Postprint: Diffuse Radio Emission from Galaxy Clusters

Authors: Wu Wenyu, Xie Fuguo

Date: 2025-07-02T00:00:00+00:00

Abstract

Galaxy clusters, as the largest self-gravitating bound systems in the universe, are not only laboratories for studying galaxy formation and evolution, but can also precisely trace the large-scale structure of the cosmos. We mainly introduce the observational characteristics and physical origins of diffuse radio emission from galaxy clusters, and its important role in galaxy cluster evolution studies. Diffuse radio emission on galaxy cluster scales originates from synchrotron radiation produced by non-thermal electrons in magnetic fields, including radio halos, mini-halos, radio relics, etc. The vast majority of radio halos appear in merging galaxy clusters, and their origin is believed to be explainable by the turbulence re-acceleration model induced by mergers; mini-halos currently have fewer observational detections, mainly existing in relaxed cool-core galaxy clusters, and their origin can also be explained by the turbulence re-acceleration model, except that the turbulence is instead induced by sloshing of gas in the cluster core region; radio relics are mostly distributed in the periphery of galaxy clusters, generally have high degrees of polarization, and their origin is related to shock waves produced during galaxy cluster merger processes. Finally, we briefly outline the prospects for galaxy cluster research in the era of LOFAR 2.0 and SKA.

Full Text

Preamble

Vol. 43, No. 2

June 2025

PROGRESS IN ASTRONOMY Vol. 43, No. 2 June 2025 doi: 10.3969/j.issn.1000-8349.2025.02.03

Diffuse Radio Emission in Galaxy Clusters

WU Wenyu[1];[2], XIE Fuguo[1]

(1. Astrophysics Division, Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030, China; 2. University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract

Galaxy clusters, as the largest self-gravitationally bound systems in the Universe, serve not only as laboratories for studying galaxy formation and evolution but also as precise tracers of cosmic large-scale structure. This paper primarily introduces the observational characteristics and physical origins of diffuse radio emission in galaxy clusters, and its significance in cluster evolution studies. Cluster-scale diffuse radio emission originates from synchrotron radiation produced by non-thermal electrons in magnetic fields, including radio halos, radio mini-halos, and radio relics. Radio halos predominantly appear in merging clusters, and their origin is thought to be explained by the merger-induced turbulent reacceleration model. Radio mini-halos, currently observed in small numbers, mainly exist in relaxed cool-core clusters, and their origin can also be explained by the turbulent reacceleration model, except that the turbulence is induced by gas sloshing in the cluster core. Radio relics are mostly distributed in cluster peripheries, generally exhibit high polarization degrees, and their origin is related to shocks generated during cluster mergers. Finally, we briefly prospect galaxy cluster research in the LOFAR 2.0 and SKA era.

Keywords: galaxy cluster; radio halo; radio mini-halo; radio relic; synchrotron emission

CLC number: P157.8 **Document code:** A

1 Introduction

Galaxy clusters, consisting of hundreds to thousands of member galaxies, are the largest self-gravitationally bound systems that can maintain virial equilibrium in the Universe. Their total mass can reach 10^{15} M , and spatial scales can extend to several Mpc [1]. Galaxy clusters are important sites for galaxy formation and evolution, but the total mass of member galaxies accounts for less than 5% of the cluster' s total mass. The main components of clusters also include dark matter halos (about 80% of the total mass) and the intracluster medium (ICM) that permeates the vast space between galaxies (accounting for 15%-20% of the total mass) [2]. From the perspective of cosmic large-scale structure, galaxy clusters located at the nodes of cosmic filaments, together with the cosmic filaments composed of unbound galaxies, constitute the cosmic web. Thus, galaxy clusters are one of the fundamental building blocks of cosmic large-scale structure.

The ICM is a high-temperature (temperature T 10^7-10^8 K), low-density (number density n 10^{-3} cm^{-3}) plasma constrained by the cluster’ s gravity. These hot gases produce thermal bremsstrahlung radiation primarily in the X-ray band. Physically, during cluster formation or mergers, ICM gas can convert gravitational potential energy into internal energy as it accretes into the central regions of clusters. The first galaxy cluster X-ray sources were observed by the Uhuru X-ray satellite in the 1970s, with well-known sources including the Perseus and Coma clusters [3]. Observations over the past half-century have shown that galaxy clusters are typically bright extended X-ray sources with luminosities L ranging from 10^{36} to 10^{38} $\mathrm{J \cdot s^{-1}}$ [1]. The X-ray luminosity exhibits clear correlations with cluster total mass and ICM gas temperature or the parameter Y (the product of ICM gas mass and temperature) [4–6]. Notably, the observed slopes of these correlations are steeper than theoretical predictions from the self-similar gravitational collapse formation model, suggesting that ICM properties may be influenced by additional or more complex physical processes such as star formation and feedback, active galactic nucleus (AGN) feedback, and cosmic ray heating [1, 5].

Galaxy clusters also exhibit rich observational information at radio wavelengths. On one hand, numerous thermal electrons in the ICM cause inverse Compton scattering of cosmic microwave background (CMB) photons, inducing distortions in the microwave background spectrum—a phenomenon known as the SZ effect [7, 8]. Since the SZ effect depends on the total pressure of hot gas along the line of sight and is independent of cluster redshift, numerous clusters, particularly high-redshift ones, have been discovered at millimeter/submillimeter wavelengths thanks to this characteristic. On the other hand, large-scale extended radio emission with smooth spectra has been detected in the ICM of some galaxy clusters. This radio emission indicates the presence of a new component in the ICM: non-thermal cosmic ray components. Diffuse radio emission originates from synchrotron radiation produced by high-energy relativistic electrons (Lorentz factor $\gamma > 10^3$) moving in cluster-scale magnetic fields of approximately 10^{-10} T. The prevailing view holds that non-thermal electrons in the ICM are primarily (re)accelerated by turbulence or low-Mach-number shocks resulting from cluster dynamical processes (mainly cluster mergers) [9]. These diffuse radio emissions exhibit diverse morphologies, mainly classified into three types: radio halos, radio mini-halos, and radio relics [9]. Radio halos are large-scale (1 Mpc) diffuse radio structures appearing in the centers (not a projection effect [10]) of merging clusters, with regular morphology, low polarization, and no optical counterpart. Radio mini-halos are diffuse radio structures resembling smaller versions of radio halos found in the centers of relaxed cool-core clusters (often surrounding central radio galaxies). They differ from radio halos not only in their smaller scales (hundreds of kpc) but also in their host clusters, with regular morphology and low polarization. Radio relics are large-scale (1 Mpc) diffuse radio structures found primarily in the peripheries of merging/relaxed clusters, with irregular and often elongated morphology, strong polarization, and no optical counterpart. All three types of diffuse radio sources share characteristics of low surface brightness and steep spectra.

Galaxy clusters can be divided into relaxed and merging clusters based on their dynamical states. Cluster mergers are arguably the most violent astronomical events since the Big Bang, releasing up to approximately 10^{57} J of energy over merger timescales of several billion years. This energy heats ICM gas, accelerates cosmic ray particles, and amplifies magnetic fields in the form of turbulence or low-Mach-number shocks [11]. Thus, cluster merger processes simultaneously affect both thermal and non-thermal components in the ICM, directly manifesting in radiation across different wavelengths such as X-ray and radio. Indirect evidence includes the clear positive correlation between radio halo power and cluster X-ray luminosity [9, 12]. Many radio relics also show direct spatial correspondence with shock positions identified in X-ray bands, providing observational constraints on relic formation mechanisms [13]. Clearly, multi-wavelength observations are more conducive to comprehensively revealing cluster states, structures, and evolution. Based on X-ray observational characteristics, clusters can also be divided into cool-core and non-cool-core clusters. The most obvious difference is that the former exhibits a pronounced peak in central X-ray surface brightness. Since the bremsstrahlung emission coefficient of hot cluster gas is proportional to the square of gas density and the square root of temperature ($j \quad n^{2}T^{1}/^{2}$), and the bremsstrahlung cooling timescale is inversely proportional to gas density and proportional to the square root of temperature (t_{cl} $nT/j \quad n^{-1}T^{1}/^{2}$), this indicates that the former has formed a cool core with high gas density, short cooling time, and temperature significantly lower than the cluster’ s characteristic temperature. Some cluster cool cores also exhibit arc-shaped or spiral cold front structures [11]—contact discontinuities between gas cloud boundaries and surrounding hotter, more tenuous gas. Mini-halos have been found to show clear spatial correlations with X-ray cold fronts in several cool-core clusters (RX J1720.1+2638, MS 1455.0+2232, PSZ1 G139.61+24.20, A1068, A3444, etc.): the emission of these mini-halos is confined within regions delineated by cold fronts [14–17]. This discovery has prompted discussion about whether mini-halos and X-ray cold fronts share a common origin [18].

Section 2 of this paper introduces the large-scale magnetic fields in galaxy clusters that play a crucial role in synchrotron radiation and describes magnetic field measurement methods. Section 3 introduces the non-thermal electrons producing diffuse synchrotron radiation, focusing on particle acceleration mechanisms in the ICM environment. Section 4 discusses observational results and origin models for the three types of diffuse sources: radio halos, mini-halos, and radio relics. Section 5 provides a brief summary and outlook.

2 Large-Scale Magnetic Fields in Galaxy Clusters

Large-scale magnetic fields permeate the entire ICM of galaxy clusters and play an important role in the acceleration of high-energy particles. The origin of these magnetic fields remains unclear. One possibility is that weak seed magnetic fields are significantly amplified through magnetohydrodynamic (MHD) dynamo effects and adiabatic compression of magnetic field lines during cosmic hierarchical structure formation and cluster mergers [25]. Seed magnetic fields may be primordial—magnetic field fluctuations from the birth of the Universe [26]—or may diffuse into the ICM from magnetic fields in early stars and (primordial) galaxies [27].

Precise measurement of cluster magnetic fields is extremely challenging. The equipartition estimate is one method for estimating magnetic field strength, assuming that the cosmic ray energy density _{CR} equals the magnetic field energy density _B in the radio-emitting region [28]. This method requires knowledge of the proton-to-electron number density ratio in cosmic rays, which cannot be constrained observationally and depends on cosmic ray production mechanisms, making the resulting magnetic field strength highly uncertain. Observations using this method estimate cluster magnetic field strengths in the range of 0.01-1 nT [9].

In addition to radio synchrotron radiation, other methods can provide crucial clues for studying ICM cosmic ray electrons. For example, inverse Compton scattering of CMB photons by cosmic ray electrons produces hard X-ray radiation with a power-law spectrum superimposed on the ICM bremsstrahlung continuum in the X-ray band. By comparing inverse Compton X-ray flux with radio synchrotron flux, magnetic field strength can be calculated [29, 30]. The main assumption of this method is that both radio and hard X-ray emissions are produced by the same population of high-energy cosmic ray electrons. Since the CMB photon density is known, this method is suitable for calculating magnetic fields in regions with both X-ray and radio emissions. However, in practice, only upper limits on inverse Compton X-ray flux from clusters are generally obtained, so this method currently can only determine lower limits on overall ICM magnetic fields.

A more reliable and direct method than the above two is Faraday rotation synthesis analysis of background radio galaxies within or behind clusters. When polarized radiation from background radio sources passes through the ICM, its polarization angle undergoes Faraday rotation due to magnetic fields and thermal electrons in the ICM. The rotation angle Δ is proportional to the square of the wavelength λ and the rotation measure (RM), i.e., $\Delta = \mathrm{RM} \cdot \lambda^2$, where RM n_e,th B_ dl (B_ is the line-of-sight magnetic field component). The RM can be obtained by comparing polarization angle variations across multiple radio bands. In cluster studies, if no foreground medium exists between the observer and the background source except the ICM, the RM depends only on the properties of the traversed ICM [31]. Combined with X-ray observations providing ICM thermal electron density distributions and modeling of magnetic field structures, we can determine cluster magnetic field properties based on the physical meaning of RM.

Faraday rotation measurements have greatly expanded our understanding of cluster magnetic fields. Due to the limited number of background polarized radio sources, current studies are mainly statistical. It is now well established that magnetic field strength generally decreases with distance from the cluster center, but may fluctuate at certain spatial scales. Statistically, the central magnetic field strength of cool-core clusters is on the order of 1 nT, while that of merging clusters is about 0.1 nT [9]. Limited by the number of background polarized sources, our understanding of large-scale magnetic field structures (coherence scales and power spectra, etc.) remains poor.

In recent years, astronomers have made progress in cluster magnetic fields through cosmological magnetohydrodynamics (MHD) simulations [32-34]. Weak (10^{-14} T) primordial seed magnetic fields are significantly amplified through small-scale dynamo effects and compression during cosmic structure formation. Simulations show that the amplified magnetic field strength distribution is closely related to the matter density distribution, and within cluster halos, the magnetic field strength is several orders of magnitude higher than theoretical values from the magnetic freezing (magnetic flux conservation) model with only gas compression. Simulated cluster magnetic field strengths decrease with increasing distance from the cluster center, consistent with observations, but the magnetic field power spectrum is more complex than the simple power-law form commonly assumed in Faraday rotation synthesis methods [35]. Recently, researchers have used power spectra derived from cosmological MHD simulations to describe magnetic field structures when applying Faraday rotation to measure ICM magnetic fields [36].

In the future, with the deployment of highly sensitive low-frequency radio observatories such as the LOFAR low-frequency array and the Square Kilometer Array (SKA), we expect to obtain more (background) polarized radio sources. This will facilitate more detailed statistical studies of cluster magnetic fields and even enable in-depth measurements of magnetic fields in individual clusters.

3.1 Radiation Power and Characteristic Lifetime

Synchrotron radiation is produced by relativistic electrons spiraling in magnetic fields and is the common radiation mechanism for three types of astrophysical radio sources: supernova remnants, large-scale jets, and large-scale diffuse sources in the ICM. The radiation power of a single electron depends on its energy (Lorentz factor) and magnetic field strength; higher magnetic field strength requires lower electron energy to produce radiation at a given frequency. Astronomical observations of synchrotron radiation correspond to the collective effect of numerous electrons. Given an isotropic, uniform non-thermal electron distribution n_e(γ) and uniform magnetic field B, the synchrotron emissivity J( ) can be calculated [19]:

$$J(\nu) = \int_{\theta_{\min}}^{\theta_{\max}} \int_{\gamma_{\min}}^{\gamma_{\max}} n_e(\gamma) F\left(\frac{\nu}{\nu_c}\right) \sin^2\theta \, d\theta \, d\gamma,$$

where c is the speed of light, e is the electron charge, m_e is the electron rest mass, is the pitch angle between the electron and magnetic field B, _c = (3/2)γ^2 _L sin (_L = eB/(2πm_{ec})) is the electron' s critical frequency, and F is the synchrotron kernel function:

$$F(x) = x \int_x^\infty K_{5/3}(y)\, dy,$$

with K_{5/3} being the modified Bessel function of order 5/3. For diffuse cluster radiation, we consider non-thermal electrons following a power-law energy distribution (n_e(γ) γ^{-δ}, where δ is the energy spectral index) and the radiation source being optically thin in the radio band. The observed spectrum then also follows a power-law distribution F_ ^{-α}, with the spectral index α related to the particle energy spectral index δ by α = (δ - 1)/2 [19, 20]. Diffuse radio emission from clusters typically has steep spectra with α 1, implying relatively few high-energy electrons (δ 3).

In the ICM, non-thermal electrons have several energy loss mechanisms besides synchrotron radiation, with inverse Compton scattering of CMB photons being the most important. Through collisions between photons and electrons, CMB photons gain energy and become hard X-ray or even γ-ray photons, while non-thermal electrons lose energy. The energy loss rates for both synchrotron radiation and inverse Compton scattering are proportional to the square of the Lorentz factor [21]; higher-energy electrons lose energy faster. Consequently, the initial power-law energy spectrum of non-thermal electrons gradually steepens at the high-energy end, with the steepening region extending toward lower energies over time. Considering only these two radiation loss mechanisms without particle acceleration, the characteristic lifetime (also called radiative cooling timescale) t_{age} of non-thermal electrons can be expressed as [9]:

$$t_{\rm age} \approx 3.2 \times 10^{10} \frac{B^{-3/2}}{\sqrt{B^2 + B_{\rm CMB}^2}} [(1+z)\nu]^{-1/2}\ \text{yr},$$

where t_{age} is in years, magnetic field strength B is in units of 10^{-10} T, B_{CMB} 3.25(1+z)^2 is the equivalent magnetic field strength of the CMB, z is the source redshift, and observation frequency is in MHz. Higher frequencies (corresponding to higher electron energies γ) have shorter lifetimes, meaning radiation intensity at higher frequencies diminishes more rapidly. Therefore, observed diffuse radio spectra often show steepening at high frequencies. For galaxy clusters, typically t_{age} 10^8 yr. Based on the Bohm approximation, high-energy non-thermal electrons with $\gamma > 10^3$ have typical diffusion scales on the order of 10 pc in the ICM [22], far smaller than the scales of various cluster diffuse radio sources. Even assuming ordered magnetic fields that make diffusion more efficient than in the Bohm case, the upper limit of diffusion scales remains far below 1 Mpc. Theoretical results indicate that non-thermal electrons producing diffuse radio emission cannot originate from some small-scale region in the ICM (e.g., radio galaxies or AGN) but must be produced or (re)accelerated in situ. This provides constraints on possible particle acceleration mechanisms.

3.2 Particle Acceleration Mechanisms

To produce relativistic non-thermal electrons over scales of 100 kpc–1 Mpc, the required acceleration mechanism should have important connections with overall cluster dynamical processes. This subsection briefly introduces several possible particle acceleration mechanisms in the ICM.

(1) **First-order Fermi acceleration**, also known as diffusive shock acceleration (DSA), describes particle acceleration in magnetohydrodynamic shocks. Scattering centers (such as intense turbulence, plasma waves, or inhomogeneous magnetic field/density structures) exist ubiquitously upstream and downstream of shocks, causing charged particles to cross the shock front repeatedly. Each crossing results in a head-on collision with the shock, gaining energy. The total energy gained by a particle is positively correlated with the number of shock crossings. The process of thermal equilibrium particles repeatedly crossing an ideal parallel shock produces non-thermal particles with a power-law distribution, with the theoretical energy spectral index δ related to shock Mach number M_s by $\delta = 2(\mathrm{M\_s}^2 + 1)/(\mathrm{M\_s}^2 - 1)$ [23].

(2) **Second-order Fermi acceleration**, also known as Fermi stochastic acceleration, describes particle acceleration through stochastic scattering in magnetically inhomogeneous fluids (such as MHD turbulence). Particles can gain energy in head-on collisions and lose energy in overtaking collisions during scattering. For random motion, head-on collisions are slightly more probable, resulting in net acceleration. However, due to its stochastic nature, second-order Fermi acceleration has relatively low energy conversion efficiency.

(3) **Secondary model**. First-order Fermi acceleration, AGN activity, and galactic outflows can all produce certain amounts of high-energy non-thermal protons in the ICM. Since the radiative lifetime of non-thermal protons in the ICM is far longer than that of non-thermal electrons (approximately the Hubble timescale), and most high-energy non-thermal protons cannot escape the cluster, a significant accumulation of non-thermal protons is expected over a cluster' s lifetime [24]. According to hadronic models, high-energy relativistic non-thermal protons colliding with thermal ions produce secondary high-energy non-thermal electrons. Overall, in the secondary model, non-thermal electrons are produced as secondary particles (decay products).

4.1.1 Main Observational Properties

Radio halos are diffuse extended sources typically with regular, smooth morphology, and their brightness distribution roughly matches that of the ICM. More massive and dynamically disturbed clusters have higher probabilities of hosting large radio halos [37]. Nearly 100 radio halos have been confirmed to date. [Figure 1: see original paper] shows a typical cluster radio halo: panel (a) displays the observed structure before subtracting discrete foreground sources, while panel (b) shows the halo emission after subtraction. As seen in [Figure 1: see original paper], typical radio halo sizes are 1–2 Mpc, with observed radiation powers at 1.4 GHz ranging from 10^{23} to 10^{26} $\mathrm{W \cdot Hz^{-1}}$.

The spectral properties of radio halos provide crucial information for revealing their origin. Radio halo spectra are steep, with typical spectral indices of 1.1–1.7. Giovannini et al. [39] noted a correlation between radio halo spectral index and ICM temperature: hotter clusters tend to have flatter-spectrum radio halos. Radio halos with spectral index $\alpha > 1.5$ are called ultra-steep spectrum radio halos (USSRHs). The appearance of ultra-steep spectra is thought to result from high-frequency cutoffs in halo spectra; measuring near the cutoff frequency yields overly steep spectral indices. Only the brightest radio halos are expected to have cutoff frequencies above ~1 GHz. Therefore, high-sensitivity observations at low frequencies can not only discover more radio halos but also reveal their spectral features in greater detail.

Radio halo power shows clear correlations with host cluster X-ray luminosity and mass. In 2013, Cassano et al. [40] presented statistical results for 25 radio halos (including 6 USSRHs), giving the relationship between radio halo power at 1.4 GHz ($P_{1\cdot4}$) and cluster X-ray luminosity within R_{500} ($L_{,500}$) as $P_{1\cdot4}$ $L_{,500}{}^{2}.{}^{11}\pm{}^{0}.{}^{20}$, and the relationship with total mass within R_{500} (M_{500}) as $P_{1\cdot4}$ $M_{500}{}^{3}.{}^{70}\pm{}^{0}.{}^{56}$. They also found that USSRHs significantly affect these correlations, steepening them when included. After eight more years of radio halo observations, Duchesne et al. [41] collected and analyzed 86 radio halos in 2021. Without distinguishing between normal radio halos and USSRHs, they presented the relationships between radio halo power and cluster mass at 1.4 GHz and 150 MHz as $P_{1\cdot4}$ $M_{500}{}^{3}.{}^{21}\pm{}^{0}.{}^{39}$ and $P_{0\cdot15}$ $M_{500}{}^{3}.{}^{15}\pm{}^{0}.{}^{41}$, respectively. Future larger and more complete samples will help reveal whether normal radio halos and USSRHs differ in these correlations.

In addition to these two correlations, Cassano et al. [40] studied a sample of 54 clusters at similar redshifts (including the 25 radio halo host clusters) and found that X-ray bright clusters ($L_{500} > 5 \times 10^{37}$ $\mathrm{J \cdot s^{-1}}$) can be divided into two branches: one with radio halos following the aforementioned $P_{1\cdot4}$-L_{500} correlation, and one without radio halos where observational upper limits on diffuse radio emission are far below this correlation (called radio-quiet clusters). This bimodality persists even after subtracting the X-ray luminosity of cool-core cluster cores. The bimodality is related to cluster dynamical states: merging clusters are more likely to have radio halos, while radio-quiet clusters are statistically more relaxed [37]. In 2021, Cuciti et al. [42, 43] selected 75 massive clusters (M$_{500}$ 6×10^{14} M) from the Planck SZ cluster catalog within redshift 0.08-0.33, discovering 28 radio halos (~37%) and 5 candidates through radio observations. Combining X-ray data providing cluster dynamical information (centroid shift w, power ratio P$_3$/P$_0$, concentration parameter c [37]), they found that over 90% of radio halos appear in merging clusters. The P$_{1\cdot4}$-M$_{500}$ correlation shows large scatter, with cluster dynamical state contributing significantly to this scatter—the deviation of radio halo power from the correlation (above or below) correlates positively with the degree of dynamical disturbance (more disturbed or more relaxed). Clusters without observed radio halos are typically relaxed, with upper limits significantly below the correlation. This study further confirms the existence of bimodality and its relationship with cluster dynamical state.

4.1.2 Origin

Historically, two main models have been discussed for radio halo origins: the secondary model and the turbulent reacceleration model. The secondary model was briefly described in Section 3.2. Numerous observational evidence now challenges this model, with the most direct evidence being the upper limit on γ-ray flux from observations of the Coma cluster [44]. The mainstream turbulent reacceleration model posits that major cluster mergers generate powerful turbulence that reaccelerates seed electrons—the second-order Fermi acceleration mentioned in Section 3.2. The strong correlation between radio halo luminosity and cluster dynamical state indicates that the primary mechanism triggering large-scale synchrotron radiation is the same as that destroying cool cores and causing cluster disturbances, strongly supporting the turbulent reacceleration model.

Under the turbulent reacceleration model, assuming isotropic seed electron distribution, the evolution of non-thermal electron energy spectra can be described by the Fokker-Planck equation [45]:

$$\frac{\partial n_e(\gamma,t)}{\partial t} = \frac{\partial}{\partial \gamma}\left[D_{\gamma\gamma}(\gamma,t)\frac{\partial n_e(\gamma,t)}{\partial \gamma}\right] - \frac{\partial}{\partial \gamma}\left[\left(\frac{d\gamma}{dt}\right)n_e(\gamma,t)\right] + Q_e(\gamma,t) - n_e(\gamma,t)R_e(\gamma,t),$$

where D_{$\gamma\gamma$} describes the diffusion (reacceleration) coefficient from turbulence-electron interactions, and Q_e and R_e terms describe electron injection and escape processes, respectively. The first and second D_{$\gamma\gamma$} terms in the equation represent systematic (advective) and random (diffusive) energy gains provided by turbulence to particles; |dγ/dt| is the electron energy loss rate, considering synchrotron radiation, free-free emission, inverse Compton scattering of CMB photons, Coulomb collisions with ICM thermal electrons, and adiabatic expansion of the medium. The strength of D_{$\gamma\gamma$} depends on the specific mechanism of turbulence-electron interactions. For plasma systems with turbulent magnetic fields, different types of MHD waves exist, such as Alfvén waves or fast/slow magnetosonic waves. Cyclotron resonance between electrons and Alfvén waves is one acceleration mechanism. Among various particle acceleration mechanisms caused by fast magnetosonic waves, one is transit-time damping (TTD), where resonance occurs when a particle' s transit time equals the wave period, and wave damping means particles gain energy from the wave [45, 46].

An unresolved question in the turbulent reacceleration model concerns the origin of seed electrons. Seed electrons may be related to galactic outflows and AGN activity, may have been accelerated in previous cluster mergers or accretion shocks, or may be secondary electrons from proton-proton interactions. The relative contributions of these three possible sources to seed electrons remain unclear. Vazza et al. [47] used passive tracer particle methods in MHD simulations to study the evolution of non-thermal electrons injected into the ICM by radio galaxies, finding that these electrons from radio galaxies can effectively fill the ICM on timescales of several hundred million years, providing a stable fossil electron reservoir.

4.2.1 Main Observational Properties

Radio mini-halos have typical sizes of ~100–500 kpc, mainly exist in relaxed cool-core clusters, and their radio emission often surrounds the brightest cluster galaxy (BCG). Mini-halos have observed radiation powers of 10^{23}–10^{25} $\mathrm{W \cdot Hz^{-1}}$ at 1.4 GHz. Currently, 25 mini-halos have been confirmed, with one reason for the small number being that it is observationally difficult to clearly distinguish mini-halos from BCG radio emission, requiring radio observations with both high spatial resolution and dynamic range, as well as detailed X-ray cavity observations. [Figure 2: see original paper] shows a typical mini-halo.

Compared to radio halos, mini-halos generally have higher synchrotron emissivity. Although radiation distributions often deviate from spherical symmetry for both halos and mini-halos, their radially averaged surface brightness profiles can typically be fitted with $\mathrm{I(r) = I_0}$e^{-r/r_e}. The work of Murgia et al. [49] shows that mini-halos have smaller distribution radii r_e than halos, higher central surface brightness $\mathrm{I_0}$, and a relatively larger range of $\mathrm{I_0}$ values. Mini-halo spectral characteristics are similar to those of halos, with steep spectra, and high-frequency steepening has been observed in a few studies [9].

Limited by the known number of mini-halos, statistical studies of mini-halo properties in relation to the ICM remain in their infancy. Unlike halos, current observational data cannot establish a clear correlation between mini-halo radio power and cluster mass [15]. However, studies have found a positive correlation between mini-halo radio power and cluster X-ray luminosity, with a slope similar to that for halos [48, 50, 51]. In 2020, Richard-Laferrière et al. [52] explored the relationship between mini-halos and AGN feedback in central galaxies based on 28 known mini-halos and 5 candidates. On one hand, after decomposing the

BCG radio spectral energy distribution into a flat-spectrum core component (related to ongoing AGN accretion) and a steep-spectrum component (related to radio lobes from past AGN jets), mini-halo radio power shows strong correlations with both components, especially the latter, with a steeper correlation slope for the steep-spectrum component. On the other hand, X-ray cavity structures are thought to be related to AGN jets, with cavity power representing the sum of work required to create cavities and their internal energy divided by cavity formation time (i.e., buoyancy time). Mini-halo radio power shows a strong correlation with central X-ray cavity power in host clusters. These results together indicate a connection between BCG AGN feedback processes and mini-halos.

4.2.2 Origin

Although smaller than radio halos, mini-halos still require in situ acceleration due to the short lifetimes of synchrotron electrons. Therefore, mini-halo radio emission does not directly originate from the central AGN, unlike radio lobes that coincide with X-ray cavities. The current mainstream view holds that mini-halo origins can be explained by a turbulent reacceleration model similar to that for halos. However, unlike the halo case, the turbulence involved in mini-halos is on much smaller scales, induced by gas sloshing in relaxed cluster cores, which itself may be stirred by sub-cluster mergers (with large impact parameters) that are not violent enough to change the overall relaxed state of the cluster. The seed electrons reaccelerated by turbulence likely originate from the central AGN and are distributed over larger spatial scales by physical processes such as gas sloshing. The observed spatial correlation between mini-halos and X-ray cold fronts supports this model. Numerical simulations also provide evidence. For example, ZuHone et al. [18] used the FLASH 3 code to simulate a merger between a massive cluster (initial mass ~10^{15} M) and a sub-cluster (initial mass ~2×10^{14} M) with initial separation and impact parameter of 3 Mpc and 500 kpc, respectively. The results showed that the merger triggered gas sloshing in the main cluster core, generating significant turbulence and magnetic field amplification within the sloshing cold front-enclosed core region, while turbulence outside the cold front was negligible. Using passive tracer particle techniques, they also tested the evolution of different initial seed electron distributions under gas sloshing, finding that seed electrons could both diffuse from small scales to fill the entire core region enclosed by cold fronts and be reaccelerated by MHD turbulence to observed mini-halo levels.

Despite differences, radio halos and mini-halos in clusters may be physically related, perhaps transitioning from one to the other or coexisting. For example, during major cluster mergers with large impact parameters, early merger stages may only trigger core gas sloshing producing mini-halos. As the merger progresses, merger turbulence fully develops and replaces mini-halos with radio halos. Alternatively, during strong sub-cluster mergers, besides mini-halos appearing within cold front-enclosed cores, the merger may also stir turbulence outside the core, producing weak halo-like diffuse emission without completely masking the mini-halo. Some special observational cases, such as the discovery of a radio halo in the cool-core cluster CL1821+643 [53] and the detection of both central mini-halo and peripheral weak halo components (with different surface brightness and spectral indices) in the non-major-merger cold front cluster Abell 2142 [54], indicate a close connection between the two types of diffuse sources, with the complexity of cluster merger processes facilitating this relationship.

4.3.1 Main Observational Properties

Radio relics mostly appear in cluster peripheries, have relatively elongated shapes, and generally have largest linear sizes (LLS) in the range of 0.5–2 Mpc. Most radio relics show asymmetric transverse brightness distributions: sharp edges on the side farther from the cluster center, gradually decreasing radiation toward the cluster center. A subtype called double relics exists: elongated, outward-curved radio relics in opposite directions relative to the cluster center (often along the merger axis). High signal-to-noise, high-resolution observations reveal that radio relics seem to ubiquitously contain filamentary substructures. Radio relics have been observed in about 60 clusters to date. [Figure 3: see original paper] shows a cluster with radio relics.

Radio relics have steep spectra with spectral indices α typically in the range 1.0-1.5. Studies of spectral index spatial distributions show that relics often exhibit clear spectral index gradients across their widths, with the flattest spectral index regions located on the side farthest from the cluster center, steepening toward the center. Panel (b) of [Figure 3: see original paper] clearly demonstrates this feature for the northern relic of the Sausage cluster.

Radio relics are among the most highly polarized extragalactic sources, with very elongated relics usually having the highest polarization degrees. At frequencies 1 GHz, polarization degrees are 20%, while stronger depolarization occurs at lower frequencies. For large relics, the spatial distribution of intrinsic polarization angles is found to be quite ordered, as shown in panel (c) of [Figure 3: see original paper], with polarization B-vectors oriented along the relic surface.

Statistical studies of relic properties help explore their origins. Feretti et al. [57] found a correlation between relic power and cluster X-ray luminosity, giving $P_{1\cdot 4}\quad L\ ^{1}.^{2}$. Based on 17 double relic pairs, Duchesne et al. [58] derived a correlation between total double relic power and cluster mass: $P_{1\cdot 4}\quad M_{500}{}^{2}.^{55}\pm^{0}.^{55}$. Based on 15 double relic pairs, de Gasperin et al. [59] found a correlation between individual relic LLS and projected distance to the cluster center (X-ray brightness peak), with larger relics located farther from the center. Studying only double relics reduces projection effects on distance measurements.

4.3.2 Origin

Based on the shape, location, spectrum, and polarization properties of radio relics, their formation is thought to be DSA of electrons by shocks generated during cluster mergers in cluster peripheries [60]. In an ideal head-on merger of two clusters, as they approach and compress each other, equatorial shocks form on the equatorial plane perpendicular to the merger axis. After the cluster cores pass through each other, two merger shocks propagate outward along the merger axis ahead of the cores. Eventually, the clusters decelerate and are pulled together by mutual gravity, while merger shocks continue propagating outward. Merger shocks accelerate electrons in situ in cluster peripheries, forming relics that can display shock morphologies. Equatorial shocks mainly propagate into low-density regions around merging clusters and are unlikely to produce observable diffuse radio emission; actual situations are more complex.

Based on this formation theory, shocks should coexist with radio relics at the same locations, and shocks can be identified in X-ray observations primarily through sharp discontinuities in X-ray surface brightness distributions and significant temperature or density changes at the same positions. Over 20 X-ray shocks coincident with radio relic positions have been detected to date [9]. Furthermore, based on Rankine-Hugoniot jump conditions, shock strength (X-ray Mach number M_X) can be obtained from X-ray observations. Meanwhile, based on DSA theory, shock strength (radio Mach number M_r) can also be inferred from relic spectral indices. Comparing these two Mach numbers can test whether relic electron acceleration follows DSA theory. However, in most cases, observations yield M_r > M_X, i.e., M_X 1.5–2.5 and M_r 2–5 [61, 62]. If this difference truly exists, it suggests that standard DSA theory is insufficient to fully explain relic formation. To reconcile this discrepancy, several solutions have been proposed. One simple idea is that shocks accelerate not only ICM thermal electrons but also fossil non-thermal electrons that may originate from radio galaxies [63]. Inchingolo et al. [64] proposed a multiple shock model, where relic non-thermal electrons may have experienced (re)acceleration by merger shocks multiple times in different periods. In their MHD simulation of a massive merging cluster with two radio relics (A and B) at $z = 0$, they used the CRATER tracer particle technique to track non-thermal electron trajectories from $z = 1$ to $z = 0$, identifying shocks encountered based on temperature Rankine-Hugoniot jump conditions. Most non-thermal electrons in relic A experienced only the final shock, while ~70% of electrons in relic B experienced multiple shocks. Relic B' s radio emission was significantly stronger than relic A' s, and its spectrum matched observations better. This model does not require fossil electrons, thus weakening the assumption that radio galaxies are the source of fossil electrons. Zimbardo and Perri [65, 66] extended the classical DSA model to superdiffusive shock acceleration (SSA) to explain M_r > M_X cases. They assumed that electron transport in the entire shock region is superdiffusive rather than normal diffusion, with superdiffusive transport caused by non-Gaussian random walks of high-energy particles, leading to nonlinear growth of mean square displacement with time: Δx^2(t) t^β, where $1 < \beta < 2$ for superdiffusion, reverting to normal diffusion as $\beta \to 1$. In the SSA framework, the relationship between shock-accelerated non-thermal particle spectral index and shock Mach number is modified to:

$$\delta = \frac{2(M_s^2 + 3)}{(2-\beta)(3-\beta)M_s^2} + 1.$$

Physical explanations for the origin of superdiffusive transport include Richardson diffusion and mechanisms from their earlier studies of interplanetary shocks in the solar wind, though further numerical studies are needed for verification.

After merger shocks detach from driving sub-clusters, their strength would decrease with distance in a uniform medium. However, in reality, as shocks propagate toward cluster peripheries, they move along steep density gradients into low-density regions, which helps shocks maintain their strength over long distances—the steeper the density gradient, the more significant this effect [67]. Generally, cluster ICM gas density profiles _{gas}(r) are relatively flat in central regions (~r^{-1}) and gradually steepen outward (~r^{-2}.^{5} near R$_{500}$). Therefore, the detachment position of shocks from driving sub-clusters significantly affects their subsequent evolution, with shocks detaching closer to the cluster center having shorter lifetimes. This may explain why radio relics are primarily found in cluster peripheries.

In a few clusters, radio relics connect or overlap with radio halos, such as in the Toothbrush cluster [68]; there are also cases where halos cover almost the entire region between double relics, such as in the Sausage cluster [55]. In both examples, relic flux is significantly stronger than halo flux, possibly reflecting a transition from first-order Fermi acceleration by shocks to second-order Fermi acceleration by turbulence in merging clusters.

5 Summary and Outlook

Galaxy clusters are the largest self-gravitationally bound systems in the Universe, serving as laboratories for galaxy formation and evolution and as precise tracers of cosmic large-scale structure. Galaxy clusters exhibit diverse and unique features in multi-wavelength observations from X-ray to radio. Diffuse radio emission reveals the existence of cosmic rays and magnetic fields in the ICM and indicates high-energy physical processes that dissipate gravitational potential energy into non-thermal components within clusters. Non-thermal components in turn affect the (micro)physical properties of the ICM and potentially influence cluster evolution itself [2]. Individual member galaxies can supply non-thermal electrons to the ICM through star formation activity and feedback from central supermassive black holes. However, due to the very large spatial scales of diffuse sources (~50 kpc–10 Mpc) and the limited propagation scales of non-thermal electrons constrained by their cooling timescales, in situ (re)acceleration mechanisms on cluster scales are required for non-thermal electrons. In the ICM, high-energy non-thermal electrons can lose energy through various mechanisms beyond synchrotron radiation, so inverse Compton scattering of CMB photons may also be observed in hard X-ray or even γ-ray bands. Furthermore, ICM magnetic fields both affect non-thermal electron acceleration and are key to producing synchrotron radiation, though our understanding of magnetic field structure remains limited.

Recently, a more extended diffuse source than radio halos—radio megahalos—has been reported [69]. In LOFAR low-frequency array survey data, four clusters were found where known radio halos are enveloped by newly discovered megahalos, with the latter being ~30 times larger in volume but with much lower surface brightness. The two can be distinguished based on differences in surface brightness radial profiles and spectral indices. This new discovery indicates that non-thermal electrons and magnetic fields exist in clusters over much larger scales than previously found, requiring electron acceleration mechanisms effective on larger scales (awaiting further verification). The diversity of diffuse radio emission in clusters opens a new path for low-frequency radio studies.

Different types of diffuse radio emission contain information about different production mechanisms ranging from turbulence to shocks and are closely related to cluster dynamical processes such as merger history. Their study helps deepen our understanding of ICM structure and properties, particularly the important physical quantity of ICM magnetic fields that remains largely unexplored. Given the steep-spectrum nature of cluster diffuse radio emission, low-frequency radio bands are suitable for in-depth studies. Upcoming upgrades like LOFAR 2.0, with its cluster survey plans offering sub-arcsecond spatial resolution and extremely low frequency windows, will powerfully expand studies of high-redshift clusters.

With the completion of the SKA low-frequency array, the number of cluster diffuse radio sources will increase significantly, expanding samples to medium-high redshift ranges and facilitating research on cluster formation and evolution, while observational precision for individual sources will be substantially improved. An important scientific goal of SKA is to detect neutral hydrogen signals from the cosmic dawn and reionization epoch. In this research, foreground source subtraction, particularly from diffuse sources, is one of the most important technical challenges. Large-scale diffuse radio emission from galaxy clusters is one of the main contributions to extragalactic diffuse foregrounds. Therefore, theoretical modeling of cluster diffuse radio emission will provide direct support for foreground subtraction. Building on previous radio halo modeling [32, 70], we have recently performed numerical modeling of radio relics. We sampled cluster populations from IllustrisTNG cosmological simulation data [71], combined particle acceleration mechanisms such as DSA and post-shock turbulent reacceleration [72] to derive electron energy spectra, and generated simulated radio relic sky maps using magnetic fields from IllustrisTNG simulations, with results shown in [Figure 4: see original paper].

References

[1] McNamara B R, Nulsen P E J. ARA&A, 2007, 45: 117 [2] Brunetti G, Jones T W. International Journal of Modern Physics D, 2014, 23: 1430007 [3] Forman W, Kellogg E, Gursky H, et al. ApJ, 1972, 178: 309 [4] Maughan B J. ApJ, 2007, 668: 772 [5] Pratt G W, Croston J H, Arnaud M, et al. A&A, 2009, 498: 361 [6] Mantz A, Allen S W, Ebeling H, et al. MNRAS, 2010, 406: 1773 [7] Sunyaev R A, Zeldovich Y B. CoASP, 1972, 4: 173 [8] Mroczkowski T, Nagai D, Basu K, et al. SSRv, 2019, 215: 17 [9] van Weeren R J, de Gasperin F, Akamatsu H, et al. SSRv, 2019, 215: 16 [10] Feretti L. IAUS, 2002, 199: 133 [11] Markevitch M, Vikhlinin A. PhR, 2007, 443: 1 [12] Cassano R, Brunetti G, Setti G. MNRAS, 2006, 369: 1577 [13] Brüggen M, Bykov A, Ryu D, et al. SSRv, 2012, 166: 187 [14] Mazzotta P, Giacintucci S. ApJL, 2008, 675: L9 [15] Giacintucci S, Markevitch M, Venturi T, et al. ApJ, 2014, 781: 9 [16] Giacintucci S, Venturi T, Markevitch M, et al. ApJ, 2024, 961: 133 [17] Biava N, Bonafede A, Gastaldello F, et al. https://arxiv.org/abs/2403.09802, 2025 [18] ZuHone J A, Markevitch M, Brunetti G, et al. ApJ, 2013, 762: 78 [19] Rybicki G B, Lightman A P. Radiative Processes in Astrophysics. New York: Wiley, 1979: 167 [20] Feretti L, Giovannini G. LNP, 2008, 740: 143 [21] Sarazin C L. ApJ, 1999, 520: 529 [22] Bagchi J, Enßlin T A, Miniati F, et al. New Astronomy, 2002, 7: 249 [23] Drury L O. RPPh, 1983, 46: 973 [24] Enßlin T, Pfrommer C, Miniati F, et al. A&A, 2011, 527: A99 [25] Kahniashvili T, Maravin Y, Natarajan A, et al. ApJ, 2013, 770: 47 [26] Subramanian K. RPPh, 2016, 79: 076901 [27] Rees M J. AN, 2006, 327: 395 [28] Beck R, Krause M. AN, 2005, 326: 414 [29] Petrosian V. ApJ, 2001, 557: 560 [30] Randall S W, Clarke T E, van Weeren R J, et al. ApJ, 2016, 823: 94 [31] Brentjens M A, de Bruyn A G. A&A, 2005, 441: 1217 [32] Marinacci F, Vogelsberger M, Pakmor R, et al. MNRAS, 2018, 480: 5113 [33] Vazza F, Brunetti G, Brüggen M, et al. MNRAS, 2018, 474: 1672 [34] Domínguez-Fernández P, Vazza F, Brüggen M, et al. MNRAS, 2019, 486: 623 [35] Vacca V, Murgia M, Govoni F, et al. A&A, 2012, 540: A38 [36] Stuardi C, Bonafede A, Lovisari L, et al. MNRAS, 2021, 502: 2518 [37] Cassano R, Ettori S, Giacintucci S, et al. ApJL, 2010, 721: L82 [38] Rojas Bolivar R A, Wik D R, Giacintucci S, et al. ApJ, 2021, 906: 87 [39] Giovannini G, Bonafede A, Feretti L, et al. A&A, 2009, 507: 1257 [40] Cassano R, Ettori S, Brunetti G, et al. ApJ, 2013, 777: 141 [41] Duchesne S W, Johnston-Hollitt M, Wilber A G. PASA, 2021, 38: e031 [42] Cuciti V, Cassano R, Brunetti G, et al. A&A, 2021, 647: A50 [43] Cuciti V, Cassano R, Brunetti G, et al. A&A, 2021, 647: A51 [44] Brunetti G, Zimmer S, Zandanel F. MNRAS, 2017, 472: 1506 [45] Donnert J, Brunetti G. MNRAS, 2014, 443: 3564 [46] Brunetti G, Lazarian A. MNRAS, 2007, 378: 245 [47] Vazza F, Wittor D, Brunetti G, et al. A&A, 2021, 653: A23 [48] Giacintucci S, Markevitch M, Cassano R, et al. ApJ, 2019, 880: 70 [49] Murgia M, Govoni F, Markevitch M, et al. A&A, 2009, 499: 679 [50] Kale R, Venturi T, Giacintucci S, et al. A&A, 2013, 557: A99 [51] Kale R, Venturi T, Giacintucci S, et al. A&A, 2015, 579: A92 [52] Richard-Laferrière A, Hlavacek-Larrondo J, Nemmen R S, et al. MNRAS, 2020, 499: 2934 [53] Bonafede A, Intema H T, Brüggen M, et al. MNRAS, 2014, 444: L44 [54] Venturi T, Rossetti M, Brunetti G, et al. A&A,

2017, 603: A125 [55] Di Gennaro G, van Weeren R J, Hoeft M, et al. ApJ, 2018, 865: 24 [56] Di Gennaro G, van Weeren R J, Rudnick L, et al. ApJ, 2021, 911: 3 [57] Feretti L, Giovannini G, Govoni F, et al. A&AR, 2012, 20: 54 [58] Duchesne S W, Johnston-Hollitt M, Bartalucci I, et al. PASA, 2021, 38: e005 [59] de Gasperin F, van Weeren R J, Brüggen M, et al. MNRAS, 2014, 444: 3130 [60] Enßlin T A, Biermann P L, Klein U, et al. A&A, 1998, 332: 395 [61] Botteon A, Brunetti G, Ryu D, et al. A&A, 2020, 634: A64 [62] Wittor D, Ettori S, Vazza F, et al. MNRAS, 2021, 506: 396 [63] van Weeren R J, Andrade-Santos F, Dawson W A, et al. Nature Astronomy, 2017, 1: 5 [64] Inchingolo G, Wittor D, Rajpurohit K, et al. MNRAS, 2022, 509: 1160 [65] Zimbardo G, Perri S. Nature Astronomy, 2017, 1: 0163 [66] Zimbardo G, Perri S. MNRAS, 2018, 478: 4922 [67] Zhang C, Churazov E, Forman W R, et al. MNRAS, 2019, 488: 5259 [68] van Weeren R J, Brunetti G, Brüggen M, et al. ApJ, 2016, 818: 204 [69] Cuciti V, de Gasperin F, Brüggen M, et al. Nature, 2022, 609: 911 [70] Li W, Xu H, Ma Z, et al. ApJ, 2019, 879: 104 [71] Nelson D, Springel V, Pillepich A, et al. Computational Astrophysics and Cosmology, 2019, 6: 2 [72] Fujita Y, Takizawa M, Yamazaki R, et al. ApJ, 2015, 815: 116

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.