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Memorie della

Observational properties of diffuse radio sources in galaxy clusters

Current knowledge and open questions

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Abstract. Diffuse radio sources in galaxy clusters, i.e. radio halos and relics, are unique signposts of cluster assembly in the Universe. It is nowadays fairly well established that massive cluster mergers are the key ingredient to account for the origin of halos and relics: they induce shocks and turbulence in the cluster volume, whose energy is able to (re)–accelerate relativistic electrons in the intracluster medium. The increasing number of halos and relics found, coupled with the high quality information available in the X–ray band for a large number of clusters, now allow to derive significant statistical correlations between the radio and X–ray properties of the diffuse sources and the hosting clusters. Galaxy clusters may be *radio–loud* or *radio–quiet* with respect to the presence of radio halos. Moreover, radio halos and relics are present only in unrelaxed clusters. A large distribution exists for the spectral index of the synchrotron spectrum of radio halos, and sources with α up to ~ 2 ($S \propto \nu^{-\alpha}$) have been recently found. A number of observational issues, however, remain open. Well defined radio spectra, from approximately hundred MHz to GHz frequencies and good spectral imaging are available only for few halos and relics. It is presently unclear if there are basic differences between clusters with ultra steep spectrum radio halos and those hosting "classical" ones, and it is unknown if less energetic mergers result in an observational signature in the radio band. With the forthcoming advent of LOFAR and of the SKA Pathfinders, we will soon be able to observe galaxy clusters with a major improvement in the radio sensitivity and frequency coverage, and we expect to be able to soon address some of these pressing questions.

Key words. Radiation mechanism: non-thermal – Galaxies: clusters: general – Cosmology: observations

1. Introduction

Radio observations are a unique tool to study the formation and evolution of galaxy clusters and their constituents. The presence of diffuse Mpc scale radio emission in a number of galaxy clusters, i.e. *radio halos* and *relics*, reveals the presence of relativistic particles and magnetic fields extending throughout the cluster volume, while the bent radio emission associated with cluster galaxies is the signature of the galaxy motion within the clusters and

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on large scale bulk motion of the intracluster medium (ICM).

It is nowadays becoming clear that halos and relics are closely connected to the cluster formation history, therefore our understanding of their origin and evolution is not only relevant in itself, but it is crucial for our global understanding of the mechanisms at play during the processes of cluster assembly in the Universe.

In the following I will provide an overview of our current observational knowledge of the radio emission from galaxy clusters, with particular emphasis on radio halos and relics. I will also underline some of the current urgent open questions, which are expected to receive an answer once the next generation radio interferometers are fully operational.

Throughout the paper I will assume $S\propto \nu^{-\alpha}$ and a ΛCDM cosmology, with H_o=70 km $s^{-1}Mpc^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$.

2. Radio emission from galaxy clusters

2.1. Radio galaxies

The most beautiful examples of radio emission from individual cluster members are the double–lobed FR I (Fanaroff & Riley 1974) radio galaxies, whose jets and lobes usually extend well beyond the optical light. Their morphology is often misaligned: jets and lobes are bent in U or C shape (narrow–angle and wide–angle tail radio galaxies respectively), possibly by the combination of galaxy motion within the cluster and local flows in the ICM due to cluster mergers (Bliton et al. 1998; Burns 1998; Feretti & Venturi 2002). A beautiful example is reported in Fig. 1, which shows a number of distorted radio galaxies in A 754. Studies of cluster radio galaxies are relevant not only to derive information on the cluster dynamics and properties of the ICM, but also for the study of the cluster magnetic field, by means of Faraday rotation and depolarization (see Murgia, present volume; Bonafede et al. 2010; Govoni et al. 2010; Vacca et al. 2010).

The radio emission from the central dominant cluster galaxy plays a special role. In some cases the location of the radio emission from the lobes shows a correlation with the presence of X–ray features (e.g., A 262, Clarke et al. 2009; NGC 5813, Randall et al. 2011; HCG 62 and other systems, Giacintucci et al. 2011a), which is suggestive of feedback between the central radio emission and the ICM (McNamara & Nulsen 2007).

2.2. Mini–halos

In very few relaxed clusters, the central radio AGN is surrounded by diffuse emission in the form of a halo, with steep spectral index ($\alpha > 1$), and linear extent of the order of few hundreds of kpc. A typical mini–halo is reported in Fig. 2. Only 9 mini–halos are known to date (Giacintucci et al. 2011b, and references therein), and their origin is an issue, since the diffusion time of the relativistic electrons is shorter than the travel time necessary to cover the whole extent of these sources. Cold fronts in the ICM have been observed in some clusters hosting a mini–halo, suggesting that gas sloshing may be responsible for the origin of the cold fronts and may provide the turbulence needed to re–accelerate seed electrons, most likely coming from the radio activity of the central AGN, to form a mini–halo (Mazzotta & Giacintucci 2008; ZuHone et al., present volume). It has been found that radio mini–halos and giant radio halos (see Sect. 2.3 and 3) share the same correlation between the radio power and X–ray luminosity, but the two classes of sources are clearly separated in the radio power–radio size diagram, indicating that the emissivity of radio mini–halos is larger than that of giant radio halos (Cassano et al. 2008a; Murgia et al. 2009).

2.3. Halos and relics

Diffuse radio emission, whose overall size may reach and exceed the Mpc size, is observed in a number (∼ 40) of galaxy clusters. Such emission comes into two main flavors. *Radio halos*, located at the center of galaxy clusters, exhibit a fairly regular morphology, in good spatial coincidence with the distribution of the

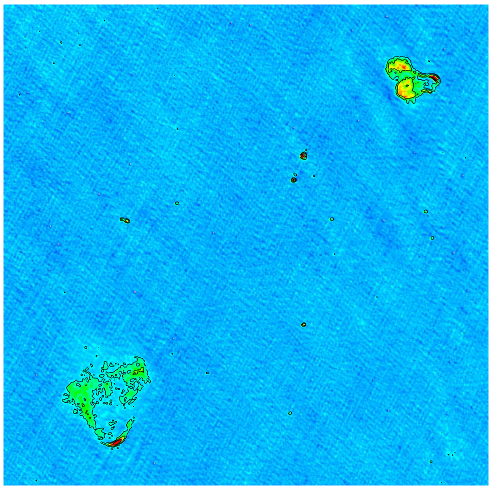

Fig. 1. *W*ide–angle tail and narrow–angle tail radio galaxies in A 754. The observations were carried out with the GMRT at 610 MHz. The resolution of the image is 5.3″ × 4.9″ and the 1σ noise level is 0.1 mJy/b. Contours are ±0.5,2,8 mJy/b.

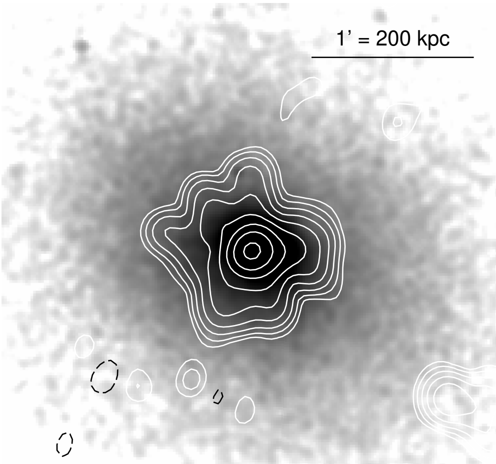

Fig. 2. *G*MRT 325 MHz contours of the mini–halo in RXCJ 1504.1–0248 overlaid on the *Chandra* X–ray emission. The resolution of the radio image is 11.3″ × 10.4″; contours start at ±0.3 mJy/b (3σ) and are spaced by a factor of two. See Giacintucci et al. 2011b.

hot X–ray emitting gas, and their radio emission is unpolarized (albeit a couple of noticeable exceptions, see Pizzo, present volume); *radio relics* may have a variety of morphologies (elongated and arc–shaped are the most common), are located at the cluster periphery and show high fractional polarization. Their monochromatic radio power at 1.4 GHz is in the range $P_{1.4\ GHz} \sim 10^{23} - 10^{25}$ W Hz^{-1}. Both types of sources have no obvious optical counterpart, suggesting that the radio emission is connected with the ICM, and implying the existence of relativistic leptons with energy of few GeV (Lorentz factor $\gamma \sim 10^4$) and μG magnetic field mixed with the hot (T~5–10 KeV) ICM (see Ferrari et al. 2008 and Cassano 2009 for recent reviews).

From a theoretical point of view, halos and relics have always been a challenge for our understanding of their origin, due to their *large extent* and *rarity*. The diffusion time of relativistic electrons to spread over the Mpc scale size exceeds their radiation lifetime by roughly two orders of magnitude (10^{10} years to be compared to $\sim 10^8$ years respectively), requiring some form of re–acceleration (e.g. Jaffe 1977). In the past few years observational evidence has accumulated in favor of the idea that the main source of electron re–acceleration in galaxy clusters comes from the injection of shocks and turbulence induced by massive cluster mergers (e.g. Brunetti et al. 2001; Brunetti & Lazarian 2007; Vazza et al. 2009).

RXCJ 2003.5–2323 (z=0.317), reported in Fig. 3, is one of the many examples of giant radio halos. It is one of the most powerful and among the most distant found so far. Its size is ~ 1.4 Mpc, and does not change in the frequency range 235 MHz – 1.4 GHz. The brightness distribution is patchy at all wavelengths, but this is not always the case. In a number of radio halos the surface brightness peaks in the central cluster region (in coincidence with the X–ray peak) and smoothly decreases at the edges.

The very low surface radio brightness of halos and relics, combined with their steep radio synchrotron spectra (average values reported for α are in the range 1.2–1.4, see Sect. 4 below) make their detection difficult. At present, about 25 radio halos have been imaged at high sensitivity (e.g. Clarke & Ensslin 2005; Brunetti et al. 2008; Bonafede et al.

2009a; Giacintucci et al. 2009; Venturi et al. 2003, 2007, 2008; Giovannini et al. 2009, and references therein), and about 25 relics are known to date (e.g. van Weeren et al. 2009a, and references therein). A number of clusters host both a radio halo and a relic (i.e. Coma, Kim et al. 1989; Brown & Rudnick 2011; A 521, Brunetti et al. 2008; A 1300, Venturi et al. 2009 and Giacintucci et al., present volume; A 2255, Pizzo et al. 2008; A 2256, Clarke & Ensslin 2005; A 2744, Orrù et al. 2007 and references therein, Giacintucci et al., present volume). A few clusters with a double relic have been recently found (i.e. A 1240 and A 2345, Bonafede et al. 2009b; A 548b, Feretti et al. 2006; CIZA J 2242.8+5301, van Weeren et al. 2010 and van Weeren et al., present volume; ZwCl 2341.1+0000, van Weeren et al. 2009b). A unique case is the cluster RXCJ 1314.4–2515, which hosts two relics and one radio halo (Venturi et al. 2007).

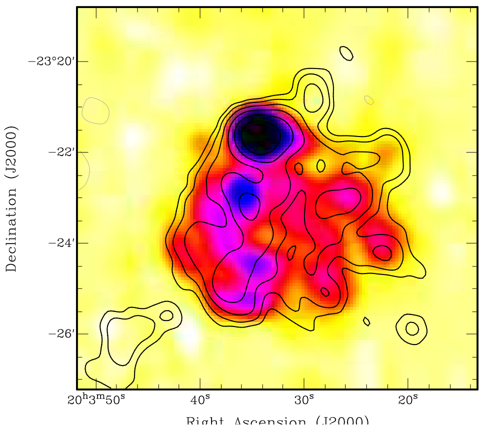

Fig. 3. *R*adio halo in RXCJ 2003.5–2323: VLA 1.4 GHz emission (grey scale) with 240 MHz GMRT contours overplotted. The restoring beam is 35″ × 35″ in both images. The first contour at 240 MHz is ± 1 mJy/b (2.5σ) and contours are spaced by a factor of 2. The distance of the cluster is z=0.317, and 1″=4.62kpc.

This long list of references clearly shows that this field is very hot, and that high sensitivity radio imaging is being collected at high rate. The amount of high quality information currently available both in the radio and in the X–ray band now allows an accurate comparison between the observations and the current models proposed for the origin of halos and relics. In the next Sections I will report on some of the recent most outstanding observational achievements in this field. The papers by Brunetti and Cassano, in this volume, will focus respectively on the theoretical and statistical side of the origin and evolution of radio halos.

3. Radio halo–cluster merger connection and cluster bimodality

The first hints of a connection between the thermal (X–ray emission from the ICM) and non–thermal (radio halos) properties of galaxy clusters date back about a decade ago, when it was found that statistical correlations exist between global cluster properties (such as temperature, mass and X–ray luminosity) and the radio power of halos. In particular, more X–ray luminous (and hence more massive) clusters host more powerful radio halos (e.g., Giovannini et al. 1999; Liang et al. 2000; Cassano et al. 2006). Govoni et al. (2004) first found a positive correlation between the local radio brightness and the X–ray flux density; Buote (2001) first provided a quantitative evaluation of the dynamical disturbance of galaxy clusters with diffuse radio emission.

The literature information was recently combined with the outcome of the 610 MHz GMRT Radio Halo Survey (Venturi et al. 2007, 2008), to constrain the statistical properties of clusters hosting radio halos in the redshift interval z=0–0.4 on much more solid grounds. It was found that the fraction of clusters hosting a radio halo increases with increasing X–ray luminosity, and hence cluster mass, at a $\sim 4\sigma$ significance level (Cassano et al. 2008b). In order to fully exploit the observational information of the GMRT survey, upper limits to the radio power of a radio halo were estimated for those clusters without detection, and such values were reported on the same $\log L_X$–$\log P_{1.4\,\mathrm{GHz}}$ correlation for radio halos (Brunetti et al. 2007).

Remarkably, the non–detections are not the result of limited sensitivity, and the clusters in the sample show a clear bimodal behavior: galaxy clusters either host a radio halo, whose radio power correlates with the cluster X–ray luminosity, or have upper limits, which populate the bottom–right part of the $\log L_X$–$\log P_{1.4\ \mathrm{GHz}}$ diagram and are placed 1.5–2 orders of magnitude below the correlation. This result supports a "transient" nature of radio halos and is in agreement with the expectation of the re–acceleration model (Brunetti et al. 2007, 2009).

Once accurately scrutinized, clusters with and without halo show clear differences in terms of X–ray properties. Using the literature information on the cluster dynamical status, Venturi et al. (2008) showed that all radio halos and relics in the GMRT cluster sample are located in clusters with some sign of disturbance. Conversely, looking at the results from the point of view of the cluster dynamical status, it is noticeable that none of the relaxed clusters hosts halos or relics, while unrelaxed clusters may or may not host a diffuse source. More recently, Cassano et al. (2010a) cross–checked the presence of a radio halo (and lack thereof) for a subsample of the GMRT radio halo cluster sample with the cluster dynamical status, derived by means of three different quantitative estimators on the basis of high quality X–ray *Chandra* imaging. The results clearly show that the cluster radio bimodality has a correspondence in terms of cluster dynamics: radio halos are found in dynamically disturbed systems, while "radio quiet" clusters are more relaxed. Their study includes also a few mini–halo clusters (see Sect. 2.2), which are confirmed to be found in relaxed systems, as already known for the historical mini–halos, such as Perseus (A 426) and A 2052 (Fabian et al. 2006 and Blanton et al. 2001 respectively).

4. Spectra of radio halos

Spectra of radio halos contain important information related to their origin. Imaging of the spectral index distribution provides information on the energy spectrum of the radiating electrons and on the magnetic field distribution. However, only for a handful of halos such observational information is available, mainly due to the decreasing sensitivity of low frequency imaging. A patchy distribution seems to be a common feature, as is observed in for instance in A 2744 (Orrù et al. 2007) and in A 3562 (Giacintucci et al. 2005). In other cases, such as Coma (Giovannini et al. 1993), a steepening is observed at increasing distance from the cluster center.

The accurate measurement of the integrated spectra of radio halos is a difficult task. Radio halos usually embed a number of individual sources, whose flux density needs to be carefully subtracted from the total diffuse emission, and this requires high quality imaging over a range of resolutions. Moreover, diffuse cluster sources are best imaged at low frequency, and high quality imaging at frequencies below 1.4 GHz has become available only very recently. For this reason, a spectrum with at least three datapoints spread over ~ 1 order of magnitude is available only for few objects . Beyond the well–known case of Coma–C (Thierbach et al. 2003), good spectra spectra are available for A 2256 (Brentjens 2008), RXCJ 2003.5-2323 (Giacintucci et al. 2009), A 521 (Brunetti et al. 2008; Dallacasa et al. 2009), A 697 (Macario et al. 2010), A 3562 (Venturi et al. 2003).

It is now becoming clear that there is not a "typical spectrum" for radio halos and that there is a considerable spread in the spectral index values. Moreover, while spectra based on few measurements tend to introduce a bias towards a single power–law shape, those cases with better frequency sampling show a high frequency cutoff (for $\nu_b \geq 1$ GHz, i.e. Coma, Thierbach et al. 2003) and a low frequency flattening (for $\nu \leq$ few hundred MHz, i.e. A 3562 and A 521, Venturi et al. 2003 and Brunetti et al. 2008 respectively). Fig. 4 shows four meaningful examples. Apart from the flux density scale, it is clear that the spectra shown are all very different.

4.1. Ultra–steep spectrum radio halos

Beyond the historical sources, most of the radio halos known so far were found either by inspection of relatively shallow surveys, such as the 1.4 GHz Northern VLA Sky

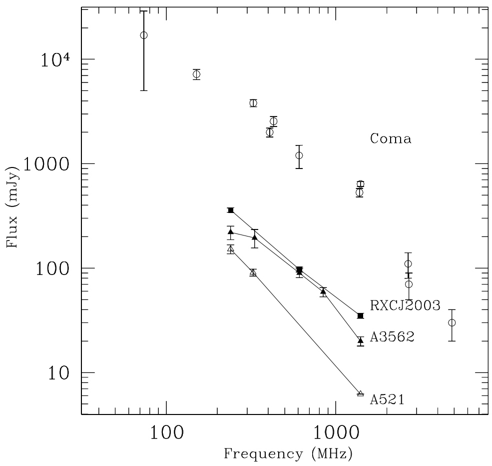

Fig. 4. *S*pectra for a few radio halos are reported. Empty triangles: A 521 (Dallacasa et al. 2009); filled triangles: A 3562 (Giacintucci et al. 2005); filled squares: RXCJ 2003.5–2323 (Giacintucci et al. 2009); empty circles: Coma (Thierbach et al. 2003).

Survey (NVSS) and the 327 MHz Westerbork Northern Sky Survey (WENSS) (Giovannini et al. 1999 and Kempner & Sarazin 2001 respectively), leading to the detection of relatively bright sources at GHz frequencies, which do have spectral index values in the range 1.2–1.4, as often reported in the literature. The 610 MHz GMRT Radio Halo Survey, roughly 5 times more sensitive than the NVSS, allowed the detection of considerably fainter sources, at the very limit of detectability on the NVSS, and led to the discovery of a new "population" of radio halos, with very steep spectrum at GHz frequencies, i.e. $\alpha \sim 2$. A 521 is the first radio halo found with spectral index $\alpha \sim 2$ (Brunetti et al. 2008; Dallacasa et al. 2009): the images published in the literature show that the source becomes bright and easily detectable at frequencies of the order of 325 MHz and below, and that the relative dominance of the halo and of the relic change considerably going to lower frequencies, as a result of the different spectral shapes of the two sources (for the relic $\alpha = 1.48$, Giacintucci et al. 2008). Another very steep spectrum halo was found in A 697 (Macario et al. 2010, Macario et al. this volume), as well as few candidates currently under investigation. Both A 521 and A 697 show that the size of the radio halo increases with decreasing frequency, which is different from what is observed in the "classical" radio halos. For instance, the shape and extent of RXCJ 2003.5–2323 (Fig. 3) does not change at least in the range 235 MHz – 1.4 GHz. The same is true also for Coma (but see Brown & Rudnick 2011).

The finding of very steep spectrum halos is opening up a new window in our understanding of the origin and formation of radio halos and on the radio halo–cluster merger connection. One of the consequences of the turbulent re–acceleration model (see Brunetti and Cassano, present volume) is the dependance of the cut-off frequency ν_b on the efficiency of the re–acceleration process during the cluster mergers: less efficient re–acceleration shifts ν_b to lower and lower frequencies. An application of the turbulent re–acceleration model (Cassano 2010b) shows that a population of ultra–steep spectrum radio halos is expected, as due to to less energetic mergers and/or less massive clusters.

These results suggest that the spectra of radio halos may be a key information for our understanding of the dynamical processes at play in the hosting clusters.

5. Relics and shocks

Radio relics show a broad variety of morphologies, and a considerable spread in size and projected distance from the cluster center, going from A 3667 and Coma, whose relics are beyond the 1.5 Mpc size and are located more than 1.5 Mpc from the cluster center (Rottgering et al. 1997; Brown & Rudnick 2011, respectively) to the small relic in A 4038 (Kale 2010). An updated summary of our knowledge of the observational properties of relics, as well as significant statistical correlations, is given in van Weeren et al. (2009a).

The location, shape and polarization properties of relics suggest that their origin is connected to the propagation of shock waves, with Mach numbers $\lesssim 3$, during cluster mergers. Indeed all models proposed so far for the formation of relics require the presence of a shock at the relic position, which may (re–)accelerate relativistic electrons or "revive" fossil radio plasma by means of adiabatic compression (Ensslin et al. 1998; Ensslin & Gopal–Krishna 2001; Markevitch et al. 2005). For a few well studied cases, the spectrum of the radio relic is consistent with Mach numbers for the shock in the range 1–3 (i.e. A 521, Giacintucci et al. 2008; CIZA J2242.8+5301, van Weeren et al. 2010; A 754, Macario et al. 2011).

So far only a few shocks have been firmly detected with *Chandra* (Markevitch et al., present volume), and it would be crucial to increase the statistics not only of confirmed shocks, but also of clusters with a clear connection between a shock front and a relic, as it has been the case for A 520 (Markevitch et al. 2005) and A 754 (Macario et al. 2011).

6. Open questions and future perspectives

Our knowledge and understanding of diffuse cluster sources, and their connection to the processes of cluster assembly in the Universe has considerably improved over the past few years. It seems now firmly established that cluster mergers are at the origin of radio halos and relics, but many details need to be clarified and understood. A few points deserve special attention, and these are summarized below.

(1) High sensitivity imaging of radio halos at low frequencies is crucial. So far only two radio halos are confirmed ultra–steep spectrum sources. It is essential that more objects are found, to safely talk of a "new population". Finding more USSRH (Ultra Steep Radio Halos) would provide further observational support in favor of the turbulent re–acceleration model. According to the statistical results of Cassano et al. (2010b), such objects should open up the study of the observational effects of the common and numerous minor mergers, expected to be the dominant mechanisms of mass assembly in the Universe.

(2) It is essential to increase the number of radio halos and relics with well defined integrated spectra, since the spectral shape and spectral index value are the signature of the underlying electron population and of the re–acceleration processes.

(3) Imaging of the spectral index distribution is another crucial piece of information which we still miss. It is relevant not only to address point (2), but also for the study the distribution of the magnetic field in the cluster volume.

(4) The number of clusters with multiple diffuse sources is steadily increasing, especially after the advent of the good quality images provided by the GMRT at low frequencies (see for instance van Weeren at al., present volume). This is most likely telling us something about the development of shocks and turbulence in the cluster volume as consequence of cluster mergers, and their signature on the diffuse radio emission.

The future is bright. LOFAR has started to deliver the first images, and it is expected to unveil the population of ultra–steep spectrum halos which the GMRT has just discovered. The few μJy sensitivity of the EVLA will lead to the detection of very faint halos at GHz frequencies, thus constraining the bright end of the radio spectrum of ultra–steep sources. At the same time, the GMRT still has a long way ahead to continue its observational contribution in this field. To conclude, I believe that a new era in the study of diffuse cluster sources is about to start.

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