Diffuse radio emission from the Intracluster medium

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An important aspect of the radio emission from galaxy clusters is represented by the diffuse radio sources associated with the intracluster medium: radio halos, relics and mini-halos. The radio halos and relics are indicators of cluster mergers, whereas mini-halos are detected at the center of cooling core clusters. SKA will dramatically improve the knowledge of these sources, thanks to the detection of new objects, and to detailed studies of their spectra and polarized emission. SKA will also provide the opportunity to investigate the presence of halos produced by radiation scattered by a powerful radio galaxy at the cluster centers.

1. INTRODUCTION

The main component of the intracluster medium (ICM) in clusters of galaxies is represented by the X-ray emitting thermal plasma, which amounts to about 15-18% of the total gravitating mass of a cluster and consists of particles with energies of several keV. In addition, a fraction of galaxy clusters exhibit large-scale radio sources, which have no optical counterpart and no obvious connection to the cluster galaxies, and are therefore associated with the ICM. Their emission, of synchrotron origin, demonstrates the existence of relativistic electrons with energies of $\sim$ GeV in $\sim \mu$G magnetic fields.

The diffuse extended cluster radio sources are currently grouped in three classes: radio *halos*, *relics* and *mini-halos*. A typical example of a cluster radio halo is shown in Fig. 1. The radio halos are permeating the cluster central regions, with typical extent $\gtrsim$ 1 Mpc and steep spectrum. Limits of a few percent to their polarized emission have been derived. The relic sources are similar to the halos in their low surface brightness, large size and steep spectrum, but they are typically found in the cluster peripheral regions (see Fig. 2). Unlike halos, relics are highly polarized ($\sim$ 20%). The mini-halos are detected around a dominant powerful radio galaxy at the center of cooling core clusters, for a total size of $\sim$ 500 kpc, as in the Perseus cluster (Fig. 3).

The importance of the diffuse cluster sources is that they are large scale features which are related to other cluster properties in the optical and X-ray domain and are thus directly connected to the cluster history and evolution. These radio sources are difficult to detect because of their low radio surface brightness and steep spectrum. Future generation instruments, as the SKA, will be crucial to study these sources at multiple frequencies and in polarization, and to establish how common these ICM non-thermal components are in all clusters.

Another interesting aspect of the ICM emission is represented by the *Thomson scattering halos* produced at the center of cooling core clusters where a strong radio galaxy is present. These halos have not been detected so far, and thus represent an important target for the SKA observations.

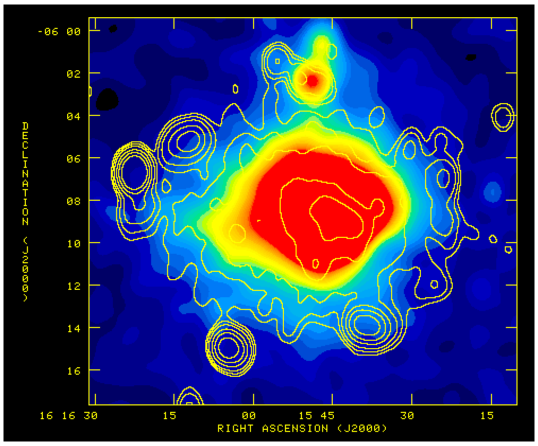

Figure 1. The cluster A2163 in radio and X-ray. The contours represent the radio emission in A2163 at 20 cm, showing an extended radio halo (from [9]). The color scale represents the ROSAT X-ray emission. The extended irregular X-ray structure indicates the presence of a recent cluster merger.

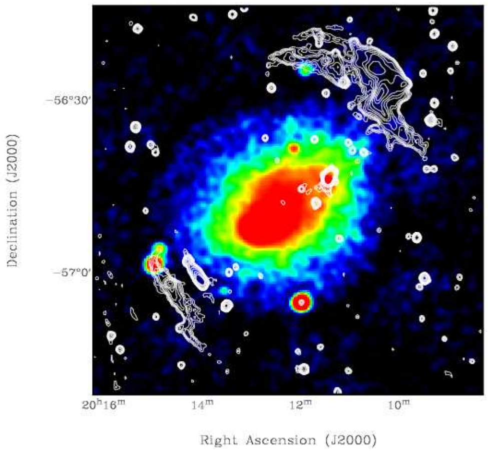

Figure 2. The cluster A3667 in radio and X-ray: the contours represent the radio emission at 843 MHz (from [23]). The color scale represents the ROSAT X-ray image emission. Two radio relics are located on opposite sides of the cluster along the axis of the merger, with the individual radio structures elongated perpendicular to this axis.

2. DIFFUSE SYNCHROTRON EMISSION

The properties of large-scale radio halos and relics are poorly known, because of the present observational limits. Due to synchrotron and inverse Compton losses, the typical lifetime of the relativistic electrons in the ICM is relatively short ($\sim 10^8$ yr), making it difficult for the electrons to diffuse over a Mpc-scale region within their radiative lifetime. The expected diffusion velocity of the electron population is indeed of the order of the Alfvén speed, $\sim$ 100 km/s. Because diffuse sources extend throughout the cluster volume, their electrons cannot have been injected or reaccelerated in some localized points of the cluster, such as an active galaxy or a shock, but they need in situ reacceleration.

Several suggestions for the mechanism transferring energy into the relativistic electron population and for the origin of relativistic electrons themselves have been made. Current models for radio halos can be grouped in two main classes, involving *primary electrons* and *secondary electrons*, respectively [5]. According to the first scenario, the primary electrons were injected in the cluster volume from AGN activity (quasars, radio galaxies, etc.), or from star formation in normal galaxies (supernovae, galactic winds, etc.) during the cluster dynamical history. This population of electrons needs to be reaccelerated [21] to compensate for the radiative losses. It is argued [10] that recent cluster mergers are likely to supply energy to the halos, through stochastic turbulent acceleration [4,12] or shock acceleration, although the efficiency of the last process is debated [14,24]. The second class of models involves secondary electrons resulting from inelastic nuclear collisions between the relativistic protons and the thermal ions of the ambient intracluster medium. The protons diffuse on large scales because their energy losses are negligible. They can continuously produce in situ electrons, distributed through the cluster volume [1,20]. In

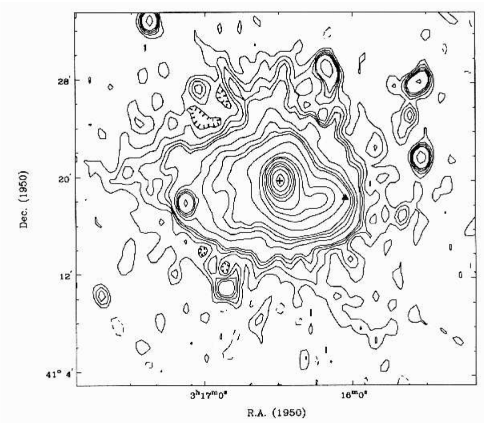

Figure 3. Radio contour map of the mini halo in the Perseus cluster, obtained at 92 cm with the Westerbork Synthesis Radio Telescope at a resolution of $51'' \times 77''$(RA$\times$DEC). The cross indicates the position of NGC1275, the triangle marks the position of NGC1272. The mini–halo size in this image is $\sim 25'$. This image is from [25].

this scenario, it is difficult to explain the observed association between mergers and radio halos, the spectral index radial steepening found in Coma C and the relatively low number of clusters with halos. However, the secondary model can ultimately be tested with future gamma ray telescopes due to its clear prediction of π^0-decay gamma ray fluxes.

Different models have been suggested for the origin of the relativistic electrons radiating in the radio relics, i.e. located in confined peripheral regions of the clusters. There is increasing evidence that the relics are tracers of shock waves in merger events. This is consistent with their elongated structure almost perpendicular to the merger axis (Fig. 2). Active radio galaxies may fill large volumes in the ICM with radio plasma, which becomes rapidly invisible to radio telescopes because of radiation losses of the relativistic electrons. These patches of fossil radio plasma are revived by adiabatic compression in a shock wave produced in the ICM by the flows of cosmological large-scale structure formation [6,7].

Unlike radio halos and relics, mini-halos are typically found at the centers of cooling core clusters and are thus not connected to recent cluster mergers. Although these sources are generally surrounding a powerful central radio galaxy, it has been argued [13] that the energetic necessary to their maintenance is not supplied by the radio galaxy itself. Current models involve electron reacceleration by MHD turbulence in the cooling core region [13] or a hadronic origin of the relativistic electrons from the interaction of cosmic ray protons with the ambient thermal protons [22].

The investigation of diffuse cluster sources and the discrimination between theoretical models is of great importance to the knowledge of the formation and evolution of clusters of galaxies.

3. RELATIVISTIC PLASMA AND CLUSTER MERGERS

The study of radio halos and relics is directly connected to the recent dynamical activity of clusters. In any scenario, cluster radio halos give us deep insight into the physics and properties of galaxy clusters. This opens a new window of investigation of the properties of clusters, through the formation of their relativistic components and the connection between thermal and relativistic plasma. Very likely radio halos give a unique probe of non-thermal processes accompanying energetic cluster merger events.

The typically low surface brightness ($\lesssim\mu$Jy arcsec^{-2} at 1.4 GHz) of cluster radio halos and their steep spectrum makes it difficult to image them accurately with the current resources. Further, at lower resolution, where beam averaging enhances the detectability of extended radio emission, true diffuse emission is sometimes difficult to distinguish from a blend of weak, discrete radio sources. Ideally, one wants high sensitivity on all angular scales.

Current maps of cluster halos often miss some of the extended structure, or show negative bowls around the imaged structure, arising from missing short spacings. Proper maps of cluster radio halos and relics are only obtained with high sensitivity to low surface brightness, i.e. a very good sampling of short baselines.

Multifrequency imaging is needed to derive spectra of these sources and spectral index maps. Low frequency (< 300 MHz) spectra are important to determine the index of electron energy distribution, while the high frequency spectra (up to 10 GHz) give information on the diffusion and aging of relativistic particles, and any reacceleration process.

Spectral index maps represent a powerful tool to study the properties of the relativistic electrons and of the magnetic field in which they emit, and to investigate the connection between the electron energy and the ICM. By combining high resolution spectral information and X–ray images it is possible to study the thermal–relativistic plasma connection both on small scales (e.g. spectral index variations vs. clumps in the ICM distribution) and on large scales (e.g. radial spectral index trends). It has been shown [4] that a relatively general expectation of models invoking reacceleration of relic particles is a radial spectral steepening in the synchrotron emission from radio halos. Because of the low diffusion velocity of the relativistic particles, the radial spectral steepening cannot be simply due to aging of radio emitting electrons. Therefore the spectral steepening must be related to the intrinsic evolution of the local electron spectrum and to the radial profile of the cluster magnetic field. In this framework, radio spectral index maps can be used to derive the physical conditions prevailing in the clusters, i.e. reacceleration efficiency and magnetic field strength. Nowadays, only for three clusters (Coma, A665, A2163) a spectral index image has been presented in the literature, with resolutions of the order of $1'$, and only between two frequencies [15,11]. Big developments are thus expected in this area with SKA, which will allow multifrequency spectral studies on higher resolution.

Polarization information on radio halos is not currently available, because of the limited sensitivity. Polarimetric studies are important to derive: i) direct information on the structure of magnetic fields related with the cluster intergalactic medium, ii) the magnetic field degree of ordering, related with the evolution of radio emitting plasma.

SKA will dramatically improve the knowledge of radio halos, thanks to spectral index studies and the detection of their polarized emission.

4. SEARCH FOR NEW HALOS AND RELICS

It is not yet clear if the ICM in every cluster has a strong relativistic component. The number of cluster sources of this class is presently around 50, the most distant being in CL 0016+16 [16] at z = 0.5545. Most of them have been found owing to searches in the NRAO VLA Sky Survey [18], in the Westerbork Northern Sky Survey [19] and in the survey of the Shapley Concentration [28]. In a complete X-ray flux limited cluster sample, the percentage of clusters showing diffuse radio sources at the sensitivity limit of the NRAO VLA Sky Survey is 11% (5% halos and 6% relics) [17]. The detection rate increases up to $\sim$35% if only the clusters with X-ray luminosity larger than 10^{45} erg s^{-1} (in the ROSAT band 0.1-2.4 keV) are considered. A correlation has been found between the radio power of a halo and the X-ray luminosity of the parent cluster (Fig. 4). The information on low power radio halos is currently unavailable. Improved sensitivity to surface brightness will be crucial to find out new cluster halos, to test if the above correlation can be extrapolated to low radio powers and low X-ray luminosities, to study their properties on a larger sample, and to test models. Questions to answer are: Do all clusters have a radio halo at some level? Do all clusters with a recent merger have halos and relics?

Large numbers of galaxy clusters are expected to be found up to high redhisfts by future surveys: e.g. the XMM Large Scale Structure Survey is expected to find $\sim 10^3$ galaxy clusters up to redshift ~ 1, SZ effect cluster detection with the Planck satellite should find $\sim 10^4$ galaxy clusters and the Sloan Digital Sky Survey is expected to identify $\sim 5\ 10^5$ clusters.

Using radio halos and relics as tracers of cluster mergers will therefore allow investigations of the properties of the merger shocks and turbulence in the accompanying clusters, and detailed

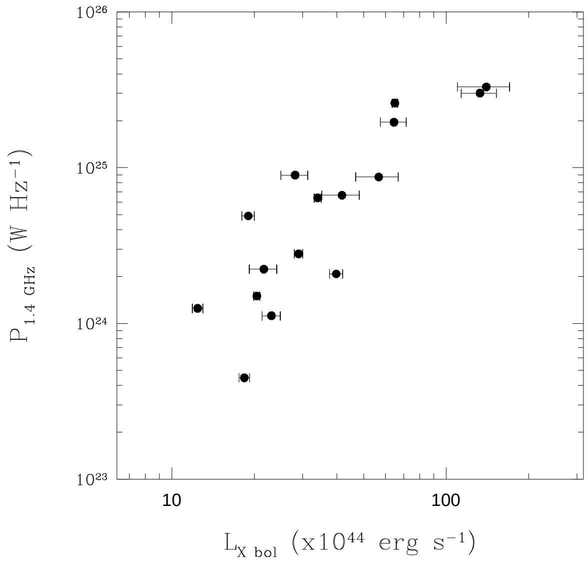

Figure 4. Halo monochromatic radio power at 1.4 GHz versus the cluster bolometric X-ray luminosity for halos with size >1 Mpc.

studies of the cluster formation process up to high resdhift.

In Table 1 we give the estimates of the number of observable halos obtained by [8]. These predictions are based on i) the fraction of clusters containing radio halos, ii) the local X-ray luminosity function and its evolution towards higher redshift, iii) the local relation between X-ray cluster luminosity and radio halo luminosity. Estimates of the number of relics were obtained by [3] under the assumption that they are produced via compression of old radio plasma. It was found that, assuming a spectral index of 1, the number of radio relics and halos roughly match at the same frequency. The possible detection of roughly symmetric halos, located on opposite sides of a cluster as in A3667 (see Fig. 2), is particularly interesting as it could help in understanding the geometry of the cluster formation process.

Table 1
Estimates of the number of expected radio halos on the full sky, which are above a given flux density S_{tot} at 1.5 GHz, in all clusters and in distant clusters(from [8]). For the details of the assumptions made for these calculation see the original paper[8].

S_{tot}	N	N(z>0.3)
1 μJy	23759	10785
10 μJy	6812	2123
0.1 mJy	1654	281
1 mJy	326	21
10 mJy	50	1

5. RELEVANCE OF STUDIES WITH SKA

The importance of the study of extended radio sources associated with the ICM can be summarized in the following points. The radio halos are indicators of cluster mergers, tracers of high energy and/or non-equilibrium plasma processes, probes of the ICM magnetic fields; they will eventually allow to constrain models of decaying/annihilating dark matter species. The radio relics are tracers of shock waves occurring during the structure formation, they will allow to determine shock properties like Mach numbers through spectral index studies, and help to clarify the nature of the seed relativistic particle populations. The radio mini-halos will allow to investigate the interaction between the relativistic plasma and thermal plasma in the cluster centers, and shed new light on the complex phenomena occurring in the cluster cooling cores. Moreover, detection of diffuse sources at different redshifts will provide a detailed study of the cluster formation process.

For the detection of extended diffuse radio sources in clusters, a radio telescope must have high sensitivity to surface brightness, thus an array with a very good coverage of short spacings. In Fig. 5, we show the estimates of the 1.4 GHz brightness of radio halos of different total fluxes, computed by assuming a total halo size of 1 Mpc.

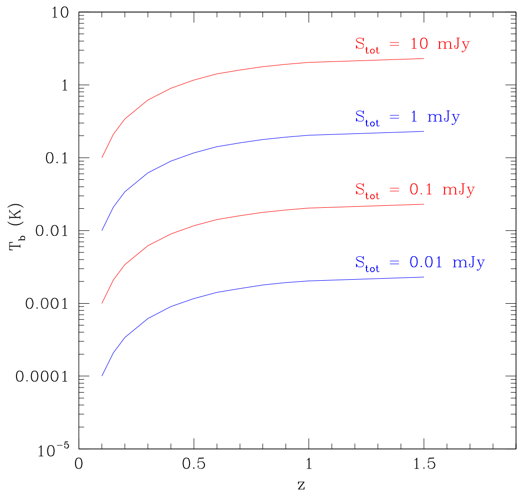

Figure 5. Brightness temperature at 1.4 GHz expected for radio halos of a given total flux, as a function of redshift. The size of a radio halos is assumed of 1 Mpc.

With 50% of the SKA collecting area within 5 km, the brightness sensitivity at 1.4 GHz, with a beam of $\sim 8''$, is $T_b \sim 5$ mK (3σ level), assuming a bandwidth of 0.5 GHz and an integration time of 1h. This will allow to detect halos of total flux down to 1 mJy at any redshift, and down to 0.1 mJy at high redshift. Indicatively, a survey of 2π sterad, would detect about 300 new halos, about half of them at redshift > 0.3 (see Table 1). A similar number of relics will also be detected. Of course, the sensitivity will be much higher in deeper exposures on targeted clusters, allowing detailed studies of the total and polarized emission, at multiple frequencies.

A minimum baseline of 20 m allows detection of structures up to $34'$ at 1.4 GHz and up to $10'$ at 5 GHz.

Whereas the detection of diffuse emission needs an intermediate angular resolution, the high resolution of the full SKA is needed to resolve and subtract discrete unrelated sources.

6. THOMSON SCATTERING OF A CLUSTER CENTRAL RADIO SOURCE

Although the hydrodynamical state and the ultimate fate of the cooling gas is still uncertain, the central regions of the clusters with cooling cores host large column densities of ionized material, as directly derived by the observations. These regions are likely to be optically thin, with typical values of the optical depth due to electron scattering of $\sim 10^{-2}$. If a powerful radio galaxy resides at the center of a cooling core cluster, then diffuse radiation originally emitted by the active nucleus and scattered by the hot electrons in the cooling core region is expected to be present.

The Thomson scattering in cluster cores has been described by [26] and [27]. Since electron scattering is independent of photon frequency, scattered radiation may in principle be detectable in any part of the spectrum. However, it is unlikely that such faint diffuse emission could be detected in the presence of other significant emissions. Radio observations seem to be very suitable to observe this effect, particularly since a very high dynamic range is attainable.

A diagnostic of the scattered radiation is the polarization. This emission should be characterized by a high degree of linear polarization, with tangential orientation, and the polarization would increase with the distance from the cluster center.

In the simple case that the cluster gas follows a King model, the intensity of the scattered radiation and the amount of polarization have the trends shown in Fig. 6. The distribution of the brightness temperature is given by the equation (from [26]):

$$T_b = 0.92 \left(\frac{S_\nu}{10 \text{ Jy}}\right) \left(\frac{\lambda}{6 \text{ cm}}\right)^2 \left(\frac{10'}{\theta_c}\right) \left(\frac{\tau_T}{10^{-2}}\right) \mathrm{f}\left(\frac{\theta}{\theta_c}\right) \quad \text{mK}$$

where S_ν denotes the monochromatic flux density, θ is the scattering angle (see the original paper [26] for an accurate definition of the geometry of the scattering), θ_c is the angular core radius of the cluster, τ_T is the maximum optical depth of the cluster, the function f$(\frac{\theta}{\theta_c})$ = f $(\frac{\rho}{a})$ is plotted in Fig. 6. It is estimated that about 1% of the luminosity of the cluster central source will be scattered (see also [27]).

Although the cluster gas approximation with a King model is too simplified, we can use the above formula to get an order of magnitude estimate of the intensity of the Thomson scattering effect. We obtain that the brightness temperature of the scattered radiation from a source of 1 Jy at 1.4 GHz is of the order of $\approx$ 10 mK at the center, and falls off very rapidly with distance (see Fig. 6).

In a full-polarization study of the Perseus cluster in the mid-1990's, de Bruyn (unpublished) found weak polarized emission. They suggested the possibility that this emission could be due to Thomson scattering. Preliminary results from 92 cm are presented by [2]. Beside the expected Galactic Faraday depths around 8 rad m^{-2}, they found polarized emission through the entire clusters at higher Faraday depth ($\sim$ 25 - 90 rad m^{-2}). The simulations obtained to estimate the magnitude of the effect in the Perseus cluster indicate that the observed emission is too bright and too uniform in intensity to be explained by Thomson scattering.

The detectability of the Thomson scattering halos will be possible with new generation very sensitive instruments, with high sensitivity to the polarized flux. An observational program designed to detect this effect should include the study of radio point sources of high-moderate strength associated with cluster-dominant galaxies in cooling core clusters. Since the scattered light is merely the emission of the central source redirected toward the observer, the diffuse scattered component will have the same spectra index as the central source. Thus, given data of sufficient dynamic range and spectral coverage, it should be possible to distinguish between scattered radio photons and those from other sources.

By comparing the X-ray emission and electron scattering in a cooling core, a distance to the cluster can be determined independently of the value of the Hubble constant [27]. In addition, observations of scattered light can provide information both on the central source and the surrounding ICM. Time variability of the central nucleus, beaming, or polarized emission all produce characteristic profiles for the scattered emission which can be used to study these processes. Deviations from spherical symmetry or clumping in the cooling flow itself can also produce characteristic variations in the scattered surface brightness profile, allowing to understand in an independent way some details of the cooling flow process.

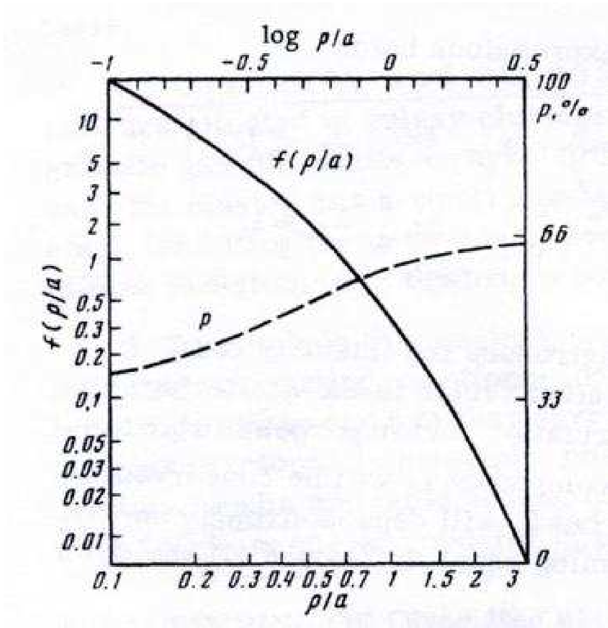

Figure 6. Solid curve: function describing the dependence of the diffuse scattered radiation intensity on the projected distance ρ from the compact radio source at the center of a cluster of core radius a. Dashed curve: percentage polarization of the diffuse radiation as a function of ρ/a (from [26]).

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