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NON THERMAL EMISSION FROM GALAXY CLUSTERS: RADIO HALOS


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The number of diffuse radio halos in clusters of galaxies has grown in recent years, making it possible to derive statistical properties of these sources and of the hosting clusters. We show that diffuse sources are associated with X-ray luminous clusters which have undergone recent merger processes. The radio and X-ray structures are often similar, and correlations are found between radio and X-ray parameters. A model for the formation and maintenance of these sources is suggested, including a first phase of relativistic particle injection by past major merger events, starbust and AGN activity and a second phase of reacceleration by the energy supplied from shocks and turbulence in a recent merger event.

1 Introduction

It is well known that the radio emission from clusters of galaxies generally originates from individual radio emitting galaxies. In addition, synchrotron emission associated with the intergalactic medium, rather than to a particular galaxy, may be detected in some cases. Clusters of galaxies may exhibit diffuse extended radio sources, which have been classified as radio halos, relics and mini-halos (Feretti & Giovannini 1996). The radio halos are the most spectacular expression of cluster non-thermal emission. They permeate the cluster centers with size of the order of a Mpc or more. They are characterized by low surface brightness, steep radio spectrum, and no polarized emission detected.

The importance of these sources is that they represent 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.

In this paper, the observational properties of radio halos are summarized, together with the properties of their parent clusters and a model of radio halo formation and evolution is described. Intrinsic parameters are calculated with H_0 = 50 km s^{-1} Mpc^{-1} and q_0 = 0.5.

2 Examples and properties of radio halos

The diffuse source Coma C in the Coma cluster, discovered 30 years ago (Willson 1970), is the prototypical example of a cluster *radio halo*. It is located at the cluster center, it has a steep radio spectrum ($\alpha \sim 1.3$) and is extended $\sim$ 1 Mpc (Giovannini *et al.* 1993). Other well studied

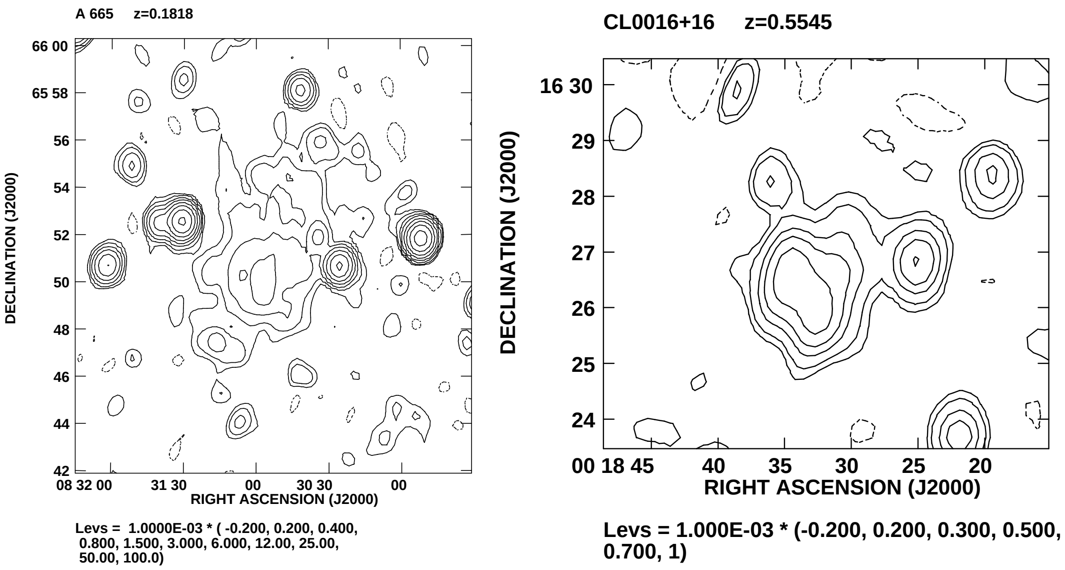

Figure 1: **Left panel**: Image of the giant radio halo detected at the center of A 665. The HPBW is 42″ × 52″ (RA×DEC). **Right panel**: Image of the radio halo present in the central region of the distant cluster CL 0016+16. The HPBW is 45″ × 60″ (RA×DEC).

radio halos are detected in the clusters A 2255 (Feretti *et al.* 1997a) and A 2319 (Feretti *et al.* 1997b).

In Fig. 1 and Fig. 2, we show images of giant and powerful radio halos discovered in distant clusters. The radio images presented here have been obtained with the Very Large Array at 20 cm. The radio halo in A 665 is one of the largest known so far, with the size of 2.4 Mpc (Giovannini & Feretti 2000). The radio emission is slightly asymmetric with respect to the cluster center, being brighter and more extended toward NW. This cluster has a temperature of 8.3 keV, no cooling flow, and is suggested by X-ray data to be in a postmerger state (Markevitch 1996, Gomez *et al.* 2000). The halo in CL 0016+16 (Giovannini & Feretti 2000) is the most distant radio halo known so far. It is extended 1.1 Mpc and is co-located with the cluster X-ray emission. The cluster has a temperature of 8.2 keV, and shows strong evidence of substructure which is possibly due to merging of a galaxy group with the main cluster (Neumann & Böhringer 1997). The halo in A 520 is extended 1.4 Mpc, with the radio structure elongated in NE-SW direction (Govoni *et al.*, in preparation). The two tailed radio sources on the eastern side are cluster radio galaxies. The cluster temperature is 8.6 keV. The halo in A 2744 shows a regular and symmetric structure, with a total size of about 2.2 Mpc (Govoni *et al.*, in preparation). The elongated diffuse emission in the NE peripheral region is classified as a cluster relic. This cluster is very hot, with a temperature of 11 keV, and shows X-ray substructure, which is possible indication of a recent merger.

In general, the sizes of radio halos are typically larger than 1 Mpc. Their radio powers are of the order of 10^{24}-10^{25} W Hz^{-1} at 1.4 GHz. Minimum energy densities are between $\sim 5\ 10^{-14}$ and $2\ 10^{-13}$ erg cm^{-3}. This implies that the pressure of relativistic electrons is much lower than that of the thermal plasma. Equipartition magnetic fields are about $\sim$0.1-1μG. These values are lower than the cluster magnetic field strenghts obtained from Rotation Measure arguments, and are of the same order as the estimates derived from Inverse-Compton X-ray emission. It should be noticed that the Rotation Measure estimates could be sensitive to the presence of filamentary sructure in the cluster and/or to the existence of local turbulence around the radio galaxies, and could therefore be higher than the average cluster value.

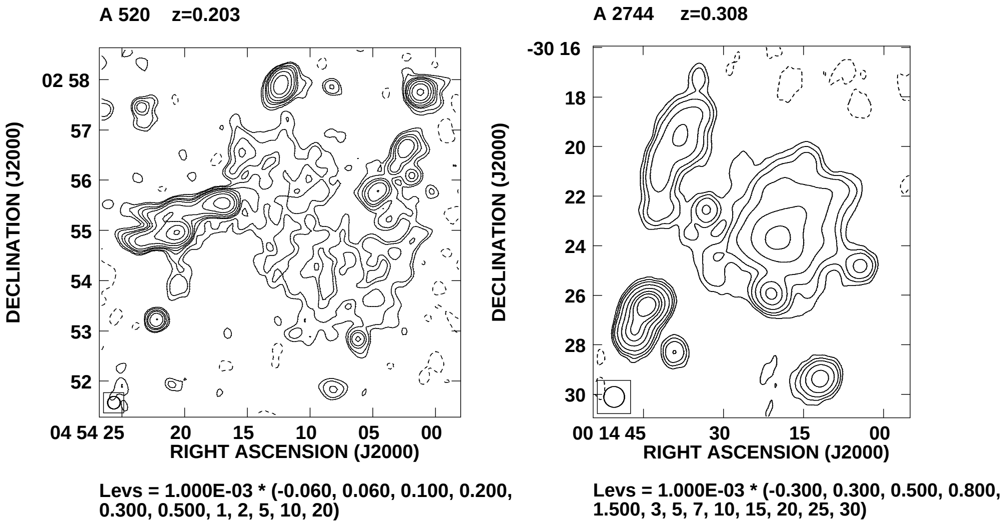

Figure 2: **Left panel**: The radio halo in A 520, imaged with a circular synthesized restoring beam with FWHM $= 15''$. **Right panel**: Image of the radio halo in A 2744. The elongated emission in the NE peripheral region is a relic. The synthesized restoring beam is a circular Gaussian with a FWHM of $50''$.

3 Properties of clusters with radio halos

Unlike the thermal X-ray emission, the radio halos are not a common feature in clusters of galaxies. Until recently, the number of halos was small, thus these sources were considered to be a rare phenomenon. Nowadays, thanks to the better sensitivity of radio telescopes and to the existence of deep surveys, more than 25 clusters are known to host radio halos at their centers (Giovannini *et al.* 1999), therefore some statistical considerations can be drawn.

The percentage of clusters showing central radio halos in the complete X-ray flux limited sample extracted from Ebeling *et al.* (1996) is of $\sim$5%. The detection rate increases with the X-ray luminosity being $\sim$30-35% in clusters with X-ray luminosity larger than 10^{45} erg s^{-1}. The clusters hosting a radio halo have a significantly higher X-ray luminosity than clusters without a diffuse source ($>$ 99.9% confidence level with a KS test) (Giovannini *et al.* 2000).

The high luminosity of clusters with radio halos implies that these clusters also have a high temperature and a large mass. This is consistent with the serendipitous detection of halos during the attempts to detect Sunyaev-Zeldovich effect in massive high redshift clusters.

In previous studies (e.g. Feretti 1999, Feretti 2000) radio halos have been found to be associated with clusters showing indication of merger processes from X-ray and optical structure, and from X-ray temperature gradients.

Moreover, a correlation is found between the monochromatic radio power at 1.4 GHz of radio halos and the bolometric X-ray luminosity of the parent clusters. This implies a correlation between radio power and cluster temperature, as shown by Liang *et al.* (2000). Since the cluster X-ray luminosity and mass are correlated as well as the temperature and mass, it follows that the halo radio power also correlates with the cluster mass.

Radio structures of halos show in many cases close similarity to the X-ray structures, suggesting a causal connection between the hot and relativistic plasma. To quantify the similarity in the radio and X-ray structures, Govoni *et al.* (2000) performed an analysis of the radio and the X-ray emission in four clusters of galaxies containing radio halos (Coma, A 2255, A 2319, A 2744). This study leads to a correlation between the radio and the X-ray brightness in all the analyzed clusters: a higher X-ray brightness is associated with a higher radio brightness. The relation between the radio and the X-ray brightness is found to be linear in A 2255 and A 2744,

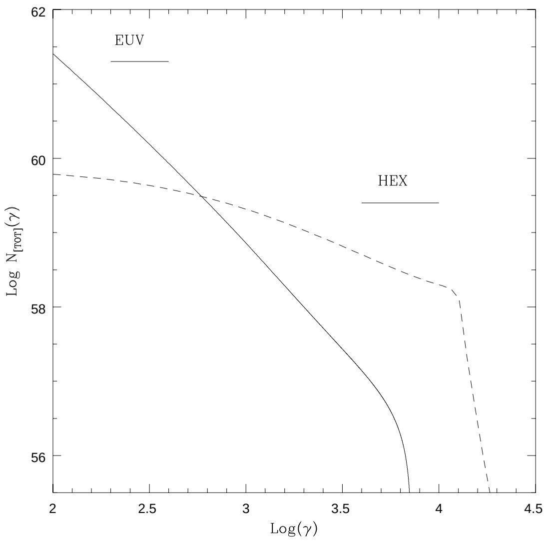

Figure 3: Plot of the energy distribution of the relativistic electron populations in the Coma cluster. The dashed line represents the main electron population, integrated over the cluster volume, injected during the *first phase* and reaccelerated during the *second phase*. The solid line refers to the additional electron population injected by the radio galaxy NGC 4869. The typical energies of the electrons emitting via IC in the hard X–ray band (HEX) and in the EUV band are also indicated.

whereas it is represented by a sublinear power-law in the other two clusters of galaxies.

4 The 2-phase model for radio halo formation and evolution

Radio halos directly demonstrate the existence of cluster–wide magnetic fields and of relativistic electrons within the cluster intergalactic medium. A number of models have been invoked to explain radio halo formation and their broad band radiative properties (see Enßlin 2000; Sarazin this meeting). Observations suggest that central radio halos are strictly related to the presence of recent merging processes, which can provide the energy for the electron reacceleration and magnetic field amplification. Furthermore, as discussed above, also the high X–ray luminosity, the large cluster mass and/or the high cluster temperature appear to be necessary conditions for their formation. One would conclude that the dynamical history of the clusters is crucial to trigger a radio halo. We have developed a *two phase* model consisting of a *first phase* during which relativistic electrons are injected in the cluster volume by strong shocks, sturburst and/or AGN activity and of a *second phase* during which the aged electrons are reaccelerated by recent merging processes (Brunetti *et al.* 2000a). In the framework of this model we find two general results:

• The formation of luminous radio halos may not be a common phenomenon. Indeed the injected relativistic electrons suffer efficient radiation and Coulomb losses and rapidly cool. This prevents the formation of a radio halo if the time gap between the *first* and *second phase* Δt is larger than $\sim 2-3$ Gyr. Furthermore, in order to allow the formation of a radio halo during the reacceleration *phase*, the number of relativistic electrons injected during the *first phase* should be large enough, increasing with increasing Δt. In this framework one could claim that the radio halo formation is favoured in the case of massive clusters which probably derive from a stronger merger activity in the past and where the injection of larger quantities of cosmic rays is more efficient.

• Central radio halos triggered during the *second phase* by diffuse reacceleration processes are expected to show a steepening in the synchrotron spectrum with increasing distance from the center of the cluster. Indeed, the magnetic field strength is expected to be a decreasing function of the radius and so probably also the reacceleration efficiency.

The model has been applied in detail to the well studied radio halo Coma C (Brunetti *et al.* 2000a). The radial steepening of the radio spectrum observed in Coma C (Giovannini *et al.* 1993, Deiss *et al.* 1997) has been used to constrain the physical conditions in the cluster, obtaining reacceleration efficiencies of the order of $10^{-8}\mathrm{yr}^{-1}$ and average magnetic field strengths ranging from 1–3 μG in the central regions to 0.05–0.1 μG in the external parts of the cluster ($\sim$ 2–3 Mpc). The model satisfactorily reproduces the total radio spectrum of Coma C and the size of the halo. The expected hard X–ray inverse Compton emission, mainly produced at relatively large distances from the cluster center ($\geq$ 1.5 Mpc), is consistent with the flux detected by BeppoSAX (Fusco–Femiano *et al.* 1999).

As previously discussed, the relativistic electrons radiating within the halo were injected during the past history of the cluster. However, additional electron injection could also derive from recent activity in the cluster. Although it has been shown that the radio halo phenomenon does not appear to be correlated with the presence of AGNs in the cluster (in particular with head tail radio sources, Giovannini & Feretti 2000), even a modest injection of star forming galaxies and AGNs could affect the broad band properties of radio halos. In a recent paper, Brunetti *et al.* (2000b) have calculated, in the framework of the above described *two phase* model, the evolution of the spectrum of relativistic electrons recently injected (in the last 0.1–0.3 Gyr) by the head tail radio galaxy NGC 4869 in Coma. It was found that the fresh–injected population does not significantly contribute to the $\geq$ 300 MHz spectrum of the radio halo but it could significantly contribute to the emission at lower frequencies. Accurate measurements at low frequencies, such as those obtainable with the VLA at 74 MHz, are of crucial importance to test the model. In this scenario, a large fraction (if not all) of the EUV excess detected in the Coma cluster (Bowyer *et al.* 1999) may be accounted for by the inverse Compton scattering of CMB photons by the recently injected population, whose contribution to the hard X–ray emission is however not relevant. The spectral distribution of the two electron populations in the Coma cluster are reported in Fig.3. Due to radiative losses and reacceleration gains, the energy distribution of the recently injected population is expected to become very similar to the main electron population with increasing time ($\geq$ 1 Gyr).

Acknowledgments

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