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Observations of Extended Radio Emission in Clusters

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Abstract We review observations of extended regions of radio emission in clusters; these include diffuse emission in 'relics', and the large central regions commonly referred to as 'halos'. The spectral observations, as well as Faraday rotation measurements of background and cluster radio sources, provide the main evidence for large-scale intracluster magnetic fields and significant densities of relativistic electrons. Implications from these observations on acceleration mechanisms of these electrons are reviewed, including turbulent and shock acceleration, and also the origin of some of the electrons in collisions of relativistic protons by ambient protons in the (thermal) gas. Improved knowledge of non-thermal phenomena in clusters requires more extensive and detailed radio measurements; we briefly review prospects for future observations.

Keywords Galaxies: clusters: general · Galaxies: intergalactic medium · Radio continuum: general · Radiation mechanisms: non-thermal · Magnetic fields · Acceleration of particles

1 Introduction

In the last 10 years, the improved capabilities (sensitivity, spectral and spatial resolution) of multi-wavelength telescopes have allowed us to study in detail the formation and evolution

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of the largest gravitationally bound systems in the Universe, i.e. galaxy clusters. Following the hierarchical scenario of structure formation, massive clusters form through episodic mergers of smaller mass units (groups and poor clusters) and through the continuous accretion of field galaxies.

It has now been proven that major cluster mergers, with their huge release of gravitational binding energy ($\sim 10^{64}$ ergs), deeply affect the physical properties of the different components of clusters, i.e. the temperature, metallicity and density distribution of the thermal intracluster medium (ICM) emitting in X-rays (e.g., Buote 2002; Sauvageot et al. 2005; Ferrari et al. 2006a; Kapferer et al. 2006; Markevitch and Vikhlinin 2007), the global dynamics and spatial distribution of galaxies (e.g., Girardi and Biviano 2002; Ferrari et al. 2003, 2005; Maurogordato et al. 2008), as well as their star-formation rate (e.g., Gavazzi et al. 2003; Poggianti et al. 2004; Ferrari et al. 2006b). The typical signatures that allow to identify merging clusters from optical and X-ray observations are: a) substructures in the X-ray and optical surface densities (see Buote 2002, and references therein), b) non-Gaussian radial velocity distributions of cluster members (see Girardi and Biviano 2002, and references therein), c) patchy ICM temperature, pressure, entropy and metallicity maps (e.g., Finoguenov et al. 2005; Kapferer et al. 2006), d) sharp X-ray surface brightness discontinuities, accompanied by jumps in gas and temperature ("cold fronts", see, e.g., Markevitch et al. 2000), e) absent or disturbed cooling-cores (e.g., Markevitch et al. 1999), f) larger core radii compared to (nearly) relaxed clusters (Jones and Forman 1999). There are also indications that recent merging events lead to a depletion of the nearest cluster neighbours (e.g., Schuecker and Böhringer 1999). Additionally, deep radio observations have revealed the presence of diffuse and extended ($\sim$1 Mpc) radio sources in about 50 merging clusters. Their radio emission is not related to a particular cluster member, but rather to the presence of relativistic electrons (Lorentz factor $\gamma \gg 1000$) and weak magnetic fields (μG) in the intracluster space.

In this review, we focus on radio observations of this non-thermal component in galaxy clusters. We outline our current knowledge on the presence of non-thermal processes in the intracluster gas, and their physical connections with the thermodynamical evolution of large-scale structure. The relevance of the study of extended cluster radio emission for cosmology is pointed out. On smaller scales, there are only few indications of the possible presence of extended radio emission in galaxy groups. These systems host diffuse $\sim$1 keV gas called intragroup medium (IGM) (see, e.g., Mulchaey et al. 1996). Radio and hard X-ray emission possibly related to a non-thermal component of the IGM has been recently pointed out by Delain and Rudnick (2006) and Nakazawa et al. (2007) respectively. The existence of diffuse radio sources in galaxy groups has indeed to be tested with observations of higher sensitivity. Radio observations of the emission from individual radio galaxies are not treated here. For a discussion on cluster radio galaxies see the reviews by Feretti and Venturi (2002) and Feretti and Giovannini (2008). X-ray observations and simulations of the non-thermal component in clusters are reviewed by Rephaeli et al. (2008—Chap. 5, this issue) and Dolag et al. (2008—Chap. 15, this issue). The adopted cosmology is ΛCDM ($H_0 = 70\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$).

2 Extended Radio Emission in Galaxy Clusters

The first detection of diffuse and extended radio emission in galaxy clusters dates back to 1959, when Large et al. mapped for the first time the Coma cluster at radio wavelengths, detecting an extended radio source (Coma C) at its centre. The existence of Coma C was later confirmed by Willson (1970), who compared the single dish data of Large et al. (1959) with interferometric observations, and determined that the observed radio emission was diffuse and not associated with any cluster galaxy. From then on, high sensitivity radio observations have revealed in about 50 clusters the existence of diffuse non-thermal radio sources, not associated with active galaxies but with the ICM. The power-law radio spectrum[1] of this class of cluster sources indicates their synchrotron nature, and thus the presence of relativistic electrons (Lorentz factor $\gamma \gg 1000$) and magnetic fields ($\sim$0.1–1 μG) permeating the cluster volume.

While the thermal gas emitting in X-rays is present in all clusters, the detection of extended radio emission only in $\lesssim$10% of the systems indicates that the non-thermal plasma is not a common property of galaxy clusters. The very low surface brightness of diffuse cluster radio sources makes them difficult to detect with current radio telescopes. However, as we discuss here and in the following sections, our current knowledge suggests that the lack of radio emission in a high fraction of known clusters is not only related to a limited sensitivity of the current instruments,[2] but also to physical reasons, as non-thermal components over $\sim$1 Mpc scales are present only in the most massive merging clusters. Discriminating between these two effects is at present extremely difficult, and it will be one of the main goals of future radio observations (see Sect. 5).

The steep radio spectral index usually observed in diffuse cluster radio sources ($\alpha \gtrsim 1$) is indicative of ageing of the emitting particles. The steepening of the electron spectrum is a direct result of their Compton-synchrotron losses. The highest energy particles lose their energy more quickly. As a result, if cosmic rays are produced in a single event with a power law energy distribution

$$N(E)\,\mathrm{d}E = N_0 E^{-\delta}\,\mathrm{d}E \tag{1}$$

following the emergence of electrons from their sources (or acceleration sites), their spectrum steepens as result of the shorter energy loss time of high energy electrons. As a consequence the synchrotron spectrum falls off rapidly beyond a certain break frequency ν^*, which shifts gradually to lower frequencies. If instead particles are re-accelerated and/or continuously injected, as suggested to occur in cluster diffuse sources, the energy spectrum of relativistic particles may adopt more complex spectral shapes.

Apart from their common properties (nature of the emission, steep radio spectra), diffuse and extended radio sources in clusters differ in their physical properties, in particular: size, position in the host cluster, intensity of polarised signal, morphology and association to other cluster physical properties (e.g., dynamical state, presence of a cooling flow). A working definition, that is usually adopted, assigns cluster diffuse radio sources to three main classes: halos, relics and mini-halos. Very schematically:

- *radio halos* are extended ($\gtrsim$1 Mpc) diffuse radio sources at the centre of clusters, with a quite regular morphology, similar to the X-ray morphology of the system;
- *radio relics* have similar extensions and are also detected in merging clusters, but usually they are located in the cluster outskirts and they have an elongated morphology;
- *radio mini-halos* are smaller sources ($\lesssim$500 kpc) located at the centre of cooling flow clusters. They surround a powerful radio galaxy.

The main observational properties of these sources, useful to test their different formation scenarios (Sect. 3), are reviewed in more detail in the following (Sects. 2.1, 2.2 and 2.3).

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[1] $S(\nu) \propto \nu^{-\alpha}$, see (3).

[2] For instance, the 3σ sensitivity limit for the NRAO VLA Sky Survey (NVSS) at 1.4 GHz, with a resolution of 45 arcsec, is $\sim$1.35 mJy/beam (Condon et al. 1998). The Very Large Array (VLA) is operated by the National Radio Astronomy Observatory.

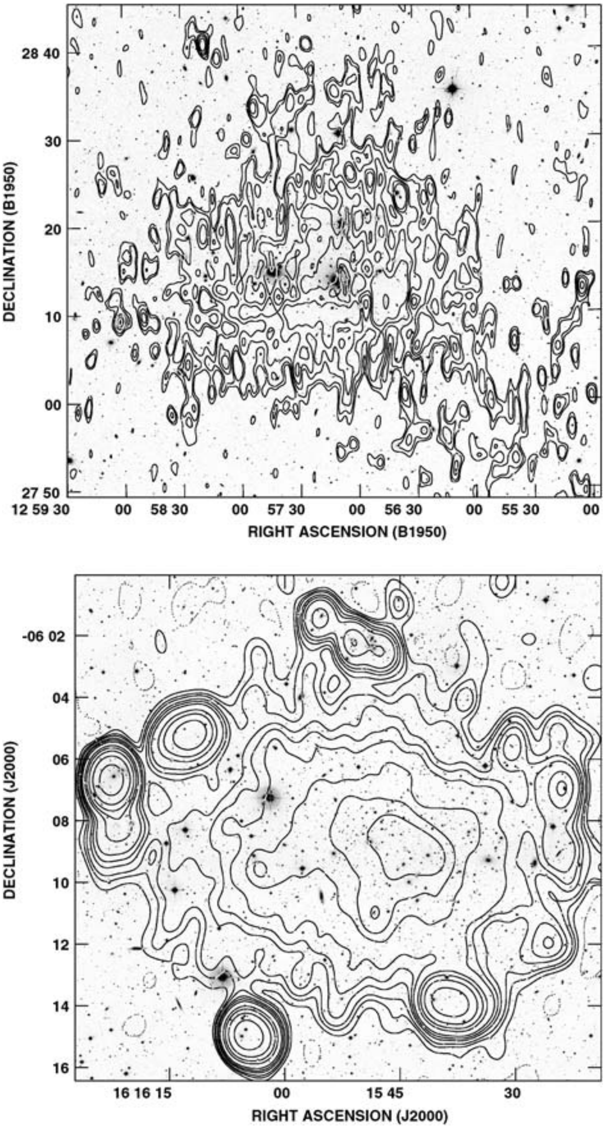

Fig. 1 *Top:* 90 cm contours of the radio halo in the Coma cluster ($z = 0.023$) are overlaid on the DSS optical image. Radio point sources have been subtracted (Feretti 2002). *Bottom:* 20 cm radio contours (Feretti et al. 2001) overlaid on the deep, R-band image (Maurogordato et al. 2008) of the galaxy cluster A 2163 ($z = 0.203$), hosting one of the most extended and powerful halos known so far

2.1 Radio Halos

Coma C is the prototype of the low surface brightness ($\sim\mu$Jy arcsec^{-2} at 1.4 GHz) and extended ($\gtrsim$1 Mpc) radio sources permeating the central volume of clusters, usually referred as "radio halos". Their radio morphology is quite regular (see Fig. 1) and their radio emission is unpolarised down to a few percent level. The first (and only) successful detection of polarised emission from a radio halo has been published recently by Govoni et al. (2005). One can find a compilation of most of the currently known radio halos in the recent review by Feretti and Giovannini (2008).

Spectral index studies of extended radio sources can give important hints on the energy spectrum of relativistic electrons and, due to the dependence of the synchrotron emissivity

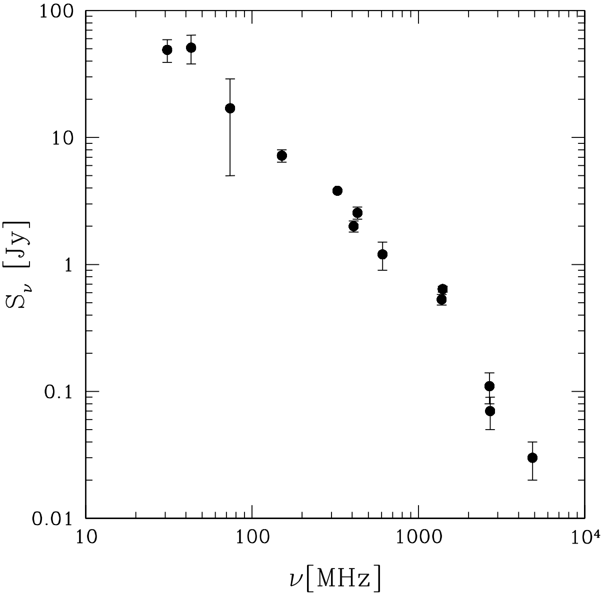

Fig. 2 Spectrum of the radio halo in the Coma cluster (Coma C). A steepening in the spectrum stands out clearly at $\nu > 1$ GHz (adapted from Thierbach et al. 2003)

on the magnetic field intensity (3), on the magnetic field distribution (Brunetti et al. 2001). In recent years, many observational efforts have thus been devoted to multi-frequency observations of radio halos, in order to get more and more accurate determinations of the integrated radio spectrum and, possibly, of spatially resolved spectral index maps. These studies are limited however by the capability of current instruments to do multi-frequency observations at the sensitivity required for studying radio halos ($\sim$mJy–μJy arcsec^{-2} going from the MHz to the GHz range). In a few cases, a steepening of the halo spectrum at high frequency (as in Fig. 2 in the case of the Coma cluster) has been detected (A 2319: Feretti et al. 1997; Coma: Thierbach et al. 2003; A 754: Bacchi et al. 2003; A 3562: Giacintucci et al. 2005). Indications that the spectral index steepens radially with the distance from the cluster centre have been pointed out by Giovannini et al. (1993) in Coma, and Feretti et al. (2004a) in A 665 and A 2163. More recently, Orrù et al. (2007) have shown that the radio halos in A 2744 and A 2219 have a mean spectral index, averaged over the whole cluster, without a clear radial steepening, but with a very patchy structure. Very interestingly, their radio/X-ray comparison shows flatter spectral indexes in regions characterised by higher ICM temperature.

Current observational results suggest other strong connections between the physical properties of radio halos and of their host clusters. All radio halos discovered up to now are at the centre of clusters with signatures of a disturbed dynamical state and without a cooling core. However, not all merging clusters host a radio halo. The detection rate of radio halos is actually quite low: 5% in a complete cluster sample at the detection limit of the NVSS, which grows to $\sim$35% when only the most luminous X-ray clusters are considered ($L_{X[0.1-2.4\ \mathrm{keV}]} > 0.6 \times 10^{45}\ \mathrm{h}_{70}^{-2}$ erg s^{-1}) (Giovannini et al. 1999; Giovannini and Feretti 2002). The fact that radio and X-ray properties of clusters are connected is also suggested by a close similarity of the morphology of radio halos and the X-ray emission of their host clusters. This has firstly been revealed in a qualitative way (Deiss et al. 1997; Feretti 1999; Liang et al. 2000), and afterwards quantitatively confirmed by the relation between

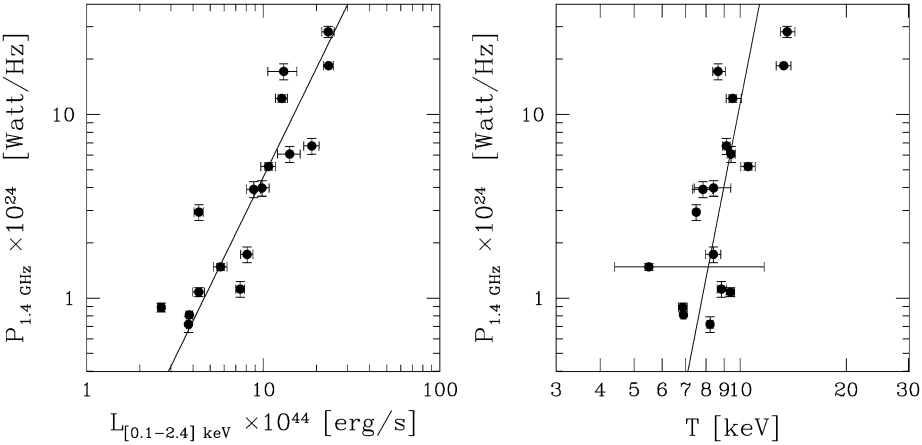

Fig. 3 Radio power at 1.4 GHz of giant ($\gtrsim$1 Mpc) radio halos vs. a) *left:* cluster X-ray luminosity, and b) *right:* cluster X-ray temperature (adapted from Cassano et al. 2006)

the point-to-point surface brightness of the cluster radio and X-ray emission (Govoni et al. 2001c; Feretti et al. 2001).

Additionally, a strong correlation has been pointed out between the radio power (P_ν) of halos and the X-ray luminosity (L_X) of their host clusters (e.g., Liang et al. 2000; Giovannini and Feretti 2002; Enßlin and Röttgering 2002; Cassano et al. 2006; see left panel of Fig. 3). A relation with a much larger scatter between radio power and X-ray temperature of the ICM (T_X) has also been suggested (e.g., Colafrancesco 1999; Liang et al. 2000) (see right panel of Fig. 3). Since both the X-ray luminosity and temperature of clusters correlate with mass (e.g., Neumann and Arnaud 1999; Neumann and Arnaud 2001), the observed P_ν–L_X and P_ν–T_X relation could reflect a dependence of the radio halo luminosity on the cluster mass, with interesting implications on the theoretical models of cosmic ray production (see Sect. 3). Current results suggest $P_{1.4\ \mathrm{GHz}} \propto M^a$, with $a = 2.3$ or larger, depending on the methods applied to estimate the cluster mass (see Feretti and Giovannini 2008 and references therein).

Recently, Cassano et al. (2007) pointed out that the fraction of the radio emitting cluster volume significantly increases with the cluster mass. This break of self-similarity can give important constraints on the physical parameters entering the hierarchical formation scenario, since it suggests that the distributions of the magnetic field and relativistic electrons change with the cluster mass.

2.2 Radio Mini-Halos

The so-called “radio mini-halos” (Fig. 4) differ from the above described radio halos not only because of their smaller size (few 10^2 kpc), as their name suggests, but also in the typical properties of their host clusters. Actually, mini-halos are diffuse radio sources with a steep spectral index, which are found around powerful radio galaxies at the centre of cooling core clusters. The total size of mini-halos is comparable to that of the cooling region. Since major mergers are able to disrupt (or at least disturb) cluster cooling flows (e.g., Buote and Tsai 1996; Gómez et al. 2002), the main physical difference between giant and mini-halos is that they are hosted in clusters with and with no evidence of *major* mergers respectively.

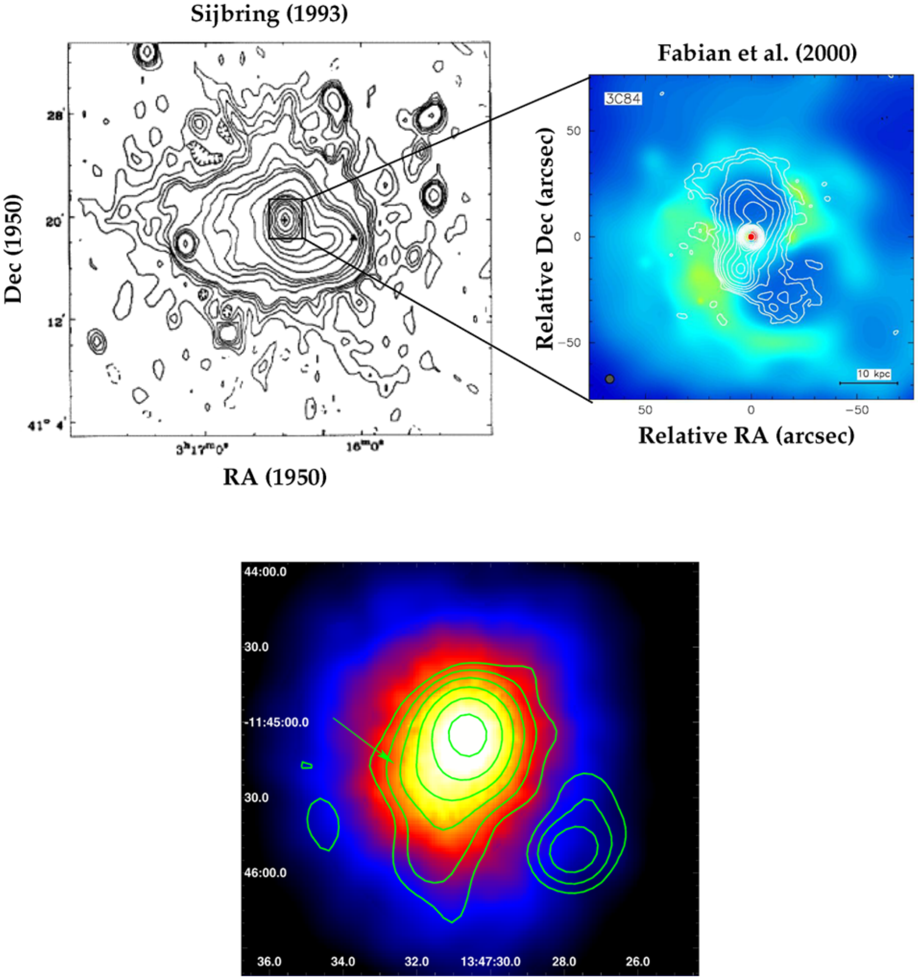

Fig. 4 *Top:* 327 MHz map of the mini-halo in the Perseus Cluster ($z = 0.018$). The source is centred on the position of the cD galaxy NGC 1275 (indicated with a *cross*). The *inset* shows radio contours overlaid on the X-ray image of the central $\sim 1'$ region of Perseus. The holes evident in the X-ray emission are due to subsonic expansion of the buoyant radio lobes of the central radio galaxy 3C 84 (adapted from Sijbring 1993 and Fabian et al. 2000). *Bottom:* 1.4 GHz contours of the radio mini-halo (the most distant ever detected) in the galaxy cluster RXJ 1347.5–1145 ($z = 0.451$), superimposed on the *XMM-Newton* image of the cluster. The green arrow indicates an elongation in the radio mini-halo morphology, corresponding to a sub-structure detected in X-rays (adapted from Gitti et al. 2007a)

However, recent results revealed the existence of two cooling flow clusters with signatures of merging activity in the central region and hosting a radio mini-halo: A 2142 (Giovannini and Feretti 2000) and RXJ 1347.5–1145 (Gitti et al. 2007a, see bottom panel of Fig. 4). Contrary to what expected in relaxed systems, both the clusters are dominated by two brightest cluster galaxies (BCGs). In A 2142, the central cooling flow has been disturbed but not destroyed by an unequal merger, observed 1–2 Gyr after the initial core crossing (Markevitch et al. 2000). The cooling flow in RXJ 1347.5–1145 is one of the most massive ever detected, suggesting a relatively long interval of time in which the central part of the cluster has evolved undisturbed to a nearly relaxed state (Gitti et al. 2007b). The X-ray analysis of Gitti et al. (2007b) reveals however a sub-structure in the south-east part of the cluster, corresponding to an elongation in the radio mini-halo morphology (see bottom panel of Fig. 4). Indications of possible *minor* mergers have been detected also in other clusters hosting radio mini halos (Perseus: Ettori et al. 1998; Furusho et al. 2001; A 2390: Allen et al. 2001; A 2626: Mohr et al. 1996). In these cases, however, the merging substructures are located well outside the diffuse radio source.

Several radio halos have been discovered in radio surveys (e.g., NVSS, Giovannini et al. 1999), where their relatively large beam provides the necessary signal-to-noise ratio to spot these elusive sources. Due to their extremely low surface brightness and large angular extent radio halos are actually best studied at low spatial resolution. Unfortunately, due to the combination of their smaller angular size and the strong radio emission of the central radio galaxy, the detection of a mini-halo requires a much higher dynamic range and resolution than those in available surveys, and this complicates their detection. As a consequence, our current observational knowledge on mini-halos is limited to less than ten known sources (PKS 0745–191: Baum and O'Dea 1991; Perseus: Burns et al. 1992; A 2142: Giovannini and Feretti 2000; A2390: Bacchi et al. 2003; A 2626: Rizza et al. 2000; Gitti et al. 2004; RXJ 1347.5–1145: Gitti et al. 2007a). This, together with the peculiar properties of A 2142 and RXJ 1347.5–1145, and the possible connection between radio mini-halos and minor cluster mergers, requires better statistics to test the current theoretical models on the origin of their radio emission, which are discussed in Sect. 3.

2.3 Radio Relics

As clearly stated by Kempner et al. (2004) there is quite a lot of confusion in the literature when speaking about "radio relics". This definition is actually adopted for at least three different kinds of radio sources in galaxy clusters, characterised by significantly different observational properties. Certain features are in common for all the different kinds of relic sources, such as their steep radio spectrum ($\alpha \gtrsim 1$) and a general filamentary morphology.

A first group of sources (see an example in the top panel in Fig. 5) has typical sizes of several 10 kpc and low/intermediate polarisation intensity ($\lesssim$20%). They are generally located in the central cluster regions, close to the cD galaxy, often showing an anti-correlation with the ICM density. Actually, in some clusters, relic as well as AGN radio emission has been detected inside holes in the central X-ray emission of the thermal gas (see for instance the inset in the top panel of Fig. 4). These cavities are actually related to the cyclic outburst activity of the central AGN. The cases in which no radio emission has been detected, or has been revealed only by low frequency radio observations (e.g., the Perseus outer cavities discovered by Fabian et al. 2002), are due to buoyant old radio lobes, whose spectrum is too steep to be detected in the GHz range. A more detailed discussion on these "radio ghosts" and X-ray cavities in clusters can be found in a recent review by McNamara et al. (2008).

Both the second and the third class of "cluster relics" (middle and bottom panel of Fig. 5) are strongly correlated with the ICM properties. They are commonly found in merging clusters, and, in some cases, a spatial correlation with shocks in the thermal gas has been pointed out (e.g., Kassim et al. 2001). Both of these classes of sources do not have a likely parent radio galaxy nearby, are generally polarised at the level of about 10–30% and located in the cluster periphery. While the (rare) objects in the second group are characterised by intermediate linear scales compared to the other two (with typical sizes of $\sim 10^2$ kpc, e.g., Slee et al. 2001), the most extended radio emission among the "relic sources" comes from the third class.

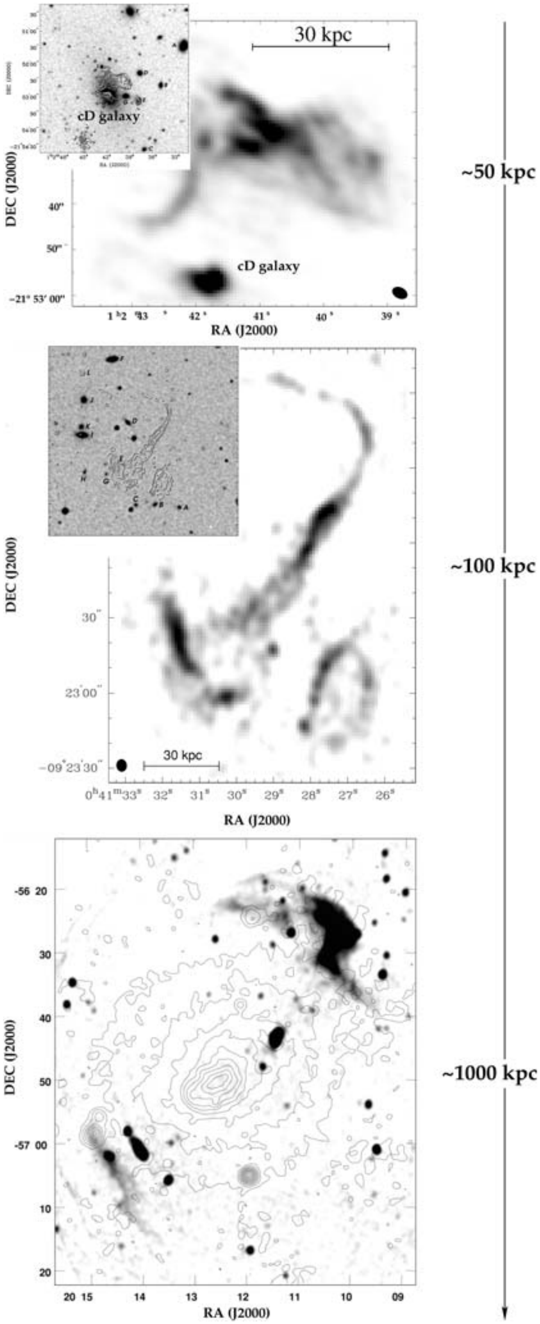

Fig. 5 Examples of different diffuse radio sources in clusters classified as "relics" in the literature. From top to bottom, an "AGN relic", a "Phoenix" and a "Radio Gischt" (see Kempner et al. 2004 and Sects. 2.3 and 3). *Top panel:* VLA image at 1.4 GHz of the "AGN relic" source in A 133 ($z = 0.056$), close to the radio emitting cD galaxy at the cluster centroid. In the inset, radio contours are superimposed on the optical, DSS-2 image of the area (adapted from Slee et al. 2001). *Middle panel:* VLA image at 1.4 GHz of the "Phoenix" source in the periphery of A 85 ($z = 0.055$) (see also Fig. 11 in Slee et al. 2001). As before, the inset shows radio contours superimposed on the optical DSS-2 image of the region around the radio source (adapted from Slee et al. 2001). *Bottom panel:* X-ray contours (ROSAT data, 0.1–2.4 keV energy band) overlaid on the 843 MHz Molonglo Observatory Synthesis Telescope (MOST) image of A 3667 ($z = 0.056$) (from Röttgering et al. 1997)

These giant relics, with extensions ranging from a few $\sim 10^2$ kpc to 10^3 kpc, have been detected in merging clusters both with and without cooling cores. The major axis of their elongated structure is generally nearly perpendicular to the direction of the cluster radius. Some of the most extended and powerful giant relics are located in clusters with central radio halos (e.g., A 2256: Clarke and Enßlin 2006). In a few cases, two symmetric relics have been observed, as in the bottom panel of Fig. 5 (A 3667: Röttgering et al. 1997; Johnston-Hollitt et al. 2002; A 3376: Bagchi et al. 2006; A 1240: Kempner and Sarazin 2001). More "exotic" giant radio relics have also been discovered, such as sources located in poor clusters (Abell S 753: Subrahmanyan et al. 2003), far away from the cluster centre (A 786: Giovannini and Feretti 2000), or even in intracluster filaments of galaxies (ZwCl 2341.1+0000: Bagchi et al. 2002). Relics elongated from the cluster centre to the periphery (A 115: Govoni et al. 2001b), or with a circular shape (A 1664: Feretti 2005) have also been detected. Similarly to radio halos (Sect. 2.1), the detection rate of giant radio relics at the sensitivity limit of NVSS is ∼6% (Giovannini and Feretti 2002), and the relic radio power correlates with the cluster X-ray luminosity (Feretti 2002), even though with a larger scatter.

3 Origin of Radio Emitting Particles

Based on the observational results summarised in Table 1 and in the previous sections, and on the theoretical models reviewed, for instance, by Brunetti (2004), Blasi et al. (2007) and Dolag et al. (2008), we have now a formation scenario for the different diffuse and extended radio sources in clusters. The current theories on the origin of the non-thermal component in galaxy clusters will be the starting point for new observational studies with the next generation radio telescopes (Sect. 5).

Giant radio halos and relics are the most spectacular radio sources in clusters, and, as stated above, their synchrotron spectrum indicates the presence of cosmic rays that gyrate around magnetic field lines, frozen in the ICM. Therefore, relativistic particles cannot stream out from the gravitational field of the cluster, but they can still diffuse along magnetic field lines. It has been shown however (Völk et al. 1996; Berezinsky et al. 1997; Völk and Atoyan 1999) that typical relativistic electrons in radio halos and relics (with $\gamma \sim 1000$–5000) have diffusion times which are longer than the Hubble time. They could therefore be simply diffused over cluster scales from one or more active radio galaxies (Jaffe 1977; Rephaeli 1977). However, the steep radio spectra of these sources indicate short lifetimes for the radiating particles ($\sim 10^8$ yr), which lose energy not only via synchrotron emission, but also due to interactions with the Cosmic Microwave Background (CMB) photons (via Compton scattering emission) and with the ICM (via Coulomb interactions and Bremsstrahlung emission). The main radiative losses of electrons are due to Compton scattering of the CMB, and synchrotron emission; the former process dominates for $B < 3$ μG (the field equivalent of the CMB energy density). The radiative lifetime of a relativistic lepton with a Lorentz factor

Table 1 Main observational properties of the different sources of diffuse radio emission in galaxy clusters. Note that linear polarisation levels of ∼20–40% have been detected in filamentary structures of the radio halo in A 2255 by Govoni et al. (2005)

Type	Position	Size	α	Polarisation	Example
Halo	Centrally peaked	$\gtrsim$Mpc	$\gtrsim 1$	<few %	Coma
Giant relic	Peripheral	∼Mpc	$\gtrsim 1$	∼10–30%	Abell 3667
Mini-halo	Centrally peaked	$\lesssim$0.5 Mpc	$\gtrsim 1.5$	<few %	Perseus
Phoenix	Peripheral	$\sim 10^2$ kpc	$\gtrsim 1.5$	∼10–30%	Abell 85
AGN relic	Close to the host galaxy	few $\times$10 kpc	$\gtrsim 1.5$	$\lesssim$20%	Abell 133

$\gamma < 10^8$ is thus approximately given by (e.g., Longair 1981; Meisenheimer et al. 1989)

$$\tau \approx 2 \times 10^{12} \gamma^{-1} \left[(1+z)^4 + \left(\frac{B}{3.3\mu\mathrm{G}} \right)^2 \right]^{-1} \text{ years.} \tag{2}$$

Since the expected diffusion velocity of the relativistic electrons is of the order of 100 km s^{-1} (Alfvén speed), cosmic rays do not have the time to propagate over the Mpc-scales of giant cluster radio sources. This excludes the hypothesis that relativistic electrons are produced at a localised point, and requires *in situ* acceleration mechanisms. Basically, two classes of models have been proposed:

- the *primary models*, which predict that electrons are accelerated by shocks and/or turbulence induced during cluster mergers. Shocks can (re-)accelerate particles via Fermi-I processes (Enßlin et al. 1998) or adiabatic compression of fossil radio plasma (Enßlin and Gopal-Krishna 2001); turbulence via stochastic, Fermi-II processes (Brunetti et al. 2001) or magnetohydrodynamic (MHD) waves (Alfvén waves: Brunetti et al. 2004; magnetosonic waves: Cassano and Brunetti 2005);
- the *secondary models*, in which relativistic electrons are continuously injected by hadronic collisions between the thermal ions of the ICM and relativistic protons, the latter (characterised by significantly longer lifetime compared to relativistic electrons) having been accelerated during the whole cluster history (e.g., Dennison 1980; Blasi and Colafrancesco 1999; Dolag and Enßlin 2000).

The observational properties of radio halos and relics (see Sects. 2.1 and 2.3) are more in favour of primary models. The strongest point leading to this conclusion is the fact that diffuse and extended radio emission has been detected up to now only in merging clusters. A strong connection between cluster mergers and cosmic ray production is required in primary models, and is not expected in secondary models. In this respect, the fact that halos and relics are quite rare in clusters is again disfavouring the hadronic collision hypothesis, based on which we should expect electron acceleration to be possible in all galaxy clusters.

Since the shape of the synchrotron spectrum depends on the last acceleration phase of cosmic rays, detailed studies of the spectral index distribution in radio halos and relics provide important information on acceleration mechanisms acting in clusters. Primary models predict a radial steepening and a complex spatial distribution of the spectral index α, due to the existence of a) a maximum energy to which electrons can be accelerated ($\gamma < 10^5$, Blasi 2004, and references therein) and b) different re-acceleration processes in different cluster regions. Secondary models assume that cosmic ray protons are accelerated during structure formation over cosmological epochs and accumulated in clusters. The collision of these protons with the thermal ICM would continuously inject electrons, resulting in a spectral index distribution unrelated to the intracluster magnetic field strength, and thus not dependent on the position in the cluster. The radial spectral steepening and/or the patchy structure of spectral index maps observed in several radio halos (Sect. 2.1) are clearly favouring primary models.

The hadronic collision hypothesis predicts power-law spectra flatter than primary models ($\alpha \lesssim 1.5$) and magnetic field values higher than a few μG. Observational results are controversial concerning these points, due to the observed intermediate values of the radio spectral index ($\alpha \sim 1$–1.5), and the widely differing estimates for mean intracluster magnetic field values (Sect. 4). Finally, emission of gamma-rays is expected in secondary models (Blasi et al. 2007), a challenging point to be tested observationally (Rephaeli et al. 2008—Chap. 5, this issue). On the other hand, it has been suggested (Bykov et al. 2000; Miniati 2003) that the detection of gamma-ray emission from clusters may not necessarily reflect the hadronic origin of cosmic rays, since it could be related to the Compton scattering of CMB photon from shock-accelerated, intracluster electrons.

Given our current observational and theoretical knowledge, cosmic rays in giant radio relics (bottom panel of Fig. 5) are most likely originating from Fermi-I diffuse shock acceleration of ICM electrons (e.g., Hoeft and Brüggen 2007; Bykov et al. 2008—Chap. 7, this issue). These radio sources would therefore trace the rim of shock fronts resulting from cluster mergers in the ICM, and they have been named "radio gischt"[3] by Kempner et al. (2004). Firstly, this hypothesis is in agreement with the morphology and the position of most of the detected giant relics, which appear as elongated, sometimes symmetric, radio sources in the cluster periphery, where we expect to find arc-like shock fronts resulting from major cluster mergers (e.g., Schindler 2002). Secondly, the quite strong linear polarisation detected in giant relics would be in agreement with the model prediction of magnetic fields aligned with the shock front. Based on some observational results, however, a clear association between shocks and giant radio relics is not always straightforward. This is true in the case of the "exotic" giant relics mentioned in Sect. 2.3 (e.g., those with circular shapes, or located in intracluster filaments). Additionally, Feretti and Neumann (2006) did not detect a shock wave corresponding to the radio relic in the Coma cluster. They suggested that, similarly to radio halos (see below), the radio emission of this relic source is instead related to turbulence in the ICM. Currently, the main observational limitation to test the origin of giant radio relics comes from X-ray data. The sensitivity of X-ray instruments is not high enough to detect shock waves in the external regions of clusters, where the gas density and thus the X-ray surface brightness are very low, and where most of radio relics have been detected (see for instance the radio relic found in A 521 by Ferrari (2003); see also Ferrari et al. 2006a; Giacintucci et al. 2006).

The second class of relic sources pointed out in Sect. 2.3 (middle panel in Fig. 5), characterised by smaller sizes than giant relics ($\sim 10^2$ kpc vs. 10^3 kpc), are most likely originating from adiabatic compression in cluster shocks of fossil radio plasma, released by an AGN whose central engine has ceased to inject fresh plasma $\lesssim 1$ Gyr ago (Enßlin and Gopal-Krishna 2001). The old non-thermal electrons, that would be undetectable at high ($\sim$GHz) frequencies, are actually re-energised by the shock. This class of sources are therefore also called "Phoenix" (Kempner et al. 2004). The main physical difference with giant relics is related to the fact that, in the latter, shocks accelerate thermal ICM electrons to relativistic velocities through Fermi-I processes, while, in the case of Phoenix sources, the shock waves energise the relativistic plasma by adiabatic compression. The sound speed inside the fossil radio plasma is actually so high that shock waves cannot penetrate into the radio cocoons. These sources are rare because they require shocks and fossil plasma in the same region of the cluster. Moreover, adiabatic compression is efficient in re-accelerating electrons only if the time elapsed since the last AGN activity is not too long, i.e. less than about 0.1 Gyr in the cluster centre and less than about 1 Gyr in the periphery. All this also explains why we detect Phoenix sources in the external regions of clusters.

Among the sources called "radio relics" in the literature, only the smallest (several tens of kpc) are real "AGN relics" (top panel in Fig. 5). They are extinct or dying AGNs, in which the central nucleus has switched off, leaving the radio plasma to evolve passively (e.g., Murgia et al. 2005; Parma et al. 2007). Their spectrum becomes steeper and steeper, making the source more and more difficult to be detected at high frequencies, until it disappears completely (see Sect. 2.3). Due to the short radiative lifetime of their electrons ($\sim 10^7$–10^8 yrs),

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[3] German for the spray on the tops of ocean waves.

these sources are usually located close to their host galaxy, which did not have time enough to move far away in the cluster potential.

In the case of giant radio halos, spectral index maps show no evidence of flattening at the location of shocks detected in X-rays (A 665: Feretti et al. 2004a; Markevitch and Vikhlinin 2001; A 2744: Orrù et al. 2007; Kempner and David 2004). This agrees with theoretical results showing that shocks in major mergers are too weak to produce relativistic particles uniformly over the whole central $\sim$1 Mpc area of clusters (Gabici and Blasi 2003). Although it cannot be excluded that shock acceleration may be efficient in some particular regions of a halo (e.g., Markevitch et al. 2005), it has been suggested that cluster turbulence generated by cluster mergers may efficiently accelerate electrons in the cluster volume (e.g., Cassano and Brunetti 2005). The observed steepening of the spectral index with the distance from the cluster centre, and the few available spectral index maps showing flatter spectra in the regions influenced by merger processes (Sect. 2.1) support the scenario that ICM turbulence supplies the energy for the radiating electrons.

However, if the predictions of primary models better agree with the observational results, the merging event cannot be solely responsible for electron re-acceleration in giant radio halos and relics, because $\gtrsim$40% of clusters show evidence of a disturbed dynamical state (Jones and Forman 1999), while only $\lesssim$10% possess radio halos and/or relics. As we have seen in Sect. 2.1, the power of observed radio halos P_ν seems to correlate with the mass M of their host cluster. The energy available to accelerate relativistic particles during cluster mergers is a fraction of the gravitational potential energy released during the merging event, that in turn scales as $\sim M^2$. The P_ν–M relation could thus suggest that only the most massive mergers are energetic enough to efficiently accelerate cosmic rays (Buote 2001). A recent model by Cassano and Brunetti (2005) is in agreement with this conclusion, showing that only massive clusters can host giant radio halos. The probability to form these extended radio sources increases drastically for cluster masses $M \geq 2 \times 10^{15}\ M_\odot$ since the energy density of the turbulence is an increasing function of the mass of the cluster. Based on the scenario of hierarchical structure formation, massive clusters result from a complex merging history, during which each cluster–cluster collision could have contributed to provide energy for cosmic ray acceleration.

Finally, as we have seen in Sect. 2.2, radio mini-halos have also been observed in clusters. They are located at the centre of cooling flow clusters and surround a powerful radio galaxy. Similarly to giant radio halos and relics, the electrons in radio mini-halos have short radiative lifetimes due to the high magnetic fields present in cooling cores (Taylor et al. 2002). The observed radio emission is thus not due to the radio lobes of the central AGN. Unlike the giant sources, mini-halos are typically found in clusters not disturbed by major mergers (Sect. 2.2). Again, two possible classes of models have been proposed. Relativistic electrons could have again an hadronic origin (Pfrommer and Enßlin 2004). Or they could be a relic population of (primary) relativistic electrons re-accelerated by MHD turbulence, with the necessary energy supplied by the cooling flow (Gitti et al. 2002). The re-acceleration model by Gitti et al. (2002) has been successfully applied to two cooling flow clusters (Gitti et al. 2002, 2004). The observed correlation between the mini-halo and cooling flow power has also given support to a primary origin of the relativistic electrons (Gitti et al. 2004, 2007a). However, there also seems to be some observational and theoretical evidence to support hadronic origin (Kempner et al. 2004 and references therein). Additionally, in two clusters (A 2142: Markevitch et al. 2000; RXJ 1347.4–1145: Gitti et al. 2007a, 2007b), we got indications that cluster mergers and cooling flows may act simultaneously in powering mini-halo emission in the rare and peculiar clusters in which they coexist. Further theoretical and observational studies are indeed essential due to the low number of known radio mini-halos (Sect. 2.2).

4 Measurement of Intracluster Magnetic Fields

As stressed above, the presence of diffuse and extended synchrotron emission in galaxy clusters indicates the existence of weak magnetic fields in the cluster volume. Different possibilities for their origin have been proposed which are reviewed by Dolag et al. (2008—Chap. 15, this issue). Radio observations of galaxy clusters allow us to measure intracluster magnetic fields and test the different theories on their origin, as reviewed by Carilli and Taylor (2002) and Govoni and Feretti (2004). In the following the main methods to study magnetic field intensity and, eventually, structure are summarised.

4.1 Equipartition Magnetic Fields

In the optically thin case, the total monochromatic emissivity $J(\nu)$ from a set of relativistic electrons in a magnetic field $\mathbf{B}$ depends on a) the magnetic field strength, b) the energy distribution of the electrons, which is usually assumed to be a power law (1), and c) the pitch angle between the electron velocity and the magnetic field direction (θ)

$$J(\nu) \propto N_0 (B \sin\theta)^{1+\alpha} \nu^{-\alpha}, \tag{3}$$

where $\alpha = (\delta - 1)/2$ is the spectral index of the synchrotron spectrum.[4]

Synchrotron emission from diffuse and extended radio sources can give us a direct measure for the intensity of cluster magnetic fields if the relativistic electron flux is measured or constrained. That can be achieved, for example, if Compton-produced X-ray (and gamma-ray) emission was detected simultaneously (see Sect. 4.2). In the case of polarised radio emission, we can also get an indication of the projected magnetic field orientation and its degree of ordering. To break the degeneracy between magnetic field strength and electron density (3), and to obtain a measure for cluster magnetic fields from the observed luminosity of radio sources, it is typically assumed that the energy density of the relativistic plasma within a radio source is minimum

$$U_{\rm tot} = U_{\rm el} + U_{\rm pr} + U_B = U_{\rm min}, \tag{4}$$

where U_B is the energy density in magnetic fields, and $U_{\rm el}$ and $U_{\rm pr}$ are the energy in electrons and in protons respectively. The energy in the heavy particles (protons) is considered to be related to the electron energy

$$U_{\rm pr} = k U_{\rm el}. \tag{5}$$

The value of k depends on the mechanism of (re-)acceleration of electrons, whose physical details, as seen above, are still unknown. A typical value of $k = 1$ is adopted for halo and relic sources. Another important assumption of this method relates to the value of the filling factor, Φ, i.e. the fraction of the source volume V occupied by magnetic field and relativistic particles. The energy density in magnetic field is given by

$$U_B = \frac{B^2}{8\pi} \Phi V. \tag{6}$$

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[4] δ is the electron energy index, see (1).

It is usually considered that particles and magnetic fields occupy the entire volume, i.e. $\Phi = 1$. It can be derived easily that the condition of minimum energy is obtained when the contributions of cosmic rays and magnetic fields is approximately equal

$$U_B = \frac{3}{4}(1+k)U_{\mathrm{el}}. \tag{7}$$

This is the so-called classical equipartition assumption, which allows us to estimate the magnetic field of a radio source from its radio luminosity L (see Pacholczyk 1970 for a rigorous derivation)

$$B_{\mathrm{eq}} \propto \left[\frac{L(1+k)}{\Phi V}\right]^{2/7}. \tag{8}$$

In the standard approach presented above, L is the observed synchrotron luminosity between two fixed frequencies ν_1 and ν_2 (usually $\nu_1 = 10$ MHz and $\nu_2 = 100$ GHz). In this way, however, the integration limits are variable in terms of the energy of the radiating electrons, since, based on (3), electron energies corresponding to ν_1 and ν_2 depend on magnetic field values. This point is particularly relevant for the lower limit, owing to the power-law shape of the electron energy distribution and to the expected presence of low energy electrons in radio halos/relics. Alternatively, it has been suggested to derive equipartition quantities by integrating the electron luminosity over an energy range ($\gamma_{\mathrm{min}} - \gamma_{\mathrm{max}}$) (Brunetti et al. 1997; Beck and Krause 2005). It can be shown that, for $\gamma_{\mathrm{min}} \ll \gamma_{\mathrm{max}}$ and $\alpha > 0.5$, the new expression for the equipartition magnetic field is

$$B'_{\mathrm{eq}} \sim 1.1\gamma_{\mathrm{min}}^{\frac{1-2\alpha}{3+\alpha}} B_{\mathrm{eq}}^{\frac{7}{2(3+\alpha)}}, \tag{9}$$

where B_{eq} is the equipartition magnetic field expressed in Gauss derived through (8). Typically, for $B_{\mathrm{eq}} \sim \mu$G, $\gamma_{\mathrm{min}} \sim 100$ and $\alpha \sim 0.75$–1, this new approach gives magnetic field values 2 to 5 times larger than the standard method.

Estimates of equipartition fields on scales as large as ∼1 Mpc give magnetic field intensities in the range 0.1–1 μG. As we have seen, these estimates are based on several assumptions both on different physical properties of the radio emitting region (e.g., the filling factor Φ and the ratio between electron and proton energies k), and on the condition of minimum energy of the observed relativistic plasma. Since the validity of these assumptions is not obvious, one has to be aware of the uncertainties and thus of the limits inherent to the equipartition determination of magnetic fields.

4.2 Compton Scattering of CMB Photons

As reviewed by Rephaeli et al. (2008—Chap. 5, this issue), 3K microwave background photons can be subject to Compton scattering by electrons in the cluster volume. If the presence of thermal particles in the ICM results in a distortion of the Cosmic Microwave Background (CMB) spectrum well known as “Sunyaev-Zel’dovich effect” (Sunyaev and Zel’dovich 1972), non-thermal hard X-ray (HXR) photons are produced via Compton scattering by the same cosmic rays that are responsible for the synchrotron emission observed at radio wavelengths. Compton scattering increases the frequency of the incoming photon through

$$\nu_{\mathrm{out}} = \frac{4}{3}\gamma^2\nu_{\mathrm{in}}. \tag{10}$$

The Planck function of the CMB peaks at $\nu_{\rm in} \sim 1.6 \times 10^{11}$ Hz. Based on (10), for typical energies of relativistic electrons in clusters ($\gamma \sim 1000$–5000), the scattered photons fall in the X-ray and gamma-ray domain ($\sim 2 \times 10^{17}$–5×10^{18} Hz, i.e. ~ 0.8–20.7 keV).

Non-thermal HXR emission from galaxy clusters due to Compton scattering of CMB photons was predicted more than 30 years ago (e.g., Rephaeli 1977) and has now been detected in several systems (Rephaeli et al. 2008—Chap. 5, this issue; Fusco-Femiano et al. 2007 and references therein). Alternative interpretations to explain the detected non-thermal X-ray emission have been proposed in the literature (Blasi and Colafrancesco 1999; Enßlin et al. 1999; Blasi 2000; Dogiel 2000; Sarazin and Kempner 2000). However, these hypotheses seem to be ruled out by energetic considerations, because of the well known inefficiency of the proposed non-thermal Bremsstrahlung (NTB) mechanism. NTB emission of keV regime photons with some power P immediately imply about 10^5 times larger power to be dissipated in the plasma that seems to be unrealistic in a quasi-steady model (Petrosian 2001, 2003). For a more detailed treatment of the origin of HXR emission from galaxy clusters, see the review by Petrosian et al. (2008—Chap. 10, this issue).

The detection of non-thermal HXR and radio emission, produced by the same population of relativistic electrons, allows us to estimate unambiguously the volume-averaged intracluster magnetic field. Following the exact derivations by Blumenthal and Gould (1970), the equations for the synchrotron flux $f_{\rm syn}$ at the frequency ν_R and the Compton X-ray flux $f_{\rm C}$ at the frequency ν_X are

$$f_{\rm syn}(\nu_R) = \frac{\Phi V}{4\pi {D_{\rm L}}^2} \frac{4\pi {\rm e}^3}{(m_{\rm e}{\rm c}^2)^{\delta}} N_0 B^{\frac{\delta+1}{2}} \left(\frac{3{\rm e}}{4\pi m_{\rm e}{\rm c}}\right)^{\frac{\delta-1}{2}} a(\delta) \nu_R^{-\frac{\delta-1}{2}}, \tag{11}$$

$$f_{\rm C}(\nu_X) = \frac{\Phi V}{4\pi {D_{\rm L}}^2} \frac{8\pi^2 {\rm r}_0^2}{{\rm c}^2} {\rm h}^{-\frac{\delta+3}{2}} N_0 (m_{\rm e}{\rm c}^2)^{(1-\delta)} ({\rm k}T)^{\frac{\delta+5}{2}} F(\delta) \nu_X^{-\frac{\delta-1}{2}}. \tag{12}$$

Here h is the Planck constant, V is the volume of the source and Φ the filling factor, $D_{\rm L}$ is the luminosity distance of the source, B the magnetic field strength, T the radiation temperature of the CMB, ${\rm r}_0$ the classical electron radius (or Thomson scattering length), N_0 and δ are the amplitude and the spectral index of the electron energy distribution (1). The values of the functions $a(\delta)$ and $F(\delta)$ for different values of δ can be found in Blumenthal and Gould (1970). The field B can thus be estimated directly from these equations

$$B \propto \left(\frac{f_{\rm syn}(\nu_R)}{f_{\rm C}(\nu_X)}\right)^{\frac{2}{\delta+1}} \left(\frac{\nu_R}{\nu_X}\right)^{\frac{\delta-1}{\delta+1}}. \tag{13}$$

Typical cluster magnetic field values of ~ 0.1–0.3 μG are obtained (e.g., Rephaeli et al. 1999; Fusco-Femiano et al. 1999, 2000, 2001; Rephaeli and Gruber 2003; Rephaeli et al. 2006). Compared to equipartition measures, this method has the great advantage of using only observables, assuming only that the spatial factors in the expressions for the synchrotron and Compton fluxes (Rephaeli 1979) are identical.

4.3 Faraday Rotation Measure

Faraday rotation analysis of radio sources in the background or in the galaxy clusters themselves is one of the key techniques used to obtain information on the cluster magnetic fields. The presence of a magnetised plasma between an observer and a radio source changes the properties of the polarised emission from the radio source. Therefore information on cluster magnetic fields along the line-of-sight can be determined, in conjunction with X-ray observations of the hot gas, through the analysis of the Rotation Measure (RM) of radio sources (e.g., Burn 1966).

The polarised synchrotron radiation coming from radio galaxies undergoes the following rotation of the plane of polarisation as it passes through the magnetised and ionised intracluster medium

$$\Psi_{\rm Obs}(\lambda) = \Psi_{\rm Int} + \lambda^2 \times RM, \tag{14}$$

where $\Psi_{\rm Int}$ is the intrinsic polarisation angle, and $\Psi_{\rm Obs}(\lambda)$ is the polarisation angle observed at a wavelength λ. The RM is related to the thermal electron density ($n_{\rm e}$), the magnetic field along the line-of-sight ($B_{\|}$), and the path-length (L) through the intracluster medium according to

$$RM_{[\rm rad\,m^{-2}]} = 812 \int_0^{L_{[\rm kpc]}} n_{\rm e\,[cm^{-3}]} B_{\|\,[\mu \rm G]}\,{\rm d}l. \tag{15}$$

Polarised radio galaxies can be mapped at several frequencies to produce, by fitting (14), detailed RM images. Once the contribution of our Galaxy is subtracted, the RM should be dominated by the contribution of the intracluster medium, and therefore it can be used to estimate the cluster magnetic field strength along the line of sight.

The RM observed in radio galaxies may not be all due to the cluster magnetic field if the RM gets locally enhanced by the intracluster medium compression due to the motion of the radio galaxy itself. However a statistical RM investigation of point sources (Clarke et al. 2001; Clarke 2004) shows a clear broadening of the RM distribution toward small projected distances from the cluster centre, indicating that most of the RM contribution comes from the intracluster medium. This study included background sources, which showed similar enhancements as the embedded sources.

We also note that there are inherent uncertainties in the determination of field values from Faraday Rotation measurements, stemming largely from the unknown small-scale tangled morphology of intracluster fields, their large-scale spatial variation across the cluster, and from the uncertainty in modelling the gas density profile (see, e.g., Goldshmidt and Rephaeli 1993; Newman et al. 2002; Rudnick and Blundell 2003a; Enßlin et al. 2003; Murgia et al. 2004).

RM studies of radio galaxies have been carried out on both statistical samples (e.g., Lawler and Dennison 1982; Vallée et al. 1986; Kim et al. 1990, 1991; Clarke et al. 2001) and individual clusters by analysing detailed high resolution RM images (e.g., Perley and Taylor 1991; Taylor and Perley 1993; Feretti et al. 1995, 1999; Govoni et al. 2001a; Taylor et al. 2001; Eilek and Owen 2002; Govoni et al. 2006; Taylor et al. 2007; Guidetti et al. 2008). Both for interacting and relaxed (cooling flow) clusters the RM distribution of radio galaxies is generally patchy, indicating that cluster magnetic fields have structures on scales as low as 10 kpc or less. RM data are usually consistent with central magnetic field strengths of a few μG. But, radio galaxies at the centre of relaxed clusters have extreme RM, with the magnitude of the RM roughly proportional to the cooling flow rate (see Fig. 6). Strong magnetic fields are derived in the high density cooling-core regions of some clusters, with values exceeding ∼10 μG (e.g., in the inner region of Hydra A, a value of ∼35 μG was deduced by Taylor et al. 2002). It should be emphasised that such high field values are clearly not representative of the mean fields in large extended regions.

Dolag et al. (2001b) showed that, in the framework of hierarchical cluster formation, the correlation between two observable parameters, the RM and the cluster X-ray surface brightness in the source location, is expected to reflect a correlation between the cluster magnetic

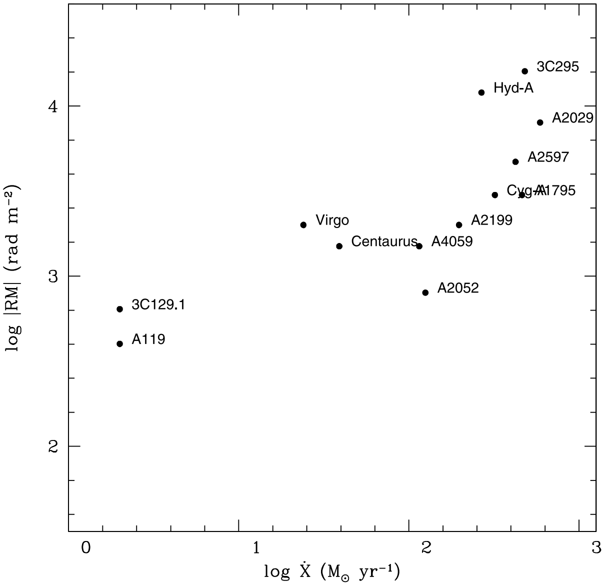

Fig. 6 RM magnitudes of a sample of radio galaxies located in cooling flow clusters, plotted as a function of the cooling flow rate $\dot{X}$ (from Taylor et al. 2002)

field and gas density. Therefore, from the analysis of the RM versus X-ray brightness it is possible to infer the trend of magnetic field versus gas density.

On the basis of the available high quality RM images, increasing attention is given to the power spectrum of the intracluster magnetic field fluctuations. Several studies (Enßlin and Vogt 2003; Murgia et al. 2004) have shown that detailed RM images of radio galaxies can be used to infer not only the cluster magnetic field strength, but also the cluster magnetic field power spectrum. The analyses of Vogt and Enßlin (2003, 2005) and Guidetti et al. (2008) suggest that the power spectrum is of the Kolmogorov type, if the auto-correlation length of the magnetic fluctuations is of the order of few kpc. However, Murgia et al. (2004) and Govoni et al. (2006) pointed out that shallower magnetic field power spectra are possible if the magnetic field fluctuations extend out to several tens of kpc.

4.4 Comparison of the Different Methods

As shown in Table 3 of Govoni and Feretti (2004), the different methods available to measure intracluster magnetic fields show quite discrepant results (even more than a factor 10). RM estimates are about an order of magnitude higher than the measures derived both from the synchrotron diffuse radio emission and the non-thermal hard X-ray emission ($\sim$1–5 μG vs. $\sim$0.2–1 μG).

This can be due to several factors. Firstly, equipartition values are severely affected by the already mentioned physical assumptions of this method. Secondly, while RM estimates give a weighted average of the field along the line of sight, equipartition and Compton scattering measures are made by averaging over larger volumes. Additionally, discrepancies can be due to spatial profiles of both the magnetic field and the gas density not being constant all over the cluster (Goldshmidt and Rephaeli 1993), or due to compressions, fluctuations and inhomogeneities in the gas and in the magnetic field, related to the presence of radio galaxies or to the dynamical history of the cluster (e.g., on-going merging events) (Beck et al. 2003; Rudnick and Blundell 2003b; Johnston-Hollitt 2004). Finally, a proper modelling of the Compton scattering method should include a) the effects of aged electron spectra,

b) the expected radial profile of the magnetic field, and c) possible anisotropies in the pitch angle distribution of electrons (Brunetti et al. 2001; Petrosian 2001).

An additional method of estimating cluster magnetic fields comes from the X-ray analysis of cold fronts (Vikhlinin et al. 2001). These X-ray cluster features, discovered by Markevitch et al. (2000) thanks to the exquisite spatial resolution of the *Chandra* satellite, result from dense cool gas moving with near-sonic velocities through the less dense and hotter ICM. Cold fronts are thus subject to Kelvin-Helmholtz (K-H) instability that, for typical cluster and cold front properties (Mach number, gas temperatures, cluster-scale length), could quickly disturb the front outside a narrow ($\lesssim 10^\circ$) sector in the direction of the cool cloud motion.[5] Through the *Chandra* observation of A 3667, Vikhlinin et al. (2001) instead revealed a cold front that is stable within a $\pm 30^\circ$ sector. They showed that a ~ 10 μG magnetic field oriented nearly parallel to the front is able to suppress K-H instability, thus preserving the front structure, in a $\pm 30^\circ$ sector. The estimated magnetic field value, significantly higher than the typical measures given by the other methods outside cluster cooling flows, is likely an upper limit of the absolute field strength. Near the cold front the field is actually amplified by tangential gas motions (see Vikhlinin et al. 2001).

Variations of the magnetic field structure and strength with the cluster radius have been recently pointed out by Govoni et al. (2006). By combining detailed multi-wavelength and numerical studies we will get more insight into the strength and structure of intracluster magnetic fields, and into their connection with the thermodynamical evolution of galaxy clusters. More detailed comparisons of the different approaches for measuring intracluster magnetic fields can be found, for instance, in Petrosian (2003) and Govoni and Feretti (2004).

5 Diffuse Radio Emission in Galaxy Clusters: Open Questions and Perspectives

Significant progress has been made recently in our knowledge on the non-thermal component of galaxy clusters. A number of open questions arise in assessing the current theoretical and observational status.

First of all, we need to test the current theories on the origin of the large-scale non-thermal component in clusters (magnetic field and cosmic rays). If at present primary models seem to be the favourite acceleration mechanisms for intracluster electrons, secondary models cannot be ruled out. Among other things, it will be necessary to establish: How common is the non-thermal component in clusters? Is it really hosted *only* in merging systems (as present observational results suggest) or do *all* clusters have a radio halo/relic? If this latter hypothesis is correct, how should we modify the radio power versus X-ray luminosity correlation (Sect. 2.1)? If shocks and turbulence related to cluster mergers are instead the mechanisms responsible for electron re-acceleration, why have extended radio sources not been detected in *all* merging clusters? Is this related to other physical effects (i.e. the merging event alone is not enough to produce intracluster cosmic rays), as the correlation between radio power and cluster mass seems to indicate, or it is due to a lack of sensitivity of the current instruments (i.e. all merging clusters host radio halos and relics, but a large fraction of these sources lies below the sensitivity limit of present telescopes)?

Among the previous questions, the most difficult to answer *at present* are those that involve the study of low-luminous X-ray clusters, for which the limits of current radio

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[5] For a more precise treatment, see Vikhlinin et al. (2001) and Markevitch and Vikhlinin (2007).

observations are particularly severe. By extrapolating to low radio and X-ray luminosity the P_ν–L_X relation (Sect. 2.1), Feretti and Giovannini (2008) have estimated that, if present, halos with typical sizes of 1 Mpc in intermediate/low-luminous X-ray clusters ($L_{X[0.1-2.4\ \mathrm{keV}]} \lesssim 5 \times 10^{44}\ \mathrm{h}_{70}^{-2}\ \mathrm{erg\ s}^{-1}$)[6] would actually have a radio surface brightness lower than the current limits obtained in the literature and in the NVSS. At higher X-ray luminosities, more constraints on radio halo statistics have recently been obtained by Venturi et al. (2007) and Brunetti et al. (2007). They carried out GMRT[7] observations at 610 MHz of 34 luminous ($L_{X[0.1-2.4\ \mathrm{keV}]} \gtrsim 5 \times 10^{44}\ \mathrm{h}_{70}^{-2}\ \mathrm{erg\ s}^{-1}$) clusters with $0.2 \lesssim z \lesssim 0.4$. The bulk of the galaxy clusters in their sample does not show any diffuse central radio emission, with radio luminosity upper limits that are well below the P_ν–L_X relation derived from the previously known radio halos. The net bimodality of the cluster distribution in the P_ν–L_X plane support primary models against secondary models. Actually, the former predict a relatively fast ($\approx 10^8$ yrs) transition of clusters from a radio quiet state to the observed P_ν–L_X correlation, where they remain for $\lesssim 1$ Gyr. A significantly wider scatter around the P_ν–L_X correlation is instead expected in the frame of secondary models, that could be reconciled with observations only assuming the existence of strong dissipation of magnetic fields in clusters (see Brunetti et al. 2007, and references therein).

On smaller scales, a larger sample of radio mini-halos is required to test the current theories on the origin of radio emission in this class of sources (Gitti et al. 2002; Pfrommer and Enßlin 2004). Recent results suggest that cooling flows and mergers could act simultaneously, when they co-exist, in providing energy to the relic population of relativistic electrons injected into the ICM by AGNs, thus powering mini-halo radio emission (Gitti et al. 2007a).

As discussed in Sect. 4, radio observations of galaxy clusters offer a unique tool to estimate strength and structure of large-scale magnetic fields, allowing to test the different scenarios of their origin. Several observational results show that magnetic fields of the order of $\sim\mu$G are common in clusters. Through combined numerical and observational analyses, Murgia et al. (2004) and Govoni et al. (2006) have shown that detailed morphology and polarisation information of radio halos may provide important constraints on the strength and structure of intracluster magnetic fields. However, discrepant results have been obtained up to now (Sect. 4.4) and more detailed information on magnetic fields is still needed.

A better knowledge of the physics of the non-thermal component in galaxy clusters will have important cosmological implications. If it will be confirmed that the presence of giant halos and relics is related to cluster mergers, the statistical properties of these radio sources will allow us to test the current cluster formation scenario, giving important hints on large-scale structure formation and, thus, cosmological parameters (e.g., Evrard and Gioia 2002).

Additionally, we will be able to estimate how the gravitational energy released during cluster mergers is redistributed between the thermal ICM and the relativistic plasma (e.g., Sarazin 2005). The effects of magnetic fields on the thermodynamical evolution of large-scale structures will be evaluated, as well as the contribution of the non-thermal pressure to the estimate of mass and temperature in galaxy clusters (e.g., Dolag and Schindler 2000; Dolag et al. 2001a; Colafrancesco et al. 2004). Cluster scaling laws, such as mass vs. temperature, are actually key ingredients to derive cosmological constraints from galaxy clusters (e.g., Ettori et al. 2004; Arnaud et al. 2005).

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[6] Converted from the bolometric X-ray luminosity limit in Feretti and Giovannini (2008) to the 0.1–2.4 keV band luminosity using Table 5 of Böhringer et al. (2004) and assuming typical ICM temperature values ($T_X \sim 5$–10 keV).

[7] The Giant Metrewave Radio Telescope (GMRT) is operated by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research (NCRA-TIFR).

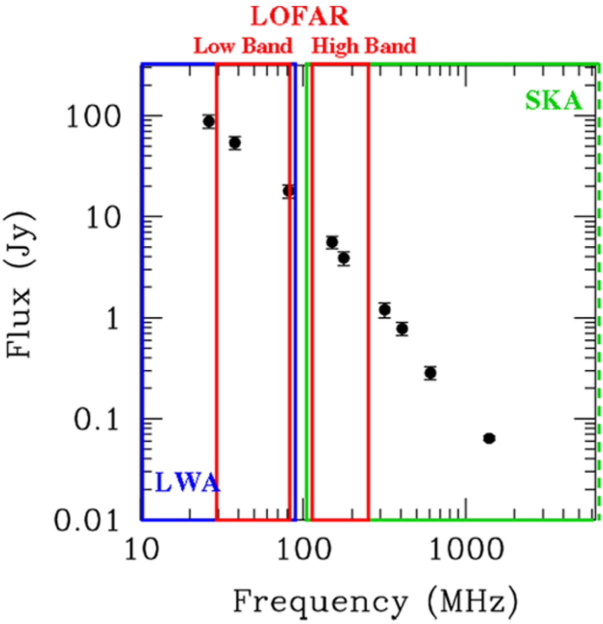

Fig. 7 Spectrum of the diffuse radio source in A 1914 (from Bacchi et al. 2003). Superimposed the frequency range covered by LWA (10–88 MHz, *in blue*), LOFAR (Low Band: 30–80 MHz, High Band: 110–240 MHz, *in red*) and SKA (100–25 GHz, *in green*). The low-frequency domain covered by the next generation radio-telescopes is optimal for the detection of high spectral index radio sources, such as radio halos, mini-halos and relics

Finally, a better knowledge of extended radio sources in clusters is indeed essential for complementary cosmological studies, e.g., the epoch of re-ionisation (EoR). It has been proven that radio halos and relics are the strongest extra-galactic foreground sources to be removed in order to probe the EoR through the study of the redshifted 21 cm emission from neutral hydrogen (e.g., Di Matteo et al. 2004). Better models for the diffuse radio emission have to be inserted into numerical simulations of the EoR 21 cm emission, in order to understand how to remove efficiently the contamination due to radio halos and relics.

An increase in the number of known radio halos/relics, as well as higher resolution and sensitivity observations, are essential to answer the main open questions, summarised at the beginning of this section, about the nature of diffuse radio emission in clusters. As shown in Fig. 7, halos and relics are difficult to detect in the GHz range due to their steep spectra. Several observations performed with the currently available low-frequency instruments (e.g., GMRT: Venturi et al. 2007; VLA: Kassim et al. 2001; Orrù et al. 2007) confirm the interest in studying this class of radio sources at high wavelengths. A short term perspective in the study of radio halos and relics is thus to fully exploit those instruments that are already available for observations in the MHz range of the electromagnetic spectrum with good enough sensitivity (approximately from some tens of μJy/beam to some mJy/beam) and angular resolution (roughly some tens of arcsec). However, in order to make a proper comparison between observational results and current theoretical models about the origin of radio halos and relics, we need multi-frequency observations of *statistical* samples of diffuse radio sources. Current telescopes require too long exposure-time per cluster ($\gtrsim$1–2 hours) to reach the sensitivity limits necessary for detecting radio halos/relics, making statistical analyses of diffuse radio emission in clusters extremely time-demanding.

The low-frequency range covered by a new generation of radio telescopes (Long Wavelength Array—LWA; Low Frequency Array—LOFAR; Square Kilometre Array—SKA), together with their gain in sensitivity and resolution, will increase dramatically the statistics on the number of known radio halos and relics. Not only these instruments will cover the optimal frequency range for halo/relic detection (see Fig. 7), but also their gain in sensitivity and resolution will be of the order of 10 to 1000 (see Table 2 of Brüggen et al. 2005), allowing observations of statistical samples of diffuse and extended radio sources. A LOFAR survey at 120 MHz, covering half the sky to a 5 σ flux limit of 0.1 mJy (1 hour integration time per pointing), could detect $\sim$1000 halos/relics, of which 25% at redshift larger than $z \sim 0.3$ (Röttgering 2003). Feretti et al. (2004b) have estimated that, with 1 hour integration time at 1.4 GHz, 50% of the SKA collecting area will allow us to detect halos and relics of total flux down to 1 mJy at any redshift, and down to 0.1 mJy at high redshift. Based on our current knowledge, more than three (fifteen) hundred diffuse cluster radio sources are expected at 1.5 GHz on the full sky at the 1 mJy (0.1 mJy) flux limit (Enßlin and Röttgering 2002).

With statistical samples of halos and relics over a wide redshift range, we will be able to a) test the correlation between the non-thermal component and the physical properties of clusters (dynamical state, mass, X-ray luminosity and temperature . . .), b) analyse the redshift evolution of halos and relics, with the advantages for cosmological studies stressed above, and c) fill the gap in our knowledge of the last phases of radio galaxy evolution in clusters (see Sect. 2.3). Particularly interesting will be the study of possible presence of non-thermal radio emission at $z \sim 1$, i.e. the epoch of formation of the massive galaxy clusters observed in the local Universe.

The excellent sensitivity, high angular resolution and large number of spectral channels of the next generation instruments, together with new techniques of RM synthesis (Brentjens and de Bruyn 2005), will allow polarisation mapping and RM studies of radio emission in clusters, significantly improving our estimates of large-scale magnetic fields.

Future radio observations of galaxy clusters, combined with the new generation instruments at other wavelengths[8] (e.g., sub-mm: ALMA; X-ray: XEUS, Simbol-X; gamma-rays: GLAST, H.E.S.S., MAGIC;[9] . . .), will allow us to open a new window in cosmological studies.

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[8] See also Paerels et al. (2008—Chap. 19, this issue).

[9] A new generation of ground based imaging Cherenkov telescopes will be available soon. The measurements above 10 TeV are crucial to distinguish between the Compton scattering and hadronic origins of gamma-ray emission from clusters of galaxies.

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