Mem. S.A.It. Vol. 82, 531

Memorie della

Radio halos, cluster mergers and the role of future LOFAR observations

R. Cassano[1,2]

[1] INAF, Istituto di Radioastronomia, via P. Gobetti 101, 4014, Bologna (Italy)
e-mail: rcassano@ira.inaf.it
[2] Dipartimento di Astronomia,Università di Bologna, via Ranzani 1, I-40127 Bologna, Italy

Abstract. A radio bimodality is observed in galaxy clusters: a fraction of clusters host giant radio halos while the majority of clusters do not show evidence of diffuse cluster-scale radio emission. Present data clearly suggest that the radio bimodality has a correspondence in terms of dynamical state of the hosting clusters. I will report on these evidences in some details and discuss the role of cluster mergers in the generation of giant radio halos and their evolution. Finally I will report on expectations on the statistical properties of radio halos assuming that the emitting electrons are re-accelerated by merger-turbulence, and discuss the role of incoming LOFAR surveys.

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 massive 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). RHs 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, $\alpha \simeq 1.2 - 1.5$ (*e.g.,* Venturi 2011, this conference).

There are well known correlations between the synchrotron monochromatic radio luminosity of RH ($P_{1.4\,\mathrm{GHz}}$) 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.

Another important fact is that RHs are found in clusters that show recent/ongoing merging activity: significant substructure and distortion in the X-ray images (*e.g.,* Schuecker et al. 2001), complex gas temperature distributions (*e.g.,* Govoni et al. 2004; Bourdin et al. 2011), shocks and cold fronts (*e.g.,* Markevitch & Vikhlinin 2001; Markevitch 2010), absence of strong cooling-flow (*e.g.,* Feretti 2003; Rossetti et al.

Send offprint requests to: R. Cassano

2011, this conference), and optical substructures (*e.g.,* Boschin et al. 2006).

In a seminal paper Buote (2001) provided the first quantitative comparison of the dynamical states of clusters with RH and the properties of RHs and discovered a correlation between the RH luminosity at 1.4 GHz and the magnitude of the dipole power ratio P_1/P_0. This implies that the more powerful RHs 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 the 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, this conference). Cluster-cluster mergers are among the most energetic events in the present Universe: two clusters with total masses M_1 and M_2 dissipate a gravitational energy (in erg) :

$$E_{\rm g} \approx 10^{64}\left(\frac{M_1}{10^{15}\,{\rm M}_\odot}\right)\left(\frac{M_2}{10^{15}\,{\rm M}_\odot}\right)\left(\frac{d_o}{6{\rm Mpc}}\right)^{-1} \quad (1)$$

d_o is the turnaround distance. The theoretical goal is to understand how a fraction of this large energy budget is channeled into the acceleration of high energy particles and amplification of cluster magnetic field (*e.g.,* Brunetti 2011, this conference).

The recent discovery of RHs with very steep spectrum provides additional support to the scenario where RHs are generated due to re-acceleration of relativistic particles by merger-driven turbulence (*e.g.,* Brunetti et al 2008, Brunetti 2011 this conference). 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 I will discuss the most recent evidences in favor of the connection between RHs and clusters mergers and the expectations of the turbulent re-acceleration scenario to test trough future low frequency observations.

2. The GMRT RH Survey and the radio bi-modality of clusters

Recently, deep radio observations of a complete sample of galaxy clusters have been carried out as part of the Giant Metrewave Radio Telescope (*GMRT*) RH Survey (Venturi et al. 2007, 2008). These observations confirmed that diffuse cluster-scale radio emission is not ubiquitous in clusters: only 30% of the X-ray luminous ($L_X(0.1-2.4\,{\rm keV}) \geq 5\times10^{44}$ erg/s) clusters host a RH. Most importantly, these observations allow to separate RH clusters from clusters without RH, showing a bimodal distribution of clusters in the $P_{1.4\,{\rm G}Hz} - L_X$ diagram (Brunetti et al. 2007): RHs trace the well known correlation between $P_{1.4\,{\rm G}Hz}$ and L_X, while the upper limits to the radio luminosity of clusters with no-RH lie about one order of magnitude below that correlation (Fig. 1). Why clusters with the same thermal properties (and at the same cosmological epoch) have different non-thermal properties ? One possibility, which was first suggested by Venturi et al. (2008) based on information from the literature available for a fraction of the clusters of the GMRT RH Survey, is that the behavior of clusters in the $P_{1.4\,{\rm G}Hz} - L_X$ diagram is connected with their dynamical state; this is supported also by a simple visual inspection of the X-ray images of those clusters (Fig. 1).

3. Dynamical state of GMRT clusters

In a more recent work Cassano et al. (2010a) using *Chandra* archive X-ray data of a subsample of clusters belonging to the GMRT RH Survey[1] provided a more quantitative measure of the degree of the cluster disturbance using three different methods: 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). The power ratio method is a multipole decomposition of the

[1] Those with archival data with at least 2000 ACIS-S or ACIS-I counts in the 0.5-2 keV band inside an aperture of 500 kpc (see Cassano et al. 2010a).

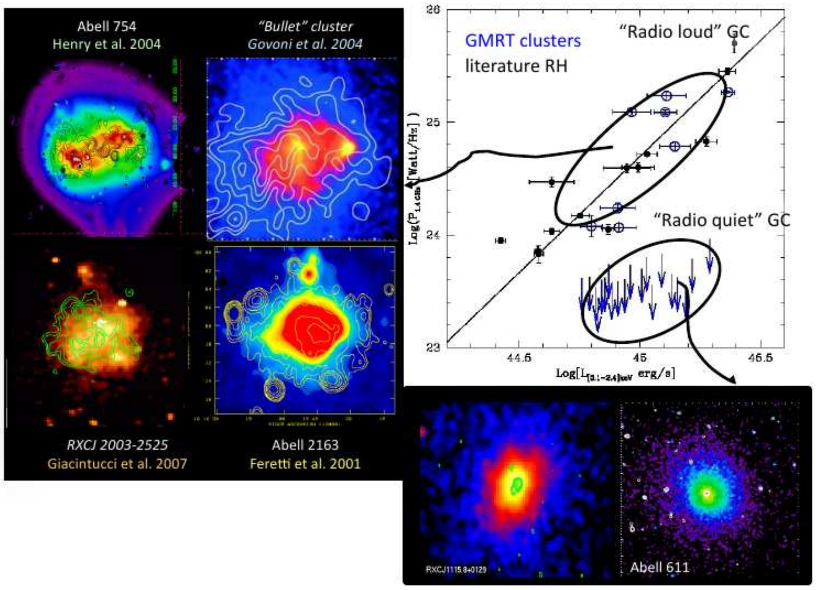

Fig. 1. Distribution of clusters in the plane radio ($P_{1.4}$) – X-ray luminosity ($L_{[0.1-2.4]keV}$) for clusters of the GMRT RH Survey (blue symbols) and for RH from the literature (black dots); adapted from Brunetti et al.(2009).

gravitational potential of the two-dimensional projected mass distribution inside a given aperture R_{ap}. Following Buote & Tsai (1995) they are usually defined as P_m/P_0, where P_m represents the square of the mth multipole of the two-dimensional potential (see eqs. 1-4 in Cassano et al. 2010a). Large departures from a virialized state are then indicated by large power ratios.

The centroid shift, w, is defined as the standard deviation of the projected separation between the peak of the X-ray emission and the centroid, derived in increasing circular apertures and expressed in units of $R_{ap} = 500$ kpc. The centroid shift, w, is a measure of the skewness of the photon distribution of a cluster, thus larger values of w indicate clusters with a more asymmetric/irregular distribution of the X-ray emission.

The concentration parameter, c, defined as the ratio of the peak over the ambient surface brightness, S, $c = \frac{S(r<100\,\mathrm{kpc})}{S(<500\,\mathrm{kpc})}$, has been used in literature for identification of cool core clusters (Santos et al. 2008). We used c to separate galaxy clusters with a compact core (higher values of c, core not disrupted from recent merger events) from clusters with a broad distribution of the gas in the core (lower values of c, core disturbed from a recent merger episode).

3.1. Results

In Fig.2 we report the distribution of the 32 clusters in the $(c, P_3/P_0)$ plane (upper panel) and in the $(w, P_3/P_0)$ plane (lower panel). We found that RH clusters (red filled dots) can be well separated from clusters without RH (black open dots) and clusters with mini-halos[2] (blue open dots). Clusters with RHs are found only in the region of low values of c ($c \lesssim 0.2$), and high values of P_3/P_0 ($P_3/P_0 \gtrsim 1.2 \times 10^{-7}$) and w ($w \gtrsim 0.012$).

[2] Radio mini-halos are diffuse synchrotron emission on smaller scales (*e.g.,* 200-500 kpc) extending around powerful radio galaxies at the center of some cool core clusters (*e.g.,* Venturi 2011, this conference).

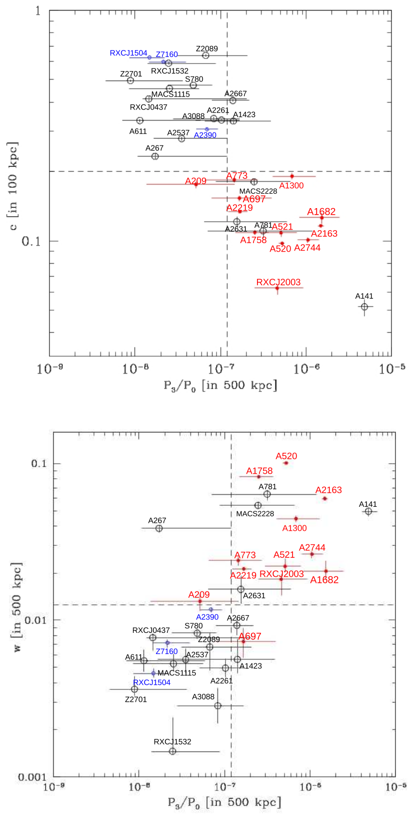

Fig. 2. Upper Panel: concentration parameter c vs. power ratio P3/P0; **Lower Panel**: centroid shift w vs. P3/P0. Symbols are: RH (red filled dots), non-RH (black open dots), mini-halos (blue open dots). Vertical and horizontal dashed lines mark : $c = 0.2$, $w = 0.012$ and $P_3/P_0 = 1.2 \times 10^{-7}$.

Both diagrams provide strong evidence that RHs form in dynamical disturbed clusters, while clusters with no evidence of Mpc-scale synchrotron emission are more relaxed systems. We also tested quantitatively this result by running Monte Carlo simulations (see Cassano et al. 2010a for details) and proved that the observed distribution differs from a random one (*i.e.,* independent of cluster dynamics) at more than 4σ. This proves that our result is statistically significant and shows, for the first time, that the separation between RHs and non-RH clusters (the observed radio bimodality of clusters) has a corresponding separation in terms of dynamical properties of the host clusters. We note that there are 4 outliers in Fig.2: Abell 781, MACS 2228, Abell 141 and Abell 2631, *i.e.,* clusters that are dynamically disturbed but that do not host a RH. [3] These clusters deserve further investigation (see also next Sect.).

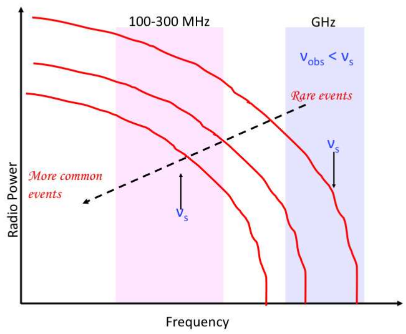

Fig. 3. Schematic representation of the synchrotron spectra of RHs with different values of ν_s (see text for details). Those with higher values of ν_s are visible up to GHz frequencies, while those with lower values would be observable only at lower frequencies.

4. Turbulent re-acceleration scenario and low frequency observations

A promising scenario proposed to explain the origin of the synchrotron emitting electrons in RHs assumes that electrons are re-accelerated due to the interaction with MHD turbulence injected in the ICM during cluster mergers (*turbulent re-acceleration* model, (*e.g.,* Brunetti et al. 2001; Petrosian 2001).

[3] For one of them, Abell 781, more recently we verified that its 0.2-2.4 keV luminosity, $L_X \sim 4-5\times 10^{44}$ erg/s, (*e.g.,* Böhringer et al. 2000; Maughan et al. 2008, S. Ettori, private communication, based on a shallow ROSAT HRI exposure) is substantially smaller than that used in the GMRT sample (taken from the Ebeling et al. (1998) catalogue, $L_X \simeq 1.13 \times 10^{45}$ erg/s) and is smaller than the threshold value ($L_X \gtrsim 5 \times 10^{44}$ erg/s) used to select clusters for the GMRT RH Survey.

This scenario naturally explain the observed bi-modality of clusters (*e.g.,* Brunetti et al 2009) and the observed connection between RHs and cluster mergers.

Stochastic particle acceleration by MHD turbulence is rather inefficient in the ICM, consequently electrons can be accelerated only up to energies of $m_e c^2 \gamma_{max} \leq$ several GeV. This entails a high-frequency cut-off in the synchrotron spectra of RHs, which marks the most important expectation of this scenario. The presence of this cut-off implies that the observed fraction of clusters with RHs depends on the observing frequency, this can be immediately understood from Fig. 3. The steepening of the spectrum makes it difficult to detect RHs 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; Cassano et al. 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 RHs generated during the most energetic merger events and characterized by relatively flat spectra ($\alpha \sim 1.1 - 1.5$) (see Fig.3). These sources should represent the tip of the iceberg of the whole population of RHs, since the bulk of cluster formation in the Universe occurs trough less energetic mergers. Low frequency observations with next generation of radio telescopes (LOFAR, LWA) are thus expected to unveil the bulk of RHs, including a population of RH which will be observable preferentially at low radio frequencies ($\nu \leq 200 - 300$ MHz). These RHs, generated during less energetic but more common merger events, should have extremely steep radio spectra ($\alpha \gtrsim 1.5 - 1.9$) when observed at higher frequencies; we defined these sources Ultra Steep Spectrum RH (USSRH). Possible prototypes of these RHs 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 with no Mpc-scale radio emission (*e.g.,* in Fig. 2) is not surprising for two main reasons. First, the expected lifetime of RHs ($\sim$ Gyr) can be smaller than the typical time-scale of a merger, during which the cluster would appear disturbed, readily implying that not all disturbed systems should host RHs (*e.g.,* Brunetti et al 2009).

Second, and most important, a fraction of clusters should host USSRH that are difficult to detect trough observations at high frequencies. 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 redshift, $z \gtrsim 0.4 - 0.5$ (Cassano et al. 2010b). In line with this scenario, 3 out of the 4 outliers 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 redshift in the GMRT sample ($z \simeq 0.42$). Interestingly, a deep GMRT follow-up at 325 MHz of one of the outliers in Fig. 2, Abell 781, has revealed the presence of a possible USSRH (Giacintucci 2011, this conference; Venturi et al. 2011, submitted), which need to be confirmed by future deeper low-frequency observations.

USSRH are expected to be less powerful than RHs with flatter spectra (see Cassano 2010) and thus very sensitive low-frequency observations are necessary to catch them. The ideal instrument to search these RHs is LOFAR (LOw Frequency ARray) that is already operating in commissioning phase (*e.g.,* Röttgering 2010). To derive quantitatively the statistical properties of RHs, we used Monte Carlo procedures (*e.g.,* Cassano & Brunetti 2005) 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. The expectations based on these procedures were found consistent with present observational constraints (*e.g.,* Cassano et al. 2008). Thus using the same procedures we derived expectations for the planned LOFAR surveys. The *Tier 1* "Large Area Survey" at 120 MHz (see Röttgering 2010) is expected to greatly increase the number of known giant RHs with the possibility to detect about 350 RHs up to redshift $z \approx 0.8$ with about half of these RHs having very steep radio spectra ($\alpha \gtrsim 1.9$, Cassano et al. 2010b). Consequently future LOFAR surveys will allow a powerful test of the merger-driven turbulence re-acceleration scenario for the origin of RHs.

5. Conclusions

We discussed the most recent evidences that demonstrate a connection between the generation of Mpc-scale radio emission in clusters, in the form of giant RHs, and the merging activity in clusters.

A step forward in this direction comes from the discovery that the radio bi-modality of clusters has a correspondence in terms of dynamical state of the clusters : clusters with RHs are found to be dynamically disturbed, while clusters without RHs are dynamically relaxed. This has been proved by applying three different methods to characterize cluster substructures to the X-ray Chandra images of GMRT clusters (Cassano et al. 2010a).

The correlation between the synchrotron radio luminosity of RHs and the cluster X-ray luminosity (mass and temperature) combined with the connection between RHs and cluster mergers suggest that there are at least two main ingredients in the generation of RHs : the cluster dynamical status and cluster mass. These observational facts are naturally understood in the framework of one of the proposed pictures put forward to explain the origin of giant RHs, the merger-induced turbulence re-acceleration scenario (Brunetti et al. 2001; Petrosian 2001). This scenario has unique expectations for the statistical properties of RHs that could be tested by future radio surveys at low frequencies.

In particular, the shape of the spectrum of RHs is connected with the energy dissipated during cluster mergers and thus ultimately with the mass of the hosting clusters and with the mass ratio (impact parameter etc) of merger events. A large fraction of RHs, those associated with less massive merging systems and those at higher redshift, should have ultra-steep spectra and glow up preferentially in deep surveys at low radio frequencies (Cassano et al. 2010b). LOFAR is thus expected to perform a powerful test of this scenario.

Acknowledgements. This work is partially supported by INAF under grants PRIN-INAF2008 and PRIN-INAF2009 and by ASI-INAF under grant I/088/06/0. I acknowledge my main collaborators S. Ettori, G. Brunetti, S. Giacintucci, T. Venturi, M. Brüggen and H. Röttgering.

References

Böhringer, H., et al. 2000, ApJS, 129, 435
Boschin, W., et al., 2006, A&A, 449, 461
Bourdin, H. et al. , 2011, A&A, 527, 21
Brunetti, G., et al., 2001, MNRAS, 320, 365
Brunetti, G., et al., 2007, ApJ, 670, L5
Brunetti, G., et al., 2008, Nat, 455, 944
Brunetti, G., et al., 2009, A&A, 507, 661
Buote D.A, 2001, ApJ 553, 15
Buote, D. A., & Tsai, J. C. 1995, ApJ, 452, 522
Cassano, R., 2009, ASPC, 407, 223
Cassano, R., 2010, A&A, 517, 10
Cassano, R., & Brunetti, G. 2005, MNRAS, 357, 1313
Cassano, R., et al. 2006, MNRAS, 369, 1577
Cassano, R., et al., 2008, A&A, 480, 687
Cassano, R., et al., 2010a, ApJL, 721, L82
Cassano, R., et al., 2010b, A&A, 509, 68
Ebeling, H., et al., 1998, MNRAS, 301, 881
Feretti, L. 2003, ASPC, 301, 143
Ferrari, C., et al., 2008, SSRv, 134, 93
Giacintucci, S., 2011, arXiv:1102.1901
Govoni F., et al. 2004, ApJ, 605, 695
Jeltema, T. E., et al., 2005, ApJ 624, 606
Liang H., et al., 2000, ApJ 544, 686
Macario, G., et al., 2010, A&A, 517, A43
Markevitch, M., 2010, arXiv:1010.3660
Markevitch, M., & Vikhlinin, A. 2001, ApJ, 563, 95
Maughan, B. J., et al., 2008, ApJS 174, 117
Mohr, J.J., et al., 1993, ApJ 413, 492
Poole, G.B., et al., 2006, MNRAS 373, 88
Petrosian V., 2001, ApJ 557, 560
Rossetti, M., et al. 2011, arXiv:1101.4183
Rottgering, H. J. A. 2010, ISKAF2010 Science Meeting, http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=112, p.50
Santos, J.S., et al. 2008, A&A, 483, 35
Sarazin, C. L. 2004, JKAS, 37, 433
Schuecker P., et al. 2001, A&A 378, 408
Venturi, T., et al., 2007, A&A, 463, 937
Venturi, T., et al., 2008, A&A, 484, 327
Venturi T. 2011, arXiv:1102.1572