telescope map at 327 MHz of the Coma cluster. The central halo source Coma C and the cluster relic 1253+275 are identified. Capital letters indicate some extended Coma cluster galaxies, A = NGC 4839, B = NGC 4827, C = NGC 4789. 10' corresponds to 400 kpc [3]

## 2.6 Radio Halos and Relics

The Coma cluster is the first cluster where a radio halo (Coma C) and a relic 1253+275 have been detected. The radio halos are diffuse through the cluster central regions, with a brightness distribution similar to that of the X-ray gas. They are characterized by steep radio spectrum. Limits and a typical extent of a few percent have been derived for their polarized emission. Relics are similar to halos in their low surface brightness, large size and steep spectrum but they are typically found in cluster outskirts regions. Unlike halos, relics are highly polarized. The number of clusters with halos and relics have been found in around  $\sim 50$  clusters. The presence of relativistic particles and large-scale magnetic fields are of great significance for a comprehensive physical description of the ICM in galaxy clusters [27].

## 2.7 Radio Surveys and Low Frequency Observations of Halos, Relics

The radio observations in the past couple of decades have provided impression on properties and occurrence of the diffuse radio sources in galaxy clusters. The initial discoveries of the radio halos and relics came to a great extent from the inspection of all sky radio surveys such as the NRAO VLA Sky Survey. A number of radio halos and relics in clusters at redshifts  $<0.2$  were discovered using NVSS and afterwards confirmed with deep follow up observations [5]. The connection between cluster mergers and occurrence of radio halos and relics has been found observationally. Cluster mergers are a natural origin for the shocks and turbulence that are proposed to play a role in the generation of such sources. Indeed a significant fraction of clusters that host radio halos and relics show appearance of both types of sources [28]

### 2.7.1 NVSS and WENSS Surveys of New Diffuse Radio Sources

Radio halos and relics are found in massive merging galaxy clusters. These radio sources demonstrate the presence of magnetic fields and in-situ particle acceleration. Galaxy clusters form through mergers with other clusters and galaxy groups as well as through continuous accretion of hot gas between clusters. Since giant radio halos and relics are found in merging clusters it has been proposed that a small fraction of the energy released during a cluster merger event is channeled into the re-acceleration of particles.

In the last decade a number of successful searches have been carried out to find new diffuse radio sources in galaxy clusters. However, our understanding of the formation of these sources is still limited. Models for the formation of relics and halos can be tested through statistical studies of correlations between the non-thermal radio emission and properties of the clusters such as mass, temperature and dynamical state. This survey discovered two large radio relics in the NVSS and WENSS surveys. These relics remained unknown for about 15 years. This suggests that more diffuse radio sources could be discovered by inspection of the NVSS and WENSS survey images and also confirm six new radio relics, including a probable double relic system [29].

### 2.7.2 The GMRT Radio Halo Survey and Low Frequency Follow-up

The GMRT Radio Halo Survey, carried out at 610 MHz to investigate the statistical properties of cluster radio halos in a complete cluster sample selected in the redshift interval between  $0.2 \sim 0.4$ . A low frequency follow-up is in progress with the GMRT at 325 MHz and 240 MHz on the diffuse sources and candidates found at 610MHz. Cluster radio halos with different radio spectral properties have been unexpectedly found. A number of new diffuse cluster sources (halos, relics and mini-halos) were found, as well as candidates.

Most of the radio halos and relics known to date have been detected and imaged only at 1.4 GHz and very little information is available on their emission properties at frequencies  $\leq 325$ MHz. Therefore GMRT low frequency follow up of the new cluster sources detected at 610 MHz. This survey also discovers A521, A781 relic A697 candidate halo, A1300 and A2744 both relic and halo candidate and RXCJ 2003.5-323 which radio halo sources [30].

### 2.7.3 Mass Complete Sample: Ongoing Survey

The detections of a large number of galaxy clusters by the Planck satellite using the Sunyaev-Zel'dovich effect resulted in a sample of clusters with well constrained total masses. A sample of galaxy clusters with mass completeness.

## 2.8 Low Mass, Merging Galaxy Clusters

The mass complete samples have focused mainly on the most massive clusters. The low mass clusters that show merging are promising sites to constrain the properties of shocks and turbulence. A radio relic was recently used to trace a low mass cluster. This search for diffuse radio emission of extent  $> 500$  kpc towards the newly detected clusters in the Early SZ Planck catalogue. This resulted in the discovery of a radio halo in the cluster PLCKG171.9-40.7 and a single radio relic in the cluster PLCK G200.9-28.2. The single relic cluster with the mass of  $2.7 \times 10^{14} M_{\odot}$  was the lowest mass host to a single relic known at that time. This search also found an even lower mass cluster with a single relic using MWA which has the best existing short baseline coverage at low frequencies  $< 200$  MHz in the southern hemisphere. The cross matching of the galaxy cluster catalogues with the

200MHz galactic and Extra-galactic All sky MWA survey led to the discovery of a radio relic in the cluster Abell [28].

## 2.9 Cluster Magnetic Fields

Magnetic fields are ubiquitous throughout the Universe and are found on all scales, from fields surrounding the planets up to fields in the ICM. The existence of magnetic fields associated with in galaxy clusters is one of the direct evidences of the cluster magnetic fields is the presence of large scale diffuse radio emission in galaxy clusters. The magnetic field plays a key role in understanding the large-scale structure formation and CRs generation. The magnetic field can be investigated by different approaches based on both the radio and X-ray observations. However, the most relevant and commonly used tracer of magnetic fields is the synchrotron radiation. The total synchrotron emission from a source provides the strength of the total magnetic field, while the linear degree of polarization is an important indicator of the structure of the magnetic field and it's uniformity. The diffuse synchrotron emission in galaxy clusters requires a co-existence of a population of GeV relativistic electrons and a magnetic field of  $\mu\text{G}$  level. Most of the matter in the Universe is composed of ionized or partially ionized gas permeated by magnetic fields. Celestial objects are magnetized and magnetic fields of significant strength found everywhere in the interstellar space, over small and very large-scales in the universe [31].

The presence of magnetic fields in clusters is directly demonstrated by the existence of large-scale diffuse synchrotron sources, that have no obvious connection to any individual cluster galaxy [32].

## 2.10 Origin of Magnetic Field

The field strengths that we observe in clusters greatly exceed the amplitude of the seed fields produced in the early Universe or fields injected by some mechanism by high redshift objects. There are two basic chances for their origin.

- 1) injection from galactic winds of normal galaxies or from active and starburst galaxies
- 2) amplification of seed fields during the cluster formation process. Support for a galactic injection in the ICM comes from the reveal that a large fraction of the gas is of galactic origin, since it contains a significant concentration of metals.

However, fields in clusters have strengths and coherence size comparable to and in some cases larger than, galactic fields. Therefore, it seems quite challenging that the magnetic fields in the ICM derive purely from ejection of the galactic fields, without invoking other amplification mechanisms [23].

## **2.11 New Halos and Relics**

The knowledge of magnetic fields in clusters of galaxies is of great significance to confirm the existence of large-scale cosmological magnetic fields and to study their properties. It is therefore crucial to obtain detailed observations of radio halos and relics, since these extended sources can give observational restrictions to the cluster magnetic fields strength and distribution [33].

## **2.12 Merging Processes in Galaxy Clusters**

Mergers are the mechanisms by which galaxy clusters are gathered through the hierarchical growth of smaller clusters and groups. Major cluster mergers are the most energetic events in the Universe since the big bang. Many of the observed properties of clusters decided by the physics of the merging process. These include substructure, shock, intracluster plasma temperature and entropy structure, mixing of heavy elements within the ICM, acceleration of high-energy particles, formation of radio halos and the effects on the galaxy radio emission.

## **2.13 Cluster Shocks in Radio Emission**

A number of diffuse, steep-spectrum radio sources without optical identification have been observed in galaxy clusters. The emission from these sources is synchrotron radiation, which argues the presence of highly relativistic electrons and  $\mu\text{G}$  range magnetic fields. Especially radio relics are thought to make out cosmological shocks. They probably trace shock fronts in which particles are accelerated via the diffusive shock acceleration mechanism. Among them are double relics with the two relics located on both sides of a cluster center. According to DSA, the integrated radio spectrum should follow a single power-law [34].

## 2.14 Particle Acceleration Mechanisms

First order Fermi acceleration (Fermi-I): This process also called DSA plays significant role in many astrophysical environments. Particles are accelerated at a shock with the acceleration taking place diffusively,

Cluster	$z$	$P_{1.4}$	L.S. (Mpc)	$L_{x,bol}$ (keV)	$T$ (keV)	Dist (Mpc)	Class
A85	0.0555	6.26	0.48	19.52	5.1	0.54	R
A115	0.1971	255.5	1.88	31.09	4.9	0.93	R
A520	0.2030	62.1	1.08	37.35	8.5	-	H
A610	0.0956	7.65	0.57	-	-	0.71	R
A665	0.1818	66.5	2.13	41.72	8.5	-	H
A773	0.2170	22.3	0.83	35.10	8.6	-	H
A1300	0.3071	92.4	0.58	47.63	10.5	0.80	H
A1367	0.0216	0.71	0.29	2.87	3.5	0.83	R
A1656	0.0232	15.0	1.09	20.42	8.2	-	H
A2163	0.2080	306.2	2.60	132.1	14.2	-	H
A2218	0.1710	12.2	0.52	21.96	9.1	-	H
A2256	0.0581	37.3	1.81	18.39	7.5	0.59	R

**Table 2.1:** Observational properties of halos in clusters.

Column Descriptions:

1. Cluster Name This column lists the names of the clusters, which are typically designated by a prefix (e.g., "A" for Abell clusters) followed by a numerical identifier. This nomenclature is standard in cluster catalogs and facilitates easy reference across scientific literature.
2. Cluster Redshift ( $z$ ) The redshift value indicates how much the light from the cluster has been stretched due to the expansion of the universe. Higher redshift values correspond to more distant clusters, providing insights into the universe's evolution over time. It is crucial for understanding the cluster's distance and the cosmological implications of its characteristics.
3. Radio Power ( $P_{1.4}$ ) The radio power of the diffuse source at 1.4 GHz, an important frequency for studying radio emissions from cluster halos and relics. These emissions help identify the presence of relativistic particles and magnetic fields, offering clues about the cluster's dynamics and history.
4. Largest Linear Size (L.S.) The largest linear size of the diffuse source provides a measure of the extent of the radio emission in the cluster. This information is vital for understanding the spatial distribution of the radio source and its relationship

to the cluster's structure and environment.

5. X-ray Bolometric Luminosity ( $L_{x,bol}$ ) This value quantifies the total X-ray energy output from the cluster, encompassing all wavelengths. It is a critical indicator of the cluster's mass and thermal state, as it reflects the hot gas's properties within the cluster's potential well.

6. Cluster Temperature ( $T$ ) The temperature is derived by averaging values from various observations in the literature. It provides insights into the thermal properties of the ICM. A higher temperature typically indicates a more massive cluster with a deeper gravitational potential.

7. Projected Distance (Dist) This column measures the distance of the diffuse source from the cluster center, which can reveal how the radio emissions relate spatially to the cluster's core. Understanding this relationship is crucial for studying the formation and evolution of cluster structures.

8. Source Classification The classification of sources as either halos (H) or relics (R) helps categorize the types of radio emissions observed. Halos are typically associated with ongoing particle acceleration processes within the cluster, while relics are remnants of past activity, often indicating interactions with cluster mergers or shock waves.

## Diffuse Radio Emissions and Classification

### 3.1 Basic Formulas from the Synchrotron Theory

#### 3.1.1 Synchrotron Radiation

The synchrotron emission is produced by the spiraling motion of relativistic electrons in a magnetic field. The energy distribution of cosmic-ray electrons in most cases synchrotron is a power-law.

$$n(E)dE \propto E^{-\delta}dE, \quad (3.1)$$

where,  $n(E)$  is the number of electron perunit volume with enegy range around  $\gamma \approx 10^4$ is relavant to radio radiation. Because  $n(E)$  is a power law and the critical frequency  $\nu_c$  is proportional to  $E^2$ . The source spectruam can be calculated with accuray from the approximation that each electron radiates all of its average power.

$$p = \frac{-dE}{dt} = \frac{4}{3}\sigma_T\beta^2\gamma^2u_B, \quad (3.2)$$

where,  $p$  is the average power emmited by electron assuming that all velocity direction is equally probable.  $\gamma$  is the Lorentz factor,  $u_B = \frac{B^2}{8\pi}$  is the energy density of magnetic field ( $B$  in gauss) and  $\sigma_T$  is the compton cross section. At single frequency

$$u \approx \gamma^2u_G, \quad (3.3)$$

$u_G = \frac{\omega_G}{2\pi}$  is the electron gyro frequency in MHZ and  $u$  is the observed photon frequency, where  $\omega_G = \frac{qB}{mc}$ . The emission coefficient of synchrotron radiation by ensemble electron is

$$j_\nu d\nu = \frac{-dE}{dt}n(E)dE, \quad (3.4)$$

$$E = \gamma m_e c^2 \approx \frac{v}{v_G} \frac{1}{2} m_e c^2, \quad (3.5)$$

differentiating equation 3.5

$$dE \approx \frac{m_e c^2 v^{-\frac{1}{2}} du}{2u_G \frac{1}{2}}, \quad (3.6)$$

so

$$j_\nu \propto \frac{4}{3} \sigma_T \beta_c^2 u_B E^{-\delta} \frac{m_e c^2 v^{-\frac{1}{2}}}{2v_G^{\frac{1}{2}}}, \quad (3.7)$$

Eliminating E and the coefficient of emission in terms of  $u_G$  and B only

$$j_\nu \propto \frac{u}{u_G} B^2 \frac{v^{-\delta}}{v_G} \frac{1}{2} \frac{1}{v u_G^{\frac{1}{2}}} \propto \frac{u}{B} B^2 \frac{u^{-\delta}}{B} \frac{1}{2} \frac{1}{u B^{\frac{1}{2}}}, \quad (3.8)$$

This simplifies

$$j_\nu = B^\delta \frac{u^{1-\delta}}{2}, \quad (3.9)$$

Thus, the spectrum of synchrotron radiation is from a power-law distribution of electron is also the power-law spectral index.

$$\alpha = \frac{d \ln s}{d \ln \nu}, \quad (3.10)$$

which depends on  $\delta$  and  $s$  is the source function.

$$\alpha = \frac{\delta - 1}{2}, \quad (3.11)$$

In our galaxy and in many synchrotron source  $\alpha \approx 0.75$  near frequency of  $\nu \approx 1 \text{ GHz}$  so the radio spectra imply  $\delta \approx 2.5$ . This value  $\delta$  reflects power-law slope of  $\delta_0$  of cosmic rays accelerated in shocks modified by loss process that deplete population of relativistic electrons. The rate at which electron losses energy to synchrotron is proportional  $E^2$ . Most astrophysical synchrotron sources are non-thermal because energy distribution of relativistic electron is a power-law. Electrons emitting energy with  $E = m_e c^2$  emit most of their synchrotron power near critical frequency.

### 3.1.2 Synchrotron Sources, Minimum Energy and Equipartition

The existence of a synchrotron source implies the presence of relativistic electrons with some energy density  $U_e$  and magnetic field whose energy density

$$U_B = \frac{B^2}{8\pi}, \quad (3.12)$$

The minimum total energy in relativistic particles and magnetic field required to produce synchrotron of a given radio luminosity.

$$l = \int_{v_{im}}^{v_{max}} E_n(E) dE, \quad (3.13)$$

which is energy density of relativistic electrons in a range of minimum to maximum energy. Where  $n(E)dE$ , is the number of density of electrons in range  $E$  to  $E + dE$ . Electrons with energy  $E$  emit most radiation at frequency  $\nu \propto E^2$  so, the energy corresponding to radiation at  $u$  satisfies Thus the energy density needed to produce a given synchrotron Luminosity source scale as

$$U_e = B \frac{-3}{2}, \quad (3.14)$$

The synchrotron life time of source is defined as the ratio of the total electron energy to  $E_e$  to energy loss rate  $L$  from synchrotron radiation.

$$T_s = \frac{E_e}{L}, \quad (3.15)$$

It approximates life of synchrotron source if the primarily loss mechanism is the synchrotron radiation. In case new relativistic electrons are injected with a power-law energy distribution into radio source after a long time electrons emitting at frequency higher than  $u$  will be depleted by radiative losses proportional to  $E^2$  and high frequency electrons will eventually reach an energy distribution of  $n(E)$  proportional to  $E^{-\delta_o+1}$  consequently the negative spectral index will be

$$\alpha_o = \frac{\delta_o - 1}{2}, \quad (3.16)$$

and at low frequency approach

$$\alpha = \alpha_o + \frac{1}{2}, \quad (3.17)$$

at high frequency. Thus the higher frequency spectrum steepens by

$$\Delta\alpha = \frac{1}{2}, \quad (3.18)$$

If the observed frequency of  $u$  of spectral band is high enough the implied life time of electrons with  $u_c \sim$  may be less than the time needed for a new relativistic electrons to travel from radio core to emitting jet or lobe. This implies the in situ acceleration, something outside of radio core e.g. Shocks in jet must replenish supply of relativistic electrons and this synchrotron emission extends to the optical frequency, so many cosmic rays must be accelerated in the bright shocked regions [35].

## 3.2 Galaxy Luminosity Functions

Each studies target different volume of universe and different luminosity range. The behaviour of luminosity function is described by schechter function. which the combination of power-law multiplied by exponential to model or fit number range of luminosity, total number of galaxies or total mass. Mathematically it takes the form :

$$\frac{d\phi}{dL} = \frac{\phi^*}{L^*} \times \left(\frac{L}{L^*}\right)^\alpha \times e^{-\frac{L}{L^*}}, \quad (3.19)$$

where  $\phi$  is the number of galaxies per unit volume and  $\phi^*$  is number of density of source. Alternatively the schechter function can be written as

$$\phi(L)dL = \frac{\phi^*}{L^*} \times \left(\frac{L}{L^*}\right)^\alpha \times e^{-\frac{L}{L^*}} dL, \quad (3.20)$$

where,  $\frac{\phi^*}{L^*}$  is the normalization  $\left(\frac{L}{L^*}\right)^\alpha$  is power-law and  $e^{-\frac{L}{L^*}}$  is the exponential and  $\phi^*$ ,  $L^*$  and  $\alpha$  are parameters. The integral of Schechter function gives

$$\phi^* L^* \Gamma(\alpha + 2), \quad (3.21)$$

## 3.3 Classification of Diffuse Radio Emissions

The variety of radio sources in galaxy clusters can be classified into two main categories. Those associated with individual galaxy in clusters like star bursts, AGN and radio galaxies and those associated with ICM like radio halos, radio relics and radio mini-halos which are non-thermal diffuse extended sources which has no obvious connection with individual galaxies. The classification of radio halo and radio relics is based on their location at the centre or cluster periphery.

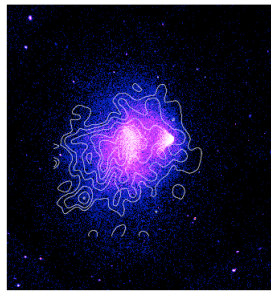
### 3.3.1 Radio Halos

Radio halos are diffuse radio sources of low surface brightness permeating the central volume of a cluster. They are typically extended,  $\geq 1$  Mpc and are unpolarized with sizes down to a few percent level, except in A2255, where polarized filaments have been observed 20 percent to 40 percent level. An example of a recently detected giant radio halo is in the cluster A209. Radio halos are typically found in clusters showing features which are suggests merging processes. However, not all merging clusters show giant radio halos. Radio halos exists in rich clusters, characterized by high X-ray luminosities and temperatures [23].

There are several correlation between the radio halo parameters and parameters related to the X-ray emission of the host cluster:

i) the radio power of halo correlates with the cluster X-ray luminosity, with the gas temperature and the total mass. At present, it is not clear if X-ray bright merging clusters with no radio halo have peculiar physical properties which do not allow the formation of a radio halo or if they host faint halos, undetected with the current observational resources.

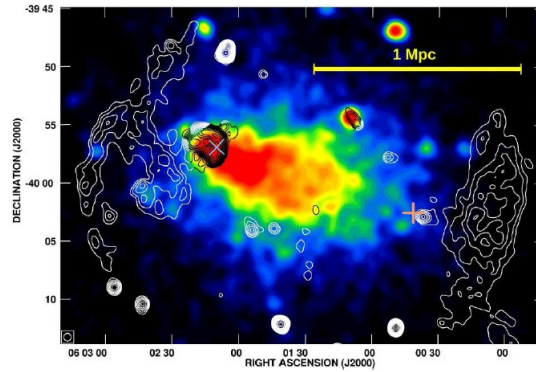
ii) in a number of well resolved clusters, a point-to-point spatial correlation is observed between the radio brightness of the halos and the X-ray brightness as detected by ROSAT a higher X-ray brightness is associated with a higher radio brightness. This correlation is found also using Chandra high resolution. This indicates that morphological features detected in X-rays are similar to those found in radio confirming the connection between hot and relativistic plasma.



**Figure 3.1:** Radio Halo, [4]

### 3.3.2 Radio Relics

Relic sources are diffuse extended sources similar to the radio halos in their low surface brightness, large size  $\sim 1Mpc$ , but they are generally founded in the cluster peripheral regions. They typically show an elongated radio structure with the major axis roughly perpendicular to the direction of the cluster radius, and they are strongly polarized (20-30) percent. A spectacular example of two likely related relics in the same cluster is found in A548b. Relics are found in clusters both with and without a cooling core, suggesting that they may be related to minor or off-axis mergers, as well as to major mergers. The radio power of relics correlates with the cluster X-ray luminosity, as found for halos, although with a larger dispersion. The existence of this correlation indicates there is link between the thermal and relativistic plasma also in peripheral cluster region [36].

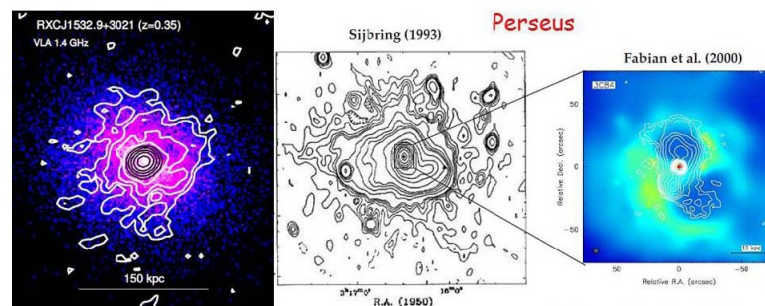


**Figure 3.2:** Radio Relic, [5]

### 3.3.3 Radio mini-halos

Mini-halos are small size  $\sim 500$  kpc diffuse radio sources at the center of cooling core clusters, usually surrounding a powerful radio galaxy, as in the Perseus cluster. The radio spectra of mini-halos are steep, as those of halos and relics. In the Perseus mini-halo, the integrated spectrum steepens at high frequency and the spectral index distribution shows a radial steepening argued that the radio emitting particles in mini-halos is not associated to central radio galaxy in terms of particle diffusion, but they are likely connected with ICM in the cooling flow region.

A number of relaxed, cool-core clusters host faint, diffuse radio emission with a steep spectrum and a size comparable to that of the cool-core region so substantially smaller than the giant halos. As a first approximation one might have thought these sources as a version of giant radio halos scaled on smaller scales of the order of few 100kpc in size rather than Mpc size. However, the two classes of radio sources show prominent differences [37].



**Figure 3.3:** Minihalo, [4]

## 3.4 Properties of Relics, Halos and mini-halos

Many studies of radio halos and their hosting clusters have been recently published, thus our knowledge of their characteristics and physical properties has largely improved about radio relics instead, the available data and knowledge are still poor and the number of well studied sources is limited. Many relics have not yet been studied or observed in detail and deep high resolution radio maps are still missing, therefore their reported size and radio flux density could be under estimated. Most radio spectra have been obtained with a poor frequency coverage and very few spectral index images have been published. Moreover many relics, being at the cluster periphery, are in the external regions or outside of the available X-ray images. In these cases a comparison between radio and X-Ray data is difficult or not possible [38]

## 3.5 Properties of Relics

Relics are an extended diffuse synchrotron emission not located at the cluster center and not identified with the activity of one or more cluster galaxies. In most cases relics show an elongated structure, a steep spectrum  $\alpha > 1$  and are linearly polarized. Most of them are rich Abell clusters, but a relic source is present in a X-ray selected cluster (RXS J1314236-251521 and one belongs to a poor clusters suggested a physical classification the properties of Relics simply according to their observational structures and location, without relating them to physically different classes. Radio observations of galaxy clusters reveal Mpc-scale diffuse emission in the ICM. Radio relics are located at the cluster periphery, with elongated shapes and typically large degrees of polarisation. We can group known relics as discussed in the following sub-sections [39].

### 3.5.1 Elongated Relics

The prototype source of this class is the relic 1253+275 in the Coma cluster Other similar relics are e.g in A2255, A2744, A1367 and A115. We note that the relic in A115 apparently starts at the main cluster center and is elongated towards the cluster periphery. Present study do not allow to understand if it really starts in the central cluster region or if this peculiarity is due to projection effects.

### 3.5.2 Circular Peripheral Relics

Two clusters A548b and A1664 host a relic radio source which is clearly at the cluster periphery but shows an extended mostly circular shape the elongated Relics might be extended disk like relics seen in projection. However, this is not the case because of the too large number of relics with elongated structure. Moreover, we note that the relic in A1664 when observed at higher resolution shows evident substructures.

### 3.5.3 Double Relics

Two relic radio sources located in the peripheral regions and symmetric with respect to the cluster center. A2345 in most cases these relic sources show a classical elongated structure. In the parent clusters no central extended halo source has been detected. The prototype and best studied cluster with two symmetric relics is A3667. These structures suggest that relics are related to the presence of shock waves originated by mergers between clusters with approximately equal masses. In this scenario, it is expected that relics should often come in pairs and be located opposite sides of the cluster along the axis merger, with the extended radio structures elongated perpendicularly to this axis.

## 3.6 Halo Properties and Diffuse Cluster Radio Source in Merging Clusters

The most spectacular example of diffuse cluster radio sources is represented by giant radio halos. They are associated with clusters undergoing merging processes and believed to be energized by the turbulence produced during the cluster mergers. Radio halos can reach a size of  $1 \sim 2$  Mpc and more, although smaller size halos have also been found. New halos have recently been detected in A851, A1213, A1351, A1995, A2034 and A2294. The most powerful radio halo known so far is found in the distant cluster MACS J0717.5 +3745 at  $z = 0.55$ . A peculiar example of a double radio halo in a close pair of galaxy clusters is represented by A399 and A401, where the two radio halos could be either originated by previous merger histories of the two clusters or due to the currently ongoing interaction.

The radio power of both small and giant halos correlates with the cluster X-ray

luminosity, i.e. gas temperature and total mass in the sense that highly luminous X-ray clusters host the most powerful radio halos. The radio halos are generally associated with clusters with X-ray luminosity in the 0.1-2.4 keV range  $gg10^{44} \text{ergs}^{-1}$ . However, radio halos have been found also in clusters with X-ray luminosity around  $10^{43} \text{ergs}^{-1}$ , which are typical of low density environments. Another important link between the relativistic and thermal plasma is represented by the connection between the cluster temperature and the radio halo spectral index. It is found that clusters at higher temperature tend to host halos with Other diffuse radio sources associated with cluster mergers are relics, located in cluster peripheral regions and characterized by high polarized emission. Remarkable are the giant double relics, located on opposite sides with respect to the cluster center, whose prototype is A3667 [40].

### 3.7 Spectral properties of mini-halos

Despite the theoretical efforts, our knowledge and understanding of the physical properties and origin of mini-halos in cool-core clusters and their relation to the core dynamics is limited by the rarity. For mini-halos there are only  $\sim 15$  confirmed detections and difficulty in separating the faint mini-halo emission from the often much brighter central radio galaxies. For these reasons, spectral information on mini-halos are an important diagnostics for the origin of the relativistic electrons is very scarce. Until recently, only three integrated spectra were known (Perseus, Ophiuchus and RXJ1532.9+3021; all consistent with a power-law with  $\alpha \sim 1.2$ , 1.6 and 1.2, respectively, with hints of a high-frequency steepening in Ophiuchus and RXJ1532.9+3021. Such information is not sufficient to differentiate between the models for mini-halos, i.e., a single power-law spectrum predicted by pure secondary models vs a high-frequency break expected in turbulent re-acceleration models obviously, more flux density measurements and a wider frequency interval are needed [41].

### 3.8 Origin of Halo and Relic Sources

Cluster size magnetic fields are known in clusters of galaxies, the crucial ingredient for the formation of a halo or relic source is the existence of relativistic particles. From the observational results it is evident that central halos are strictly related to high luminosity X-ray clusters (high mass clusters) showing recent merger activity. The existence of a merger process is crucial to provide the energy for the relativistic

particle re-acceleration and magnetic field amplification.

However as pointed out before, not all clusters have a halo source and in particular not all merger clusters show a diffuse radio halo. Therefore, we suggest that also the dynamical history of the cluster is relevant the formation process of a massive cluster seems to be crucial to trigger the formation of a halo. Relic sources show the same strong connection as halos to the presence of recent mergers in the host clusters, but their relation to the cluster X-ray luminosity and mass is weaker. This could suggest a different origin for the relativistic electrons [42].

### 3.9 Dynamics of relativistic particles in galaxy clusters

Radio halos and relics prove the existence of non-thermal components such as magnetic field and relativistic particles mixed with the thermal ICM. Understanding the energetics and physics of these new components is of great significance not only to draw the picture of the non-thermal phenomena in galaxy clusters but also to understand how these components may eventually produce an effect on the physics of the thermal ICM[43].

<b>Type</b>	<b>Size</b>	<b>Location</b>
Halo	Typically >1 Mpc	Center of galaxy clusters
Relic	Up to 1 Mpc	Peripheral regions of clusters
Mini-halo	<1 Mpc	Surrounding bright galaxies

**Table 3.1:** Diffuse Radio Emission Types

## Different Models and Acceleration Mechanisms

### 4.1 Models for halo, relic and minihalo origin

Both relics and halos are related to a recent merger event in galaxy clusters. The formation of radio halos can be subdivided into “hadronic models” where secondary electrons, generated by hadronic collisions of relativistic protons with thermal nuclei, cause the radio emission and “turbulence models” in which electrons are reaccelerated by the turbulence in the intraclustermedium in the aftermath of the cluster merger[44].

The link between extended diffuse radio sources and cluster evolution, in particular the link between merger processes and halos/relics, on one hand, and the link between mini-halos and relaxed clusters. Major cluster mergers can supply energy to the radio emitting particles, as well as amplify magnetic fields. This magnetic field amplification is spread over the complete history of cluster formation and related to the various merger processes, therefore it is not expected to directly affect the formation of diffuse radio sources. Since magnetic fields have been found to be ubiquitous in galaxy clusters the pivotal ingredient for the existence of diffuse synchrotron radio sources is the existence of relativistic particles.

Radio halos are most challenging to explain because of their very large size. Radiating electrons cannot travel such large distances within their lifetime, because of strong radiative losses by synchrotron and inverse Compton emission. Two main classes of models have been suggested for the origin of relativistic electrons present in the cluster volume and responsible for the diffuse radio emission. The primary electron model which predict that relativistic particles are continuously accelerated in the cluster volume and the hadronic (secondary electrons) model, in which relativistic electrons are produced through the cluster volume by proton-proton collisions.

### 4.1.1 Primary Electrons

Primary relativistic electrons are present in the cluster volume, because they were injected by AGN activity (quasars, radio galaxies, etc.) or by star formation in normal galaxies (supernovae, galactic winds, etc.) during the cluster dynamical history. This population of electrons suffers strong radiation losses mainly because of synchrotron and inverse Compton emission, thus re-acceleration is needed to maintain their energy to the level necessary to produce the relatively weak magnetic fields. Primary electron models can also be referred to as re-acceleration models. There are two main ways that entail the transfer of energy from the cluster ICM to the radiating particles these are cluster turbulence and cluster shocks.

### 4.1.2 Reacceleration by Turbulence: Radio halos and mini-halos

During cluster mergers, turbulence is generated throughout the cluster over  $\sim Mpc$  scales. Energy can thus be transferred from the ICM into the non-thermal component through resonant or non-resonant interaction of electrons with MHD turbulence. The emerging scenario is that turbulence re-acceleration is likely the major mechanism responsible for the supply of energy to the electrons radiating in radio halos. Turbulent acceleration is like a second order Fermi process related with a random processes and consequently not quite efficient.

The time during which the process is effective is relatively short a few  $10^8$  years, so that the radio emission is expected to correlate with ongoing or most recent merger events. These models predict that re-accelerated electrons will have a maximum energy  $\sim \gamma \sim 10^5$  which produces a high frequency cut off in the resulting synchrotron spectrum. The evidence of the presence of faint diffuse magnetic fields in galaxy clusters.

In mini-halos, the MHD turbulence associated with the cool-core region has been also suggested to be responsible for re-acceleration of radiating particles This is consistent with the spectral properties and the observed correlation between the mini-halo radio power and the cooling rate power. An other possibility, recently suggested that turbulence in cool-core clusters could arise from the sloshing motions of the cluster core gas. This hypothesis is supported by the detection of spiral shaped cold fronts in the X-ray emission of cool-core clusters, suggested to be the signature of gas sloshing [4].

### 4.1.3 Reacceleration by shocks: Relics

Shock acceleration is a first-order Fermi process of great importance in radio astronomy, as it is the mechanism responsible for particle acceleration. The acceleration occurs diffusively, in that particles scatter back and forth across the shock, gaining at each crossing and re-crossing an amount of energy proportional to the energy itself. The acceleration efficiency is mostly determined by the shock mach number. Because of the short electron radiative lifetimes, radio emission is produced close to the location of the shock waves. These models also predict that the magnetic field within the relic is aligned with the shock front and that the radio spectrum is flatter at the shock edge, where the radio brightness is expected to decline sharply. These expectations are consistent with the classic elongated structure of relics, almost perpendicular to the merger axis and their polarization properties. Shock acceleration may also be productive of desired effects in some particular regions of a halo however, the radio emission of halos can be very extended up to large scales, thus it is hardly associated with localized shocks. Moreover, some clusters exhibit a spatial correlation between the radio halo emission and the hot gas regions however, this is not a general feature and in some cases the hottest gas regions don't exhibit radio emission[19].

## 4.2 Secondary Electrons

In the hadronic model, secondary electrons are injected as secondary particles by inelastic nuclear collisions between the relativistic protons and the nuclei of the thermal ambient intracluster medium. There is a chance that the high-energy electrons, responsible for the synchrotron emission. Secondary electron models have been proposed for the emission of radio halos and mini-halos. They cannot work for relics, since peripheral cluster regions do not host a sufficiently dense thermal proton population required as targets for the efficient production of secondary electrons [45].

### 4.2.1 Fermi Acceleration

First-order Fermi acceleration (at shocks):

$$\frac{dE}{dt} = \frac{1}{3} u_s \left( \frac{v_e}{c} \right) E, \quad (4.1)$$

Second-order Fermi acceleration (in turbulence):

$$\frac{dE}{dt} = \frac{4}{3} \left(\frac{v_e}{c}\right)^2 \left(\frac{\delta B}{B}\right)^2 cE, \quad (4.2)$$

### 4.2.2 Synchrotron Emission

$$P_{\text{synch}} = \frac{4}{3} \sigma_T c B^2 \gamma^2 \sin^2 \alpha, \quad (4.3)$$

### 4.2.3 Diffusion and Transport

$$\frac{\partial n}{\partial t} = \nabla \cdot (D \nabla n) - \frac{\partial (bn)}{\partial E}, \quad (4.4)$$

## Energy Losses

Synchrotron energy loss rate:

$$b_{\text{synch}} = \frac{4}{3} \sigma_T c \gamma B^2, \quad (4.5)$$

Inverse Compton energy loss rate:

$$b_{\text{IC}} = \frac{4}{3} \sigma_T c \gamma U_{\text{CMB}}, \quad (4.6)$$

Coulomb energy loss rate:

$$b_{\text{Coul}} = \frac{2\pi e^4 n_e \ln \Lambda}{m_e v_e^2}, \quad (4.7)$$

Total energy loss rate:

$$b = b_{\text{synch}} + b_{\text{IC}} + b_{\text{Coul}}, \quad (4.8)$$

## Parameters

$E$  Electron energy

$u_s$  Shock velocity

$v_e$  Electron velocity

$c$  Speed of light

$\delta B$  Turbulent magnetic field fluctuations

$B$  Mean magnetic field strength

- $\sigma_T$  Thomson cross-section
- $\gamma$  Electron Lorentz factor
- $\alpha$  Angle between electron velocity and magnetic field
- $n$  Electron number density
- $D$  Diffusion coefficient
- $b$  Energy loss rate
- $U_{\text{CMB}}$  Energy density of the cosmic microwave background
- $e$  Elementary charge
- $n_e$  Thermal electron number density
- $\ln \Lambda$  Coulomb logarithm
- $m_e$  Electron mass

### 4.3 Components of Hybrid Models

1. **Thermal Protons and Electrons:** The ICM is primarily composed of hot, ionized gas where thermal protons and electrons contribute to the bulk of the pressure and dynamics. Their temperature is typically in the range of several million degrees Kelvin.
2. **Non-Thermal Protons:** Relativistic protons can exist in a non-thermal state, contributing to cosmic rays. These protons can interact with thermal particles, leading to secondary particle production.
3. **Relativistic Electrons:** Generated through collisions between relativistic protons and thermal particles, or through processes like MHD turbulence. These electrons are responsible for synchrotron radiation, observable as radio emissions.

#### 4.3.1 Processes in Hybrid Models

**MHD Turbulence:** Magnetohydrodynamic turbulence plays a key role in re-accelerating both primary and secondary particles, enhancing radio emission. The turbulence is a result of interactions between the hot plasma and magnetic fields within the ICM.

Particle Acceleration: Relativistic particles can be accelerated via Fermi acceleration mechanisms, especially in shock regions or turbulent areas. These accelerated particles may produce non-thermal emissions observable in radio wavelengths.

### 4.3.2 Applications of Hybrid Models

Cosmology: Hybrid models contribute to understanding the large-scale structure of the Universe and the role of dark matter and baryonic matter. They provide insights into phenomena like cosmic ray propagation and the evolution of galaxy clusters. In the most general situation, relativistic hadrons in the ICM may store an appreciable fraction of the thermal energy and inject a significant component of secondary electrons into the cluster volume. While these electrons cannot solely account for the observed synchrotron radio spectra, they may be efficiently re-accelerated at higher energies, leading to a novel population of radio-emitting particles [46].

## 4.4 Properties of Cluster Hosting Diffuse Source

Diffuse sources appear to occur in clusters of galaxies. Clusters that host diffuse sources are characterized by high x-ray luminosity and they have high temperature and mass. Massive clusters of galaxy showing strong dynamical activity and merger process can host diffuse emission, demonstrates the existence of relativistic particles and magnetic field in the ICM.

Radio halos are Mpc diffuse synchrotron emission found mostly in merging clusters mini halos are found in some relaxed cool core clusters with typical size of around  $\sim 500$  kpc and relics are diffuse emission size have low surface brightness and they can appear in circular and elongated morphology.

## 4.5 Giant Radio Halos and Relics

Cluster-wide, centrally located halos and peripheral relics are found in disturbed systems, suggesting that cluster mergers play a role in their origin. In particular, while relics probably trace merger shocks, giant halos may arise from the re-acceleration of pre-existing, low-energy relativistic electrons in the ICM for instance, injected by cluster radio galaxies or hadronic collisions in the large-scale turbulent wakes of in-falling subclusters or turbulent reacceleration models. As an alternative

to re-acceleration models, hadronic or secondary models propose that appreciable synchrotron radiation can be emitted by secondary electrons continuously generated by inelastic collisions between relativistic cosmic-ray protons accumulated in the cluster and the thermal protons in the ICM. Statistical studies of the properties of giant halos and of their relation to mergers in particular the 610 MHz GMRT Radio Halo Survey, its extension and lower-frequency follow up.

## 4.6 Mini-Halos

Unlike giant halos, mini-halos are found at the centers of relaxed, cool-core clusters, where they are typically fill the cooling region  $\sim 500kpc$  and encompass albeit they are not obviously connected to the radio source associated with the cluster dominant galaxy. As for the larger-scale halos, diffusion of electrons leaking for instance, from the central radio galaxy cannot explain the few hundred kpc scale of mini-halos, thus requiring a continuous injection or re-acceleration in situ of electrons throughout the core volume. Hadronic collisions or turbulent particle re-acceleration have been considered also for mini-halos.

High-resolution Chandra and XMM-Newton X-ray images have revealed cold fronts sharp, arc-like gas density discontinuities in most, if not all, relaxed cool-core clusters.

## 4.7 Origin of Relativistic Electron

secondary model, continuously injected in the inter cluster medium by in elastic pp collision through the production and decay of charged pions in the ICM. primary model; the in situ acceleration of relativistic electrons by MHD turbulence This model Fermi I, which known as the DSA. Cluster merger leads to shocks and turbulence then leads to particle acceleration which causes diffuse emission.

## 4.8 Importance of Studying about Diffuse Radio Emission in Clusters

The study of diffuse radio emission in clusters, halos and relics are important because they are the largest particle accelerators in the Universe and probe of

magnetic fields as well as important quantity for cosmology. The study of halos and relics are also basic of physics applicable to other astronomical fields. The study of diffuse radio sources is essential to our knowledge of the physical conditions in clusters of galaxies and of the role that large scale magnetic fields play in the propagation of the relativistic particles in the ICM.

#### 4.8.1 Shock Acceleration

Fermi Acceleration; A process where particles gain energy through repeated interactions with shock waves. Shock waves can form in clusters due to mergers or explosive events.

#### 4.8.2 Turbulent Acceleration and Magnetic Reconnection

Role of Turbulence; The ICM is often turbulent due to gravitational interactions. This turbulence can scatter electrons and enhance their energy through collisions, leading to higher-energy emissions. Magnetic field lines rearranging in plasma can release energy, accelerating particles. This process is significant in regions with strong magnetic fields in clusters.

## Summary and Conclusion

### 5.1 Summary

A number of galaxy clusters are known to contain large-scale diffuse sources that have no obvious connection with individual galaxies. These sources are radio halos, radio relics and small-scale diffuse source mini-halos. Halos appear projected in cluster center while relics are at the cluster periphery. Physically because of projection effects, the distinction between halos and relics is debatable but it provides basic information of their classification. Radio halos and relics are direct probes of non-thermal diffuse emission in clusters. To improve our knowledge on the origin and properties of diffuse sources comprehensive view of those sources is very important. Halos and relics have different physical origin produced by synchrotron emission from population of relativistic electrons that have accelerated or re-accelerated.

Halos are found in clusters that shows being in some stage of merger. The most common explanation for physical origin of halos and relics is that they originate from particle acceleration in merger shocks. Information from different studies of diffuse sources done so far would help and provide a strong basis for finding of more sources. It would also allow some of the theoretical model to be compared to wider range of empirical data. Even if, significant progress has been made recently in our knowledge of non-thermal emission components in galaxy clusters these theories must be tested on their origin. A new generation of different radio telescopes may enter into unexplored territories to cluster scale emission over broad of different frequency range.

Significant improvement in our understanding of the properties of giant halos and of the physical mechanism behind their formation has been possible thanks to dedicated and extensive statistical studies such as the GMRT radio halo Survey and its ongoing extension. Mini-halos are still poorly understood because they are rare. The ICM is also permeated by magnetic fields and ultra-relativistic particles, whose energy densities are very uncertain. These non-thermal components reveal themselves in the radio band as low-surface brightness, steep-spectrum and diffuse giant radio halos, smaller-scale mini-halos and large peripheral relics. How these synchrotron sources form and evolve is still debated, but their existence seems to be closely related to the cluster dynamical state. In galaxy clusters electron acceleration mechanisms such as shock acceleration and turbulent reacceleration play a crucial role in accelerating electrons to high energies.

## 5.2 Conclusion

Shock waves generated during cluster collision or mergers can accelerate electrons to relativistic speed. Turbulent motions within cluster can scatter and accelerate electrons to the production of high-energy electrons that emit synchrotron radiation at radio wavelengths. The diffused radio emission in clusters are primarily results from synchrotron radiation produced by high energy electrons spiraling around magnetic field. The interplay between electron acceleration mechanisms and diffused radio emission in clusters provides valuable insights into physics of galaxy clusters and properties of ICM. The diffuse radio emission in clusters is a complex interplay of cosmic ray physics, magnetic field dynamics, and the large-scale structure of the Universe, primarily driven by the energetic processes associated with galaxy cluster formation and evolution.

## 5.3 Future prospects

The future prospects in the study of electron acceleration mechanisms and diffused radio emission in clusters hold a great promise to expand our understanding of cosmic structures and processes. Advancement in radio astronomy will enable researchers to study diffused radio emission in clusters with great detail and precision.

Investigating alternative particle acceleration mechanisms beyond shock acceleration and turbulent reacceleration, could uncover new pathways for electron acceleration in clusters and enhance our understanding of high energy processes occurring in these cosmic environments. Studying electron acceleration mechanisms and diffused radio emission in clusters can also have broader cosmological implications, providing clues about formation and evolution of large scale cosmic structures and the role of magnetic field in forming the universe. Leveraging advances in observational and theoretical techniques, researchers can continue to deepen our knowledge of electron acceleration mechanisms and diffused radio emission in clusters, unlocking further mysteries of Universe.

As someone specializing in the study of Astrophysics, I will try to focus on leading research projects, conducting observations, analysing data, collaborating with international teams to advance knowledge in the field.

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