Mem. S.A.It. Vol. 79, 176

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Radio emission in clusters and connection to X-ray emission

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Abstract. The most spectacular aspect of cluster radio emission is represented by the large-scale diffuse radio sources, which cannot be obviously associated with any individual galaxy. These sources demonstrate the existence of relativistic particles and magnetic fields in the cluster volume, thus indicating the presence of non-thermal processes in the hot intracluster medium. The knowledge of the properties of these sources has increased significantly in recent years, owing to sensitive radio images and to the development of theoretical models. An important piece of information on the origin and evolution of these sources can be obtained by the cluster X-ray emission of thermal origin, and by its relation to the radio emission. Moreover, non-thermal X-ray emission of inverse Compton origin gives direct information on the energy density of radio emitting particles and the intensity of magnetic field.

Key words. Galaxy clusters – Cluster formation – Intracluster matter; cooling flows – Radio sources – Cosmic rays

1. Introduction

The presence of diffuse radio emission in clusters of galaxies demonstrates the existence of new components of the intracluster medium (ICM), in addition to the hot gas: these are non-thermal components, consisting of cluster-wide magnetic fields of the order of $\sim$ 0.1-1 μG, and of a population of relativistic electrons with Lorentz factor $\gamma >> 1000$. The knowledge of the properties of non-thermal components is crucial for a comprehensive physical description of the intracluster medium in galaxy clusters.

The diffuse radio emission shows different phenomenology depending on the cluster evolutionary state: radio halos and relics are detected in clusters which have recently undergone a merger event, while mini-halos are associated with cooling core relaxed clusters. In these clusters, moreover, powerful radio sources detected at the center often show low brightness radio features filling cavities in the X-ray gas. This represents a striking example of the interaction between thermal and relativistic plasma.

The cluster dynamical activity plays an important role in the formation and evolution of diffuse radio sources, thus the information in the X-ray band is needed to analyze the interplay between the thermal and non-thermal emission. I will describe here the current knowledge about non-thermal components of the ICM, with particular emphasis on the in-

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formation which is derived from observations in the X-ray band.

2. Radio sources

2.1. Radio halos

Radio halos are diffuse radio sources of low surface brightness permeating the central volume of a cluster. They are typically extended, with sizes $\gtrsim$ 1 Mpc, and are unpolarized down to a few percent level, except in A2255, where polarized filaments have been observed at 20%-40% level (Govoni et al. 2005). An example of a recently detected giant radio halo is in the cluster A209 (Fig. 1, Giovannini et al. 2006). Radio halos are typically found in clusters showing features which are indication of merging processes, i.e. significant substructure, deviation from spherical symmetry in the X-ray morphology, and strong gas temperature gradients (Feretti 2005). However, not all merging clusters show giant radio halos. Radio halos are present in rich clusters, characterized by high X-ray luminosities and temperatures. Their detection rate at the detection limit of the NRAO VLA Sky Survey (NVSS) is $\sim$ 5% (Giovannini et al. 1999). The detection rate increases with X-ray luminosity to $\sim$ 35% for clusters with X-ray luminosity larger than $10^{45}h_{50}^{-2}$ erg s^{-1} (0.1-2.4 keV) (Giovannini & Feretti 2002).

There are several correlation between the radio halo parameters and parameters related to the X-ray emission of the host cluster:

i) the radio power of a halo correlates with the cluster X-ray luminosity and consequently with the gas temperature and the total mass (see recent results in Cassano et al. 2006). At present, it is not clear if X-ray bright merging clusters with no radio halo have peculiar physical properties which do not allow the formation of a radio halo, or if they host faint halos, undetected with the current observational resources;

ii) in a number of well-resolved clusters, a point-to-point spatial correlation is observed between the radio brightness of the halo and the X-ray brightness as detected by *ROSAT* (Govoni et al. 2001, Feretti et al. 2001): a higher X-ray brightness is associated with a higher radio brightness. This correlation is found also using *Chandra* high resolution data (Kempner & David 2004, Giacintucci et al. 2005). This indicates that morphological features detected in X-rays are strickingly similar to those found in radio, confirming the connection between hot and relativistic plasma;

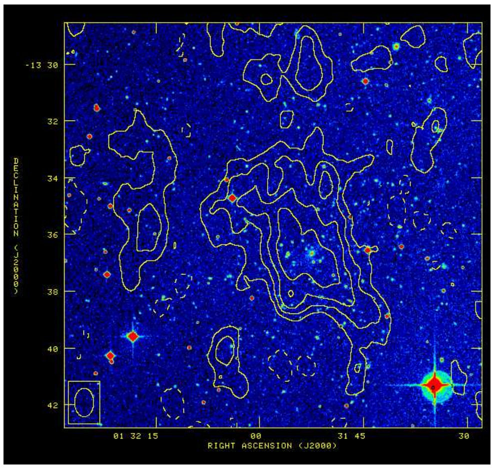

Fig. 1. The giant radio halo in A209 (contours) overlayed onto the optical map from the DSS (color). See Giovannini et al. (2006).

iii) the integrated radio spectra of halos are steep ($\alpha \gtrsim 1$, with $S(\nu) \propto \nu^{-\alpha}$), with a steepening at higher frequencies, as typically found in aged radio sources. In the clusters where maps of the spectral index are available, the radio spectrum steepens radially with the distance from the cluster center (Giovannini et al. 1993, Feretti et al. 2004, Orru' et al. 2007). In addition, it is found that the spectrum in A665 and A2163 is flatter in the regions influenced by merger processes (Feretti et al. 2004). In A2744, Orru' et al. (2007) showed that the region of highest gas temperature is associated with the flat spectrum clump of the radio halo, and that, in general, steep spectrum regions correlate with lower temperature regions.

All the above correlations favour the idea that a fraction of the gravitational energy which is dissipated during mergers is supplied to the halo, for the reacceleration of relativistic particles and amplification of magnetic field. Current observations are consistent with the scenario that turbulence following a cluster shock might be the major mechanism responsible for the supply of energy to the electrons radiating in radio halos. Numerical simulations indicate that mergers can generate strong fluid turbulence on scales of 0.1 - 1 Mpc. The time during which the process is effective is of $\sim 10^8$ years, so that the emission is expected to correlate with the most recent or ongoing merger event. Recent theoretical developments of this aspect can be found in Blasi 2004, Brunetti et al. (2004), Cassano & Brunetti (2005).

2.2. Radio relics

Relic sources are diffuse extended sources similar to the radio halos in their low surface brightness, large size ($\gtrsim$ 1 Mpc) and steep spectrum ($\alpha \gtrsim$ 1), but they are generally detected in the cluster peripheral regions. They typically show an elongated radio structure with the major axis roughly perpendicular to the direction of the cluster radius, and they are strongly polarized (~ 20-30%). A spectacular example of two likely related relics in the same cluster is found in A548b (Fig. 2, Feretti et al. 2006).

The detection rate of radio relics is ~ 6%, in a complete sample of clusters (Giovannini & Feretti 2002) at the detection limit of the NVSS. Relics are found in clusters both with and without a cooling core, suggesting that they may be related to minor or off-axis mergers, as well as to major mergers. The radio power of relics correlates with the cluster X-ray luminosity (Giovannini & Feretti 2004), as found for halos, although with a larger dispersion. The existence of this correlation indicates a link between the thermal and relativistic plasma also in peripheral cluster regions.

Current theoretical models propose that relativistic particles radiating in radio relics are powered by energy dissipated in shock waves produced in the ICM during merger events. This is consistent with their elongated structure, almost perpendicular to the merger axis. This picture is supported by numerical simulations on cluster mergers (Ricker & Sarazin 2001, Ryu et al. 2003), which predict that shocks forming at the cluster center at the early

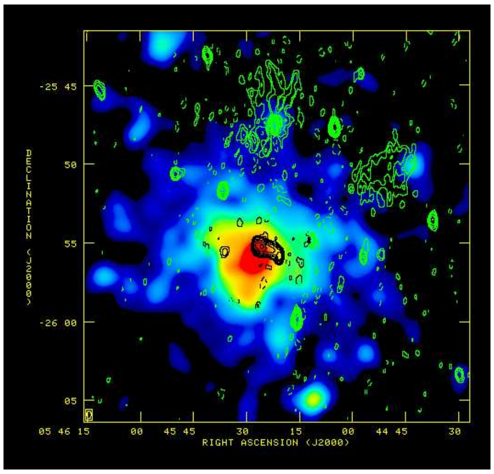

Fig. 2. Image of the radio relics in A548b (contours) overlayed onto the cluster X-ray emission from *ROSAT* (color). See Feretti et al. (2006).

stages of a cluster merger further propagate to the cluster periphery. It should be also mentioned the possibility that relics may be tracers of cosmic shock waves related to the large-scale structure formation process, as suggested by Bagchi et al. (2006) for A3376.

2.3. Mini-halos

Mini-halos are small size (~ 500 kpc) diffuse radio sources at the center of cooling core clusters, usually surrounding a powerful radio galaxy, as in the Perseus cluster (Sijbring 1993). The radio spectra of mini-halos are steep, as those of halos and relics. In the Perseus mini-halo, the integrated spectrum steepens at high frequency and the spectral index distribution shows a radial steepening (Sijbring 1993).

Gitti et al. (2002) argued that the radio emitting particles in mini-halos cannot be connected to the central radio galaxy in terms of particle diffusion or buoyancy, but they are likely associated with the ICM in the cooling flow region. The correlation observed between the mini-halo radio power and the cooling flow power supports the idea that the mini-halos are powered by the energy of the cooling flow (Gitti et al. 2007 and references therein).

A mini-halo has recently been detected in the most X-ray-luminous cluster RX J1347.5-1145, characterized by a massive cooling flow (Gitti et al. 2007). This cluster follows the above correlation. In addition, it is found that the diffuse radio emission shows and elongation coincident with the position of a hot subclump detected in X-rays. Thus it is argued that additional energy for the electron reacceleration might be provided in this cluster mini-halo by the sub-merger event.

2.4. Radio sources in X-ray cavities

A clear example of the interaction between the radio plasma and the hot intracluster medium was found in the *ROSAT* image of the Perseus cluster (Böhringer et al. 1993), where X-ray cavities associated with the inner radio lobes of the bright central radio galaxy 3C84 have been first detected. The high spatial resolution of *Chandra* has confirmed the presence of such X-ray holes (Fabian et al. 2000), coinciding with the radio lobes and showing rims cooler than the surrounding gas. *Chandra* has permitted the detection of X-ray deficient bubbles in the inner region of many cooling flow clusters (see e.g. Birzan et al. 2004). A spectacular example of a radio source filling X-ray cavities is detected in the cluster RBS797 (Fig. 3, Gitti et al. 2006).

The X-ray emission in the cores of relaxed galaxy clusters is sharply peaked and the radiative cooling time is much shorter than the likely age of the systems, implying the establishement of a cooling flow toward the cluster center. However, *Chandra* and *XMM-Newton* spectra have shown that the effective cooling rate is greatly reduced, thus some heating process must be taking place. The AGN in the central galaxy is the most viable mechanism for heating the core regions of clusters. Indeed, most of the dominant galaxies have active radio sources, which are obviously blowing bubbles of relativistic plasma in the central X-ray gas, mostly in the form of mechanical energy in jets.

To investigate the energy exchange between the central galaxy and the cooling gas, a detailed radio - X-ray study is needed.

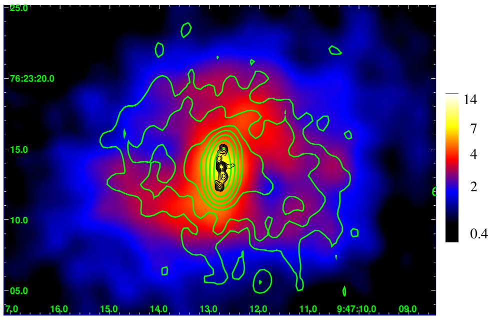

Fig. 3. Radio emission in RBS797 (contours) filling X-ray cavities as detected by *Chandra*. Note that the innermost radio jets are oriented almost perpendicularly to the extended radio emission (Gitti et al. 2006).

Moreover, the radio bubbles are magnetized. It is expected that when they get mixed with the IGM, they are likely to contribute to the intracluster magnetic field.

3. Cluster magnetic fields

The existence of ICM magnetic fields, directly demonstrated by the diffuse synchrotron radio emission, can also be proved by studies of the Faraday rotation measure (RM) of polarized radio sources both within and behind clusters. Since the RM is related to the cluster electron density $n_{\rm e}$, and to the magnetic field $B_{\|}$ along the line of sight l , through the relation: $\mathrm{RM} \propto \int_0^L n_{\rm e} B_{\|} dl$, the interpretation of RM data, and consequently the inference of the magnetic field strenght, relies on the determination of the density of the ionized medium along the line of sight, which is obtained from X-ray data.

Overall, the data are consistent with cluster atmospheres containing magnetic fields in the range of 1-5 μG, regardless of the presence or not of diffuse radio emission (see Govoni & Feretti 2004 for a review). At the center of cooling core clusters, magnetic field strenghts can be much larger, up to a few tens μG. Magnetic fields, however, are not constant and uniform through the cluster, thus the magnetic field structure, coherence lenght, radial decline, relation between magnetic field strenght and gas density must be investigated.

Detailed and sensitive RM data, which will be obtained with future generation radio telescopes, will be of little use without the X-ray information. Future X-ray maps of the X-ray sky at low energies will provide a precise knowledge of the X-ray surface brightness of clusters, i.e. of their thermal gas density, allowing the accurate and correct interpretation of the sensitive RM measurements.

4. Non-thermal X-ray emission

Non-thermal phenomena can be directly studied in the X-ray band, through the detection of X-ray inverse Compton emission due to the scattering between the radio-emitting electrons and the CMB photons. This emission falls in the hard X-ray domain, owing to the very high energy of radio emitting electrons ($\gamma \sim 10^4$). Since the X-ray and radio emissions are produced by the same population of electrons undergoing inverse Compton and synchrotron energy losses, respectively, the ratio between the X-ray and the radio luminosities is proportional to the ratio between the CMB and the magnetic field energy densities. Thus the comparison between radio and hard X-ray emission enables the determination of the electron density and of the mean magnetic field directly, without invoking the equipartition assumptions needed for the determination of these parameters from radio data.

A significant breakthrough in the measurement of hard X-ray emission was obtained owing to the improved sensitivity and wide spectral capabilities of the BeppoSAX and the Rossi X-ray Timing Explorer (RXTE) satellites (see e.g. Fusco-Femiano et al. 2003, Govoni & Feretti 2004, and references therein). However, the data still refer to a handful of clusters. Measurements on large samples of objects will be crucial. In addition, images of the hard X-ray distribution will be particularly valuable to understand the origin of radiating electrons and check reacceleration models. Indeed, under the assumption of electron reacceleration, Brunetti et al. (2001) argue that most of the X-ray non-thermal emission in the Coma cluster is produced in the outer volume, i.e. between 30-50 arcmin from the cluster center. This is the region which contains the large majority of the relativistic electrons able to scatter the cosmic microwave background photons, and where the magnetic field strength is lower than at the center.

5. Future prospects

Diffuse radio emission demonstrating the existence of relativistic particles in the ICM is detected in both merging and relaxed clusters, although with different phenomenology. At the detection limits of the present radio telescopes, not all merging clusters show halos or relics, and not all cooling core clusters show mini-halos at their centers. Thus it is possible that there are two classes of clusters, those hosting relativistic particles and those without relativistic particles. Alternatively, relativistic particles may be quite common in the cluster volume, but more sensitivity is needed to detect their radio emission.

The study of the non-thermal processes in clusters is basically carried out at radio waveleghts, however the understanding of these phenomena strictly relies on the information at other wavelenths, from the optical to gamma-ray, with a large impact coming from the X-ray band. Future prospects to shed light on this field in the radio regime with next generation radio telescope (LOFAR, LWA, SKA) include: i) search for new sources of the different classes, in particular at low powers and at large redshifts, to improve the information on the statistical properties of cluster diffuse sources; ii) polarization information on halos to get direct information on the magnetic field structure and degree of ordering; iii) accurate integrated spectra on a large frequency range and detailed spectral index distributions at high resolution; iv) detailed knowledge of the magnetic field strength and structure, through rotation measure studies of embedded and background radio sources.

At the same time, observations in the X-ray will be crucial to: i) establish the cluster conditions, the merger evolutionary stage, the presence and properties of shocks, the signatures of cluster turbulence, and compare with radio structures and spectra; ii) get information on the faint peripheral cluster regions where relics are located; iii) compare radial profiles of the radio surface brightness and the X-ray brightness; iv) analyse correlations between radio power and cluster parameters (mass, X-ray luminosity, cooling flow power, etc.) on large samples and over a large range of parameters and at different redshifts, to compare with expectations from theoretical models; v) get accurate determinations of the X-ray gas density, for a correct inference of magnetic field strength and structure from RM data; v) obtain measurements and images of the non-thermal inverse Compton emission in the hard X-ray domain (particularly relevant here is SIMBOL-X) on several clusters, with and without diffuse emission, to get independent information on the existence of relativistic particles, and their location.

Acknowledgements. I am grateful to the organizers for the invitation to this interesting and fruitful meeting.

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