

The Connection between Radio Halos and Cluster Mergers and the Statistical Properties of the Radio Halo Population

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Abstract. We discuss the statistical properties of the radio halo population in galaxy clusters. Radio bi-modality is observed in galaxy clusters: a fraction of clusters host giant radio halos while a majority of clusters do not show evidence of diffuse cluster-scale radio emission. The radio bi-modality has a correspondence in terms of dynamical state of the hosting clusters showing that merging clusters host radio halos and follow the well-known radio-X-ray correlation, while more relaxed clusters do not host radio halos and populate a region well separated from that correlation. These evidences can be understood in the framework of a scenario where merger-driven turbulence re-accelerate the radio emitting electrons. We discuss the main statistical expectations of this scenario underlining the important role of the upcoming LOFAR surveys to test present models.

Key words. Galaxy: clusters: general—radio continuum: general—X-rays: general—radiation mechanisms: non-thermal.

1. Introduction

Radio and X-ray observations of galaxy clusters prove that thermal and non-thermal components coexist in the intra-cluster medium (ICM). While X-ray observations reveal thermal emission from diffuse hot gas, radio observations of an increasing number of galaxy clusters unveil the presence of ultra-relativistic particles and magnetic fields through the detection of diffuse, giant Mpc-scale synchrotron *radio halos* (RH) and *radio relics* (e.g., Ferrari *et al.* 2008; Cassano 2009). RH are the most spectacular evidence of non-thermal components in the ICM. They are giant radio sources located in the cluster central regions, with spatial extent similar to that of the hot ICM and steep radio spectra, $\alpha > 1.1$ (e.g., Venturi 2011).

There are well-known correlations between the synchrotron monochromatic radio luminosity of RH ($P_{1.4}$) and the host cluster X-ray luminosity (L_X), mass and temperature (e.g., Liang *et al.* 2000; Feretti 2003; Cassano *et al.* 2006; Brunetti *et al.* 2009). The most powerful RH are found in the most X-ray luminous, massive and hot clusters. These correlations suggest a close link between the non-thermal and the thermal/gravitational cluster physics.

Most importantly, RH are presently found only in clusters that show recent/ongoing merging activity. In this regard, Buote (2001) provided the first quantitative comparison of the dynamical states of clusters with RH and the properties of RH. He discovered a correlation between $P_{1.4}$ and the magnitude of the dipole power ratio P_1/P_0 : the more powerful RH are hosted in clusters that experience the largest departures from virialization.

The RH-merger connection and the thermal–non-thermal correlations suggest that the gravitational process of cluster formation may provide energy to generate the non-thermal components in clusters through the acceleration of high-energy particles via shocks and turbulence (e.g., Sarazin 2004; Brunetti 2011).

The origin of RH is still debated. One possibility is that RH are due to synchrotron emission from secondary electrons generated by p–p collisions (e.g., Dennison 1980), in which case clusters must be gamma ray emitters due to the decay of the π^0 produced by the same collisions. However, the non-detections of nearby galaxy clusters at GeV energies by FERMI puts strong constraints to the contribution of secondary electrons to the non-thermal emission (Ackermann *et al.* 2010). Most important, the spectral and morphological properties of a number of well-studied RH appear inconsistent with a pure hadronic origin of the emitting particles (e.g., Brunetti *et al.* 2008, 2009; Donnert *et al.* 2010; Macario *et al.* 2010; Brown & Rudnick 2011).

A second hypothesis is based on turbulent re-acceleration of relativistic particles in connection with cluster-merger events (e.g., Brunetti *et al.* 2001; Petrosian 2001). This model received recently support from the discovery of RH with very steep spectra (e.g., Brunetti *et al.* 2008; Macario *et al.* 2010). Future low-frequency radio telescopes (such as LOFAR and LWA) have the potential to test this scenario and to further explore the connection between RH and the process of cluster formation.

Here we focus on the most recent advances in the study of the statistical properties of RH and their connection with cluster mergers, and discuss the importance of future surveys at low radio frequencies to test present models.

2. The GMRT RH survey

2.1 The radio bi-modality of clusters

An important step forward in our understanding of the statistical properties of RH and of their connection with the process of cluster formation has been recently carried out, thanks to the Giant Metrewave Radio Telescope (GMRT) RH survey (Venturi *et al.* 2007, 2008), a deep observational campaign of a complete sample of X-ray selected galaxy clusters (with X-ray luminosity $\geq 5 \times 10^{44}$ erg/s in the red-shift range 0.2–0.4) is performed at 610 MHz with the GMRT.

These observations allowed for the first time to prove statistically that diffuse cluster-scale radio emission is not ubiquitous in clusters: only 30% of the X-ray luminous ($L_{X[0.1-2.4\text{keV}]} \geq 5 \times 10^{44}$ erg/s) clusters host a RH. Most important, it was possible to separate RH clusters from clusters without RH, showing a bimodal distribution of clusters in the $P_{1.4} - L_X$ diagram (Brunetti *et al.* 2007): RH trace the well-known correlation between $P_{1.4}$ and L_X , while the upper limits to the radio luminosity of clusters without RH lie about one order of magnitude below that correlation (Fig. 1, left panel). Why clusters with the same thermal X-ray luminosity

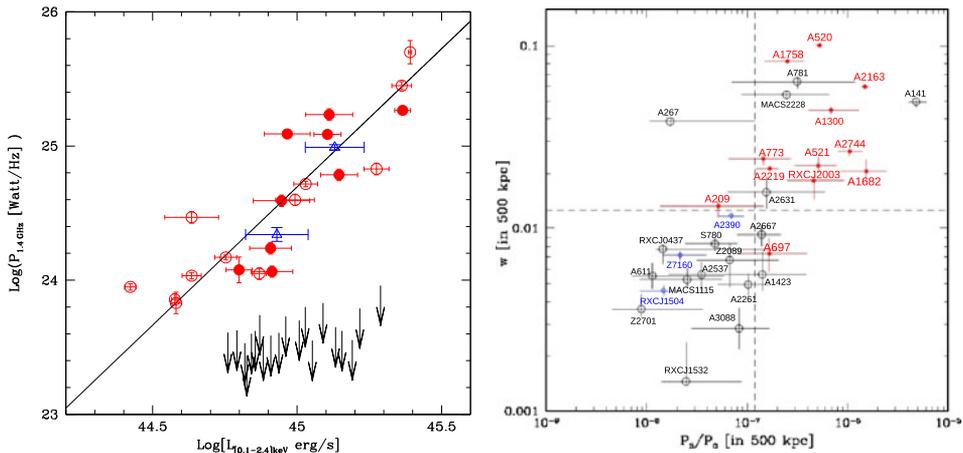


Figure 1. *Left panel:* Distribution of clusters in the plane $P_{1.4} - L_{[0.1-2.4] \text{ keV}}$ for clusters of the GMRT RH survey (RH: red filled dots; non-RH: black arrows; mini-halos: blue symbols) and for RH from the literature (red open dots). *Right panel:* Centroid shift w vs. P_3/P_0 . Symbols are: RH (red filled dots), non-RH (black open dots), mini-halos (blue open dots). Vertical and horizontal dashed lines mark: $w = 0.012$ and $P_3/P_0 = 1.2 \times 10^{-7}$.

(and at the same cosmological epoch) have different non-thermal properties? Based on information from the literature available for a fraction of the clusters of the GMRT RH survey, Venturi *et al.* (2008) suggested that the behavior of clusters in the $P_{1.4} - L_X$ diagram is connected with their dynamical state.

2.2 The dynamical state of GMRT clusters

To test the connection between RH and cluster mergers, Cassano *et al.* (2010a) using *Chandra* archive X-ray data of a sub-sample of GMRT clusters provided a quantitative measure of the degree of the cluster disturbance adopting three different methods: the power ratios (e.g., Buote & Tsai 1995; Jeltema *et al.* 2005), the emission centroid shift (e.g., Mohr *et al.* 1993; Poole *et al.* 2006), and the surface brightness concentration parameter (e.g., Santos *et al.* 2008). A detailed descriptions of these measurements is given in Cassano *et al.* (2010a) and references therein.

They found a clear segregation between clusters with and without RH in terms of their dynamical state: RH are only found in dynamically disturbed clusters (those with high values of P_3/P_0 , $P_3/P_0 \gtrsim 1.2 \times 10^{-7}$ and w , $w \gtrsim 0.012$, and low values of c , $c \lesssim 0.2$), while clusters with no evidence of Mpc-scale synchrotron emission are more relaxed systems. As an example in Fig. 1 (right panel) we report the distribution of clusters in the $(w, P_3/P_0)$ plane. This result was also tested quantitatively by running Monte Carlo simulations (see Cassano *et al.* (2010a) for details) that proved that the observed distribution differs from a random one (i.e., independent of cluster dynamics) at more than 4σ .

We also note also that not all the disturbed systems host RH: specifically, we found 4 ‘radio anomalies’ in Fig. 1 (right panel), Abell 781, MACS 2228, Abell 141 and Abell 2631, i.e., clusters that have the same morphological parameters (P_3/P_0 , w and c) of clusters with RH but that do not host a RH.

3. The evolution of RH in the $P_{1.4} - L_X$ diagram

The radio bi-modality of galaxy clusters and the connection with their dynamical state suggest the following coupled evolution between RH and clusters:

- (a) Galaxy clusters host giant RH for a period of time, in connection with cluster mergers, and populate the $P_{1.4} - L_X$ correlation (Fig. 1, left panel);
- (b) At later times, when clusters become dynamically relaxed, the Mpc-scale synchrotron emission is gradually suppressed and clusters populate the region of the upper-limits.

The 19 clusters of the GMRT sample have $L_X \geq 8.5 \times 10^{44}$ erg/s, in which case the radio power of halos is ~ 1 order of magnitude larger than the level of radio upper limits. Among these 19 clusters: 5 host giant RH, 11 are ‘radio-quiet’ and only one is in the transition region (not reported in Fig. 1, left panel here). This allows to estimate the lifetime of RH, $\tau_{RH} \approx 1$ Gyr, and the time clusters spent in the ‘radio-quiet’ phase, $\tau_{rq} \approx 2-2.5$ Gyr (Brunetti *et al.* 2009). Most important, at these luminosities, the ‘empty’ region between RH and ‘radio quiet’ clusters in the $P_{1.4} - L_X$ diagram constrains the time-scale of the evolution (suppression and amplification) of the synchrotron emission (Brunetti *et al.* 2007, 2009) to be much shorter than both the lifetime of clusters in the sample and the period of time clusters spent in the RH stage. Monte Carlo analysis of the distribution of clusters in Fig. 1 (left panel) shows that the time interval that clusters spent in the ‘empty’ region (thus the corresponding time-scale for amplification and suppression of RH) is $\tau_{evol} \approx 200$ Myr, with the probability that τ_{evol} is as large as 1 Gyr $\leq 1\%$ (Brunetti *et al.* 2009).

The evolution of the radio properties of galaxy clusters in the plane $P_{1.4} - L_X$ is driven by the evolution of the relativistic components (B and particles) in the ICM. The tight constraints on the time-scale of this evolution, $\tau_{evol} \approx 200$ Myr, provides crucial information on the physics of the particle acceleration and magnetic field amplification.

3.1 The role of cluster magnetic field

A possible explanation of the bi-modality is that cluster mergers amplify the magnetic field in the ICM leading to the amplification of the synchrotron emission on Mpc scales. In this case, merging clusters hosting RH should have larger magnetic fields, $\delta B + B$, with excess δB being generated during mergers and then dissipated when clusters become ‘radio quiet’ and dynamically more relaxed (Brunetti *et al.* 2007, 2009; Kushnir *et al.* 2009; Keshet & Loeb 2010).

A magnetic field evolution was postulated to reconcile a secondary origin of RH with the observed bi-modality; these models would indeed predict RH in all clusters, provided the ICM is magnetized at similar (few μG) levels¹.

A suppression of a factor ≥ 10 in terms of synchrotron emission (Fig. 1, left panel) constrains the ratio $\delta B/B$. At $z \approx 0.25$ (typical of GMRT clusters) in the case $\delta B + B \ll B_{\text{cmb}}$ (where $B_{\text{cmb}} = 3.2(1+z)^2 \mu\text{G}$ is the equivalent magnetic field of the CMB) the energy density of the magnetic field in RH clusters should

¹See, however, EnBlin *et al.* (2011) where it is proposed a (ad hoc) super-Alfvénic diffusion of cosmic rays to have radio (and γ -rays) evolution driven by cosmic ray diffusion.

be ≥ 10 times larger than that in ‘radio quiet’ clusters, and even larger ratios must be assumed if $\delta B + B \gg B_{\text{cmb}}$ (Brunetti *et al.* 2009).

This significant difference between the magnetic field strength in RH and ‘radio quiet’ clusters is a prediction of this scenario that, however, is not supported by present observations. Faraday rotation measurements (RM) in galaxy clusters do not show any statistical difference between the energy density of the large scale (10–100 kpc coherent scales) magnetic field in RH clusters and that in ‘radio quiet’ clusters (e.g., Carilli & Taylor 2002). In a recent paper, Govoni *et al.* (2010) studied the $\sigma_{\text{RM}} - S_X$ distribution (σ_{RM} is the σ of the RM and S_X the thermal X-ray cluster brightness, see Govoni *et al.* 2010 for details) of radio sources in a sample of hot galaxy clusters, including both ‘radio-quiet’ and RH clusters. They showed that all clusters follow the same $\sigma_{\text{RM}} - S_X$ trend, and since $\sigma_{\text{RM}} \propto \Lambda_c \int (n_{\text{th}} B_{\parallel})^2 dl$ (Λ_c the field coherent scale) this allow to conclude that, despite the poor statistics, the magnetic field strength in ‘radio-quiet’ and RH clusters is similar (see also Brunetti & Cassano 2010).

More recently, Bonafede *et al.* (2011) analysed the fractional polarization of radio sources in a sample of 39 massive galaxy clusters to investigate the fractional polarization trends in clusters with different non-thermal properties. They found no statistical evidence for a difference in the depolarization trend observed in cluster with and without RH, concluding that there is no evidence for different magnetic fields in these clusters.

All these results suggest that the bi-modality in the $P_{1.4} - L_X$ plane cannot be attributed to the bi-modality in magnetic field properties.

3.2 The role of relativistic particles

Since present data suggest that the magnetic field is not the main field responsible for the evolution of the radio properties of galaxy clusters, relativistic electrons must drive the generation and fading away of RH.

Turbulent acceleration models provide a natural way to explain the observed radio bi-modality of galaxy clusters and the fast evolution of RH. In these models relativistic electrons are re-accelerated *in situ* by turbulence on Mpc-scales during cluster mergers and cool as soon as the clusters become more relaxed due to the dissipation of turbulence. The cooling time of relativistic electrons emitting in the radio band is $\sim 10^8$ yrs (e.g., Sarazin 1999) which is very short and consistent with (smaller than) the evolution timescale of RH constrained by the distribution of galaxy clusters in Fig. 1 (left panel).

This scenario predicts that during a merger as soon as the turbulence reaches small (resonant) scales, particles are accelerated and generate synchrotron emission at GHz frequencies (the clusters move from the region of the upper limits to the $P_{1.4} - L_X$ correlation and should appear dynamically disturbed) within a timescale of few 100 Myrs. The process should persist for a few crossing times of the central cluster Mpc region, that is fairly consistent with the RH lifetime $\tau_{\text{RH}} \sim \text{Gyr}$, this is the period that the clusters would appear on the $P_{1.4} - L_X$ correlation. As soon as the turbulence starts to dissipate (at the end of the merging phase) the synchrotron power is suppressed and the synchrotron emission at higher frequencies will fall below the detection limit of radio observations (the clusters move again in the region of the upper limits and appear more relaxed at X-rays wavelength). A significant

suppression of the synchrotron luminosity occurs in a time-scale of the order of a turbulent-eddy turnover time, $\approx 10^8$ years, consistent with observations.

4. Testing the re-acceleration scenario with low frequency observations

The turbulent re-acceleration scenario explains the connection between RH and cluster mergers, the presently observed radio bi-modality of clusters and the fast evolution of clusters in the $P_{1.4} - L_X$ diagram.

It is important to point out that the peculiarity of this scenario is the fact that turbulent acceleration is a poorly efficient process; this has consequences on model expectations and allow for a prompt test of this scenario with future observations. Electrons indeed can be accelerated only up to energies of $m_e c^2 \gamma_{\max} \leq$ several GeV, entailing a high-frequency cut-off in the synchrotron spectra of RH, which marks the most important and unique expectation of this scenario (see Fig. 2). The presence of this cut-off implies that the observed fraction of clusters with RH depends on the observing frequency. The steepening of the spectrum makes it difficult to detect RH at observing frequencies larger than the frequency ν_s where the steepening becomes severe. The frequency ν_s depends on the acceleration efficiency in the ICM, which in turns depends on the flux of MHD turbulence dissipated in relativistic electrons (e.g., Cassano *et al.* 2006, 2010b). Larger values of ν_s are expected in more massive clusters and in connection with major merger events. As a consequence, according to this model, present radio surveys at \sim GHz frequencies can reveal only those RH generated during the most energetic merger events and characterized by relatively flat spectra ($\alpha \sim 1.1-1.5$) (see Fig. 2). These sources should represent the tip of the iceberg of the whole population of RH, since the bulk of cluster formation in the Universe occurs through less energetic mergers. Low frequency observations with new generation of radio telescopes (LOFAR, LWA) are thus expected to unveil the bulk of RH, including a

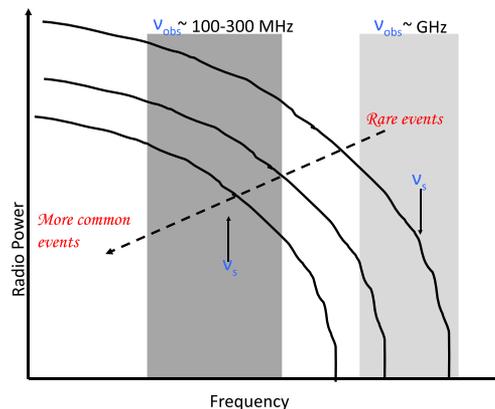


Figure 2. Schematic representation of the synchrotron spectra of RH with different values of ν_s (see text for details). Those with higher values of ν_s are visible up to GHz frequencies, while those with lower values would be observable only at lower frequencies.

population of RH which will be observable preferentially at low radio frequencies ($\nu \leq 200\text{--}300$ MHz). These RH, generated during less energetic but more common merger events, should have extremely steep radio spectra ($\alpha \gtrsim 1.5\text{--}1.9$) when observed at higher frequencies; we defined these sources Ultra Steep Spectrum RH (USSRH). Possible prototypes of these RH are those found in Abell 521 ($\alpha \sim 2$, Brunetti *et al.* 2008) and in Abell 697 ($\alpha \sim 1.7$, Macario *et al.* 2010).

In the framework of the *turbulent re-acceleration* scenario, the existence of merging clusters without Mpc-scale radio emission (Fig. 1, right panel; see also the case of Abell 2146 by Russell *et al.* (2011)), is not surprising for two main reasons. First, the expected lifetime of RH (\sim Gyr) can be smaller than the typical time-scale of a merger, during which the cluster would appear disturbed, implying that not all disturbed systems should host RH (e.g., Brunetti *et al.* 2009).

Second, and most important, a fraction of disturbed systems may host RH with very steep radio spectra (USSRH), difficult to detect even at low frequencies if the observations are not sensitive enough. USSRH are mainly expected in disturbed clusters with masses $M_v \lesssim 10^{15} M_\odot$ (in the local Universe), or in merging (massive) clusters at higher red-shift, $z \gtrsim 0.4\text{--}0.5$ (Cassano *et al.* 2010b). In line with this scenario, 3 out of the 4 outliers in Fig. 1 have X-ray luminosity close to the lower boundary used to select the GMRT sample ($L_X = 5 \times 10^{44}$ erg/sec), and the other is the cluster with the highest red-shift in the GMRT sample ($z \simeq 0.42$). Interestingly, a deep GMRT follow-up at 325 MHz of one of the outliers in Fig. 1, Abell 781, has revealed the presence of a possible USSRH (Venturi *et al.* 2011), which need to be confirmed by future deeper low-frequency observations. The recent case of Abell 2146 may also be in line with these hypothesis: it has a moderate X-ray luminosity ($L_{[0.1\text{--}2.4] \text{ keV}} \sim 6 \times 10^{44}$ erg/s) and it is at $z \sim 0.23$. Only 5 RH are presently known in clusters with the same (or lower) X-ray luminosity but are all at smaller red-shifts, which could suggest that the increase of the inverse Compton losses of relativistic electrons with red-shift ($\propto (1+z)^4$) contribute to disfavour the formation of RH emitting at GHz frequencies in these less massive clusters.

USSRH are expected to be less powerful than RH emitting at GHz frequencies (see Cassano 2010) and thus very sensitive low-frequency observations are necessary to catch them. The ideal instrument to search these RH is LOFAR (LOW Frequency ARray) that is already operating in the commissioning phase (e.g., Röttgering 2010). Monte Carlo procedures, that follow the process of cluster formation, the injection and dissipation of turbulence during cluster-cluster mergers and the ensuing acceleration of relativistic particles in the ICM, allowed to derive quantitatively the statistical properties of RH (e.g., Cassano & Brunetti 2005). The expectations based on these procedures were found consistent with the present observational constraints (e.g., Cassano *et al.* 2008) and were used to derive expectations for the planned LOFAR surveys. Accordingly to these predictions the *Tier 1* ‘Large Area Survey’ at 120 MHz (see Röttgering 2010), with an expected rms sensitivity of 0.1 mJy/beam, should greatly increase the number of known giant RH with the possibility to detect about 350 RH up to red-shift $z \approx 0.6$ in the northern hemisphere ($\delta > 0$ and at high galactic latitude $|b| \geq 20$) with about half of these RH having very steep radio spectra ($\alpha \gtrsim 1.9$, Cassano *et al.* 2010b). This implies that future LOFAR surveys will allow a powerful test of the merger-driven turbulence re-acceleration scenario for the origin of RH.

5. Conclusions

We discussed the most recent statistical evidences demonstrating the connection between giant RH and cluster mergers and the ‘transient’ nature of the RH phenomenon.

A step forward in this direction comes from the discovery that the radio bimodality of clusters has a correspondence in terms of dynamical state of the clusters: clusters with RH are found to be dynamically disturbed, while clusters without RH are more dynamically relaxed. These observational evidences suggest that RH form in galaxy clusters and live for a period of time during mergers, when the clusters appear dynamically disturbed, while at later times, when the clusters become dynamically relaxed, the synchrotron emission fades away. Two main ingredients may drive the evolution of the cluster synchrotron emission: the magnetic field and the relativistic electrons. Faraday rotation measurements and observations of depolarization of cluster galaxies suggest that the magnetic field has a marginal role, and favour a scenario where the generation of RH is connected with the acceleration of relativistic particles.

These facts are naturally understood in the framework of one of the proposed pictures put forward to explain the origin of giant RH, the merger-induced turbulence re-acceleration scenario (Brunetti *et al.* 2001; Petrosian 2001). The main expectation of this scenario, which is related to the poorly efficient nature of the turbulent acceleration mechanism in the ICM, is the existence of a population of clusters hosting RH with very steep radio spectra, USSRH. These RH, that should glow up preferentially at low radio frequency, are hidden in massive clusters undergoing minor merging and/or less massive clusters interested by major merger events.

LOFAR is an ideal instrument to test these expectations, and it is expected to discover ~ 350 RH in the *Tier 1* ‘Large Area Survey’ at 120 MHz, half of which should be USSRH.

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