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PROPERTIES AND SPECTRAL BEHAVIOUR OF CLUSTER RADIO HALOS

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ABSTRACT

Several arguments have been presented in the literature to support the connection between radio halos and cluster mergers. The spectral index distributions of the halos in A665 and A2163 provide a new strong confirmation of this connection, i.e. of the fact that the cluster merger plays an important role in the energy supply to the radio halos. Features of the spectral index (flattening and patches) are indication of a complex shape of the radiating electron spectrum, and are therefore in support of electron reacceleration models. Regions of flatter spectrum are found to be related to the recent merger. In the undisturbed cluster regions, instead, the spectrum steepens with the distance from the cluster center. The plot of the integrated spectral index of a sample of halos versus the cluster temperature indicates that clusters at higher temperature tend to host halos with flatter spectra. This correlation provides further evidence of the connection between radio emission and cluster mergers.

Key words : clusters of galaxies – intergalactic medium – radio emission – X-ray emission

I. INTRODUCTION

Radio halos are the most spectacular expression of cluster non–thermal emission. They are low brightness extended radio sources permeating the cluster centers, similarly to the X-ray emitting gas, with sizes of more than a Mpc. The prototype of this class is Coma C (Fig. 1), the halo source in the Coma cluster, which was first shown to be diffuse by Willson (1970) and mapped later at various radio wavelengths by several authors (Giovannini et al. 1993, Thierbach et al. 2003, and references therein).

Studies of several radio halos and of their hosting clusters have been recently performed, thus improving the knowledge of the characteristics and physical properties of this class of radio sources. Giant radio halos have been detected in A665 (Giovannini & Feretti 2000), A2163 (Feretti et al. 2001), A2219 (Bacchi et al. 2003), A2255 (Feretti et al. 1997a), A2319 (Feretti et al. 1997b), A2744 (Govoni et al. 2001a), 1E0657 − 56 (Liang et al. 2000), and CL0016 + 16 (Giovannini & Feretti 2000). The latter cluster, at z = 0.555, is the most distant cluster with a radio halo known so far. Radio halos of small size, i.e. << 1 Mpc, have also been revealed in the central regions of some clusters, as in A401 (Giovannini & Feretti 2000), A1300 (Reid et al. 1999), A2218 (Giovannini & Feretti 2000) and A3562 (Venturi et al. 2003).

In this paper we outline the general properties of radio halos, and we focus on the spectral index maps recently obtained for the halos in the clusters A665 and A2163. 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 distribution and the intracluster medium (ICM).

The intrinsic parameters quoted in this paper are computed with a Hubble constant H_0 = 70 km s^{-1} Mpc^{-1} and a deceleration parameter $q_0 = 0.5$.

II. GENERAL PROPERTIES

The general properties of radio halos, derived from observational data, can be summarized as follows:

a) Under the standard equipartition conditions, assuming equal energy in relativistic protons and electrons (k = 1) and a volume filling factor Φ = 1, the minimum energy density in halos is of the order of $10^{-14} - 10^{-13}$ erg cm^{-3}, i.e. much lower than the energy density in the thermal gas. The corresponding equipartition magnetic field strengths range from ≃ 0.1 to 1 μG (e.g. Govoni & Feretti 2004).

b) The spectra of halos are steep, as typically found in aged radio sources ($\alpha \gtrsim 1$, assuming $S_\nu \propto \nu^{-\alpha}$). Steepening at high frequencies is reported in most cases with adequate spectral coverage; e.g. in Coma (Thierbach et al. 2003), A754 (Bacchi et al. 2003), A1914 (Komissarov & Gubanov 1994), A2319 (Feretti et al. 1997b). The radiative lifetime of the relativistic electrons, derived from the integrated spectra considering synchrotron and inverse Compton energy losses, is of the order of $\sim 10^8$ yr. This implies that, to allow for the large sizes of the radio emitting regions, the radiating particles need to be reaccelerated by some mechanism,

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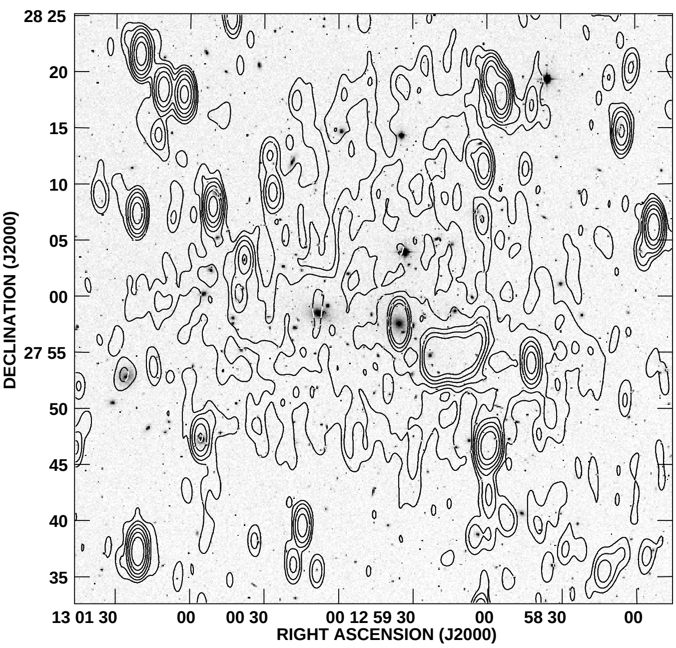

Fig. 1.— Isocontour map at 0.3 GHz of the central region of the Coma cluster superimposed onto the optical image from the DPSS. The resolution of the radio image is 55″× 125″(FWHM, RA × DEC); contour levels are: 3, 6, 12, 25, 50, 100 mJy/beam.

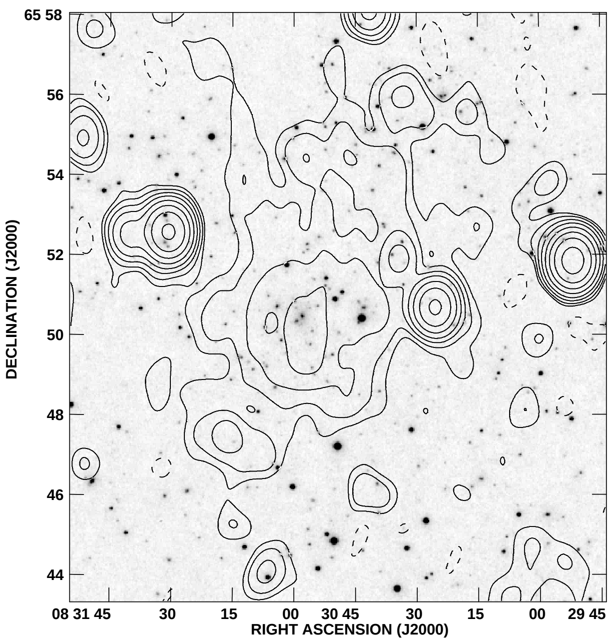

Fig. 2.— Isocontour map at 1.4 GHz of the central region of A665 superimposed onto the optical image from the DPSS. The resolution is 42″× 52″(FWHM, RA × DEC). Contour levels are: -0.2, 0.2, 0.4, 0.8, 1.5, 3, 6, 12, 25 mJy/beam.

acting with an efficiency comparable to the energy loss processes.

c) Radio properties of halos are linked to properties of the host clusters. Indeed, the radio power of a halo correlates with the cluster X-ray luminosity (Bacchi et al. 2003), the thermal gas temperature (Liang et al. 2000), and the total cluster mass (Govoni et al. 2001a). Moreover, 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. 2001b). This correlation is visible e.g. in A2744 also in the *Chandra* high resolution data (Kempner & David 2004).

d) The detection rate of radio halos in a complete X-ray flux–limited sample of clusters is $\simeq 5\%$ (at the detection limit of the NRAO VLA Sky Survey). The halo fraction increases with the X-ray luminosity, up to $\simeq 33\%$ for clusters with $L_X > 10^{45}$ erg s^{-1}. Thus, halos are present in rich clusters, characterized by high X-ray luminosities and temperatures (Giovannini & Feretti 2002).

e) Halos are typically found in clusters showing distorted X-ray morphology and significant substructure (Schuecker et al. 2001, Buote 2001), and strong gas temperature gradients (Govoni et al. 2004). Some clusters show a spatial correlation between the radio halo brightness and the hot gas regions, although this is not a general feature. Thus, radio halos are strictly related to the presence of cluster merger processes. According to recent suggestions, a recent major cluster merger event is the relevant factor for the formation of a radio halo by supplying the energy for the reacceleration of radiating electrons (e.g., Feretti 2003 and references therein).

III. SPECTRAL INDEX MAPS

The distribution of the radio spectral index is an important observable in a radio halo, since it is related to the shape of the electron energy distribution and to the properties of the magnetic field in which they emit. By combining high resolution spectral information and X-ray images it is possible to investigate the connection between the thermal and relativistic plasma 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).

The first spectral index image of a radio halo has been obtained by Giovannini et al. (1993) for Coma C, using data at 0.3 GHz from the Westerbork Synthesis Radio Telescope (WSRT) and data at 1.4 GHz from the Very Large Array (VLA) and the Dominion Radio Astronomy Observatory. The image shows a flatter

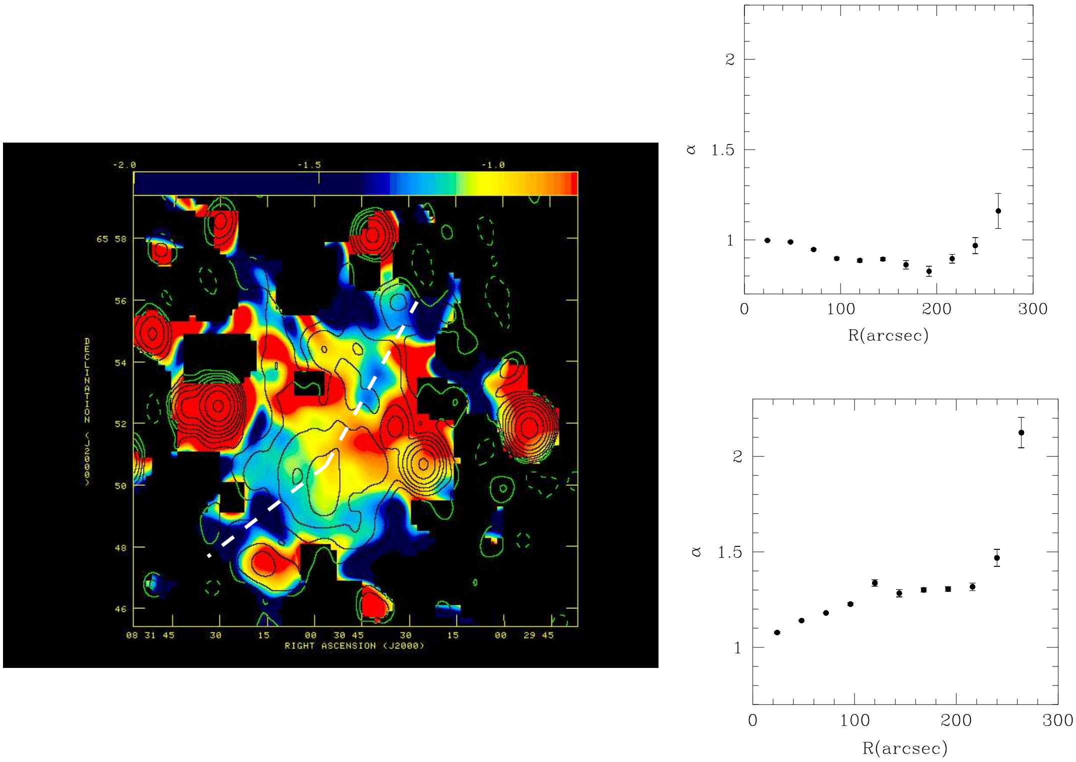

Fig. 3.— **Left panel**: color–scale image of the spectral index between 0.3 GHz and 1.4 GHz of A665, obtained with a resolution of 68″× 59″(PA= 25°) FWHM. The contours indicate the radio emission at 1.4 GHz (Fig. 2). **Right panels**: radial profiles of the spectral index along the two directions indicated by the dashed lines in the spectral index map. The cluster core radius, derived from X-ray data, is 96″, corresponding to 270 kpc.

spectrum in the central region ($\alpha \simeq 0.8$) and a progressive steepening with increasing distance from the center (up to $\alpha \simeq 1.8$ at a distance of about 15′). This trend is confirmed by a new spectral index map derived by comparing the 1.4 GHz image obtained with the Effelsberg single dish by Deiss et al. (1997), and the 0.3 GHz image obtained from the combination of VLA and WSRT data (Giovannini et al. in preparation). The high sensitivity of the images allows the computation of the spectral index up to $\sim 30'$ from the cluster center, where the spectral index is $\alpha \simeq 2$. The high resolution X-ray data of the Coma cluster obtained with XMM-Newton provide the evidence of recent merger activity at scales larger than 10′, whereas the cluster core is suggested to be in a basically relaxed state (Arnaud et al. 2001).

New spectral index images have been recently obtained for the clusters A665 and A2163 using VLA data at 0.3 and 1.4 GHz. They are presented below. For a more detailed analysis see Feretti et al. (2004).

A 665 (z = 0.1818). The radio halo in this cluster is shown in Fig. 2 (Giovannini & Feretti 2000). The radio emission, of $\sim 1.3\ h_{70}^{-1}$ Mpc in size, is asymmetric with respect to the cluster center, being brighter and more extended towards the NW. This is the direction where the X-ray brightness distribution detected from Chandra data is elongated, probably due to the merging of a smaller subcluster (Markevitch & Vikhlinin 2001). The Chandra data also reveal the presence of a remarkable shock in front of the cool cluster core, indicating that the core is moving with a relatively high Mach number. The shock is located near the southern boundary of the radio halo. The complex temperature structure is confirmed by more sensitive data published by Govoni et al. (2004).

The spectral index map is clumpy (Fig. 3). The spectrum in the central halo region is rather constant, with spectral index values between 0.8 and 1.2 within one core radius from the cluster center (i.e. within $\sim$ 96″). In the northern region of lower radio brightness the spectrum is flatter than in the southern halo region.

Starting from the approximate radio peak position, we obtained profiles of the spectral index trend by averaging the values of the spectral index within small sectors around the two directions marked by dashed lines in Fig. 3. The spectrum in the NW direction flattens up to a distance of about 200″ from the center (Fig. 3, top right panel). This is the region where the asymmetric extended X-ray emission indicates the existence of an ongoing merger with another cluster. The gas temperature in this region (Markevitch & Vikhlinin 2001, Govoni et al. 2004) shows strong variations, from about 12 keV in the NE to about 8 keV in the SW. The spectral index flattening follows the X-ray morphology, but there is no one–to–one correspondence with the

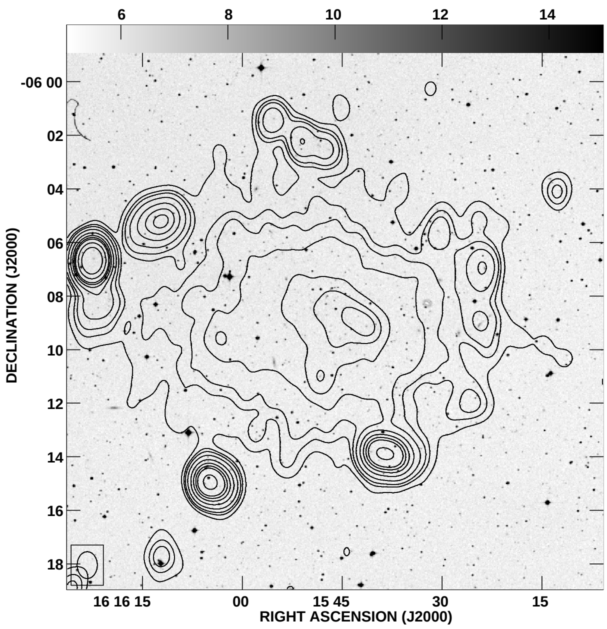

Fig. 4.— Isocontour radio map at 1.4 GHz of A2163 superimposed onto the optical image from the DPSS. The resolution is 60″× 45″(FWHM, RA × DEC). Contours are 0.2, 0.5, 0.8, 1.5, 3.0, 5.0, 7.0, 9.0, 15.0 mJy/beam.

value of the gas temperature. Therefore, it seems that this region, which is strongly influenced by the merger, is a shocked region, where the gas at different temperatures is still in the process of mixing.

In defining a profile in the southern cluster region, we tried to avoid the region where there is a possible contamination of discrete sources. The spectrum in this direction (Fig. 3, bottom right panel) steepens significantly from the center to the periphery. The spectral index increase from $\alpha \sim 1$ to $\alpha \gtrsim 2$ is gradual at the beginning, and occurs on a scale of less than 3 cluster core radii. The region of constant spectral index at distance between 120″ and 220″ from the center is located NE of a discrete source and could be affected by its presence. We note that this path crosses the region of the hot shock detected by Chandra at the southernmost edge of the radio halo (Markevitch & Vikhlinin 2001). The shock is located at about 100″ from the center along the profile. No significant spectral flattening is detected at this position.

A 2163 (z = 0.203). This cluster is one of the hottest and most X-ray luminous among known clusters. It hosts a powerful radio halo, extended $\sim 2\ h_{70}^{-1}$ Mpc (Fig. 4), studied in detail by Feretti et al. (2001).

X-ray ROSAT and ASCA data (Elbaz et al. 1995, Markevitch et al. 1996) suggest that this cluster is likely to be have experienced a recent merger. The X-ray brightness distribution indicates elongation in the E-W direction, suggesting that this could be the merger direction. Recent Chandra data (Markevitch & Vikhlinin 2001, Govoni et al. 2004) reveal a complex morphology indicating that the cluster central region is in a state of violent merger. The temperature map is also complex, with variations by at least a factor of 2, suggesting streams of hot and cold gas flowing in different directions, as well as a possible remnant of a cool gas core, surrounded by shock–heated gas. The structure in the temperature map is too complicated to easily infer the geometry of the merger.

The spectral index map (Fig. 5, left panel) is clumpy in the central cluster region, but it is rather constant within one core radius, showing spectral index values between 1 and 1.1. On a larger scale, there is evidence that the western halo region is flatter than the eastern one. In particular, there is a vertical region crossing the cluster center and showing flatter spectrum, with a clear evidence of spectral flattening both at the northern and at the southern halo boundaries.

Radial profiles of the spectral index along two interesting directions (see dashed lines) have been obtained, as in A665, by averaging the values of the spectral index within small sectors around the two directions. The spectral index profile along the N-S direction (Fig. 5, top right panel) is globally rather flat and shows a significant flattening at about 300″ from the center (note that the strong flattening of the two last points is due to the presence of a discrete radio source). In the eastern cluster region, in the area free of discrete sources, the spectrum becomes progressively steeper from the center to the periphery. This is well seen in the profile along the S-E direction (bottom right panel). The spectral steepening is weaker than in A665, and occurs over a much larger scale. The vertical region of flatter spectrum coincides with the region of highest temperature detected from Chandra, thus it is likely related to the strong dynamical activity at the cluster center. The N-S extent of the region with flat spectrum is in support of a merger occurring in the E-W direction, as indicated by the X-ray brightness distribution. The complexity of the merger is, however, reflected in the complexity of the spectral index map.

IV. CONNECTION TO CLUSTER MERGER

The spectral index maps of A665 and A2163 indicate the existence of patches of different spectra, with significant variations on scales of the order of the observing beam (∼ 200 kpc). This suggests a complex shape of the electron spectrum, as generally expected in the case of particle reacceleration.

The regions influenced by an ongoing merger show a different behaviour with respect to the relatively undisturbed regions. Regions of flatter spectra are indication of the presence of more energetic radiating particles, and/or of a larger value of the local magnetic field strength. Flatter spectra are found in regions in-

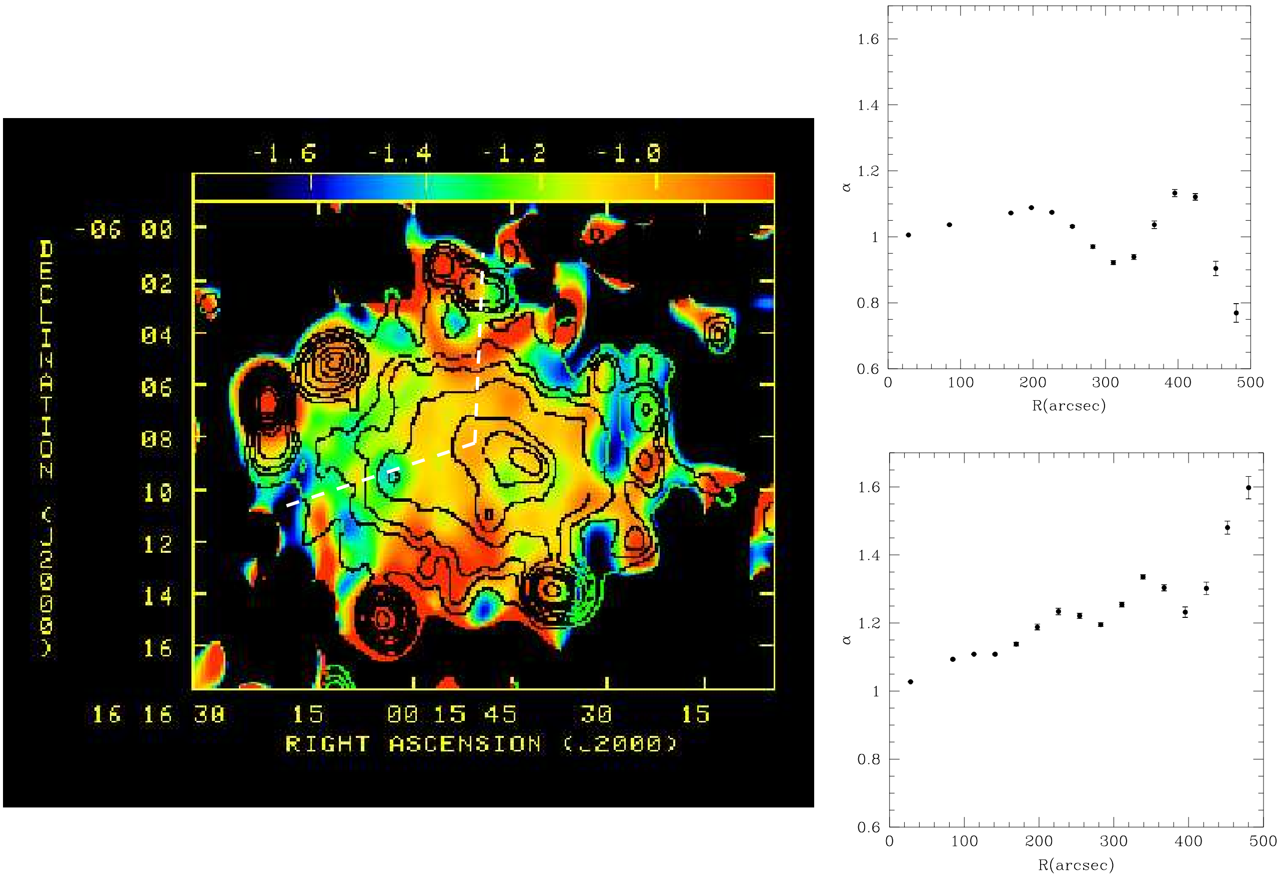

Fig. 5.— Left panel: color-scale image of the spectral index between 0.3 GHz and 1.4 GHz of A2163, obtained with a resolution of 60″× 51″(PA=0°) FWHM. The contours indicate the radio emission at 1.4 GHz (Fig. 4). **Right panels**: radial profiles of the spectral index along the two directions indicated by the dashed lines in the spectral index map. The cluster core radius is 72″, corresponding to 220 kpc.

fluenced by merger processes, while a general radial spectral steepening is found in more undisturbed cluster regions. This behaviour is qualitatively expected by electron reacceleration models.

We have attempted the evaluation of the energy supplied to the halos in the regions of flatter spectral index, by matching the reacceleration gains and the radiative losses of the radio emitting electrons. In regions of identical volume and brightness at 0.3 GHz, a flattening of the spectral index from 1.3 to 0.8 implies that the energy injected into the electron population is larger by a factor of ∼2.5. Since the lifetimes of the radio emitting electrons at ∼ 1 GHz in a 0.5 μG field are of the order of ∼ 10^8 yr, the energy injection event should be recent. Electrons in flatter spectrum regions have a spectral cutoff at higher energies, thus they have been reaccelerated more recently.

These results prove that the radio spectral index can be a powerful tracer of the current physical properties of clusters, and confirms the importance of cluster mergers in the energetics of relativistic particles responsible for halo radio emission. On the other hand, the spectral index steepens progressively with the distance from the cluster center in the more relaxed regions. This is another indication that the energy of relativistic particles is sensitive to the effect of mergers.

It is worth noticing that there is no evidence of spectral flattening at the location of the hot shock detected in A665 (Markevitch & Vikhlinin 2001). This is consistent with the fact that shocks in major mergers are too weak to produce a significant number of high energy particles (Gabici & Blasi 2003, Berrington & Dermer 2003) and indeed the Mach number of the shock in A665 is ∼ 2 (Markevitch & Vikhlinin 2001). Our result supports the scenario that cluster turbulence might be the major mechanism responsible for the supply of energy to the radiating electrons.

To check if there is a more general connection between the radio halo spectra and the cluster properties, we have investigated the existence of a possible correlation between the spectral index of a sample of radio halos with good spectral information and the cluster temperature. In Fig. 6, we plot the integrated average spectral index obtained over the available frequency range versus the average cluster temperature derived from the X-ray data. The plot may suggest that clusters at higher temperature tend to host halos with flatter spectra, although the data are still scarce and the

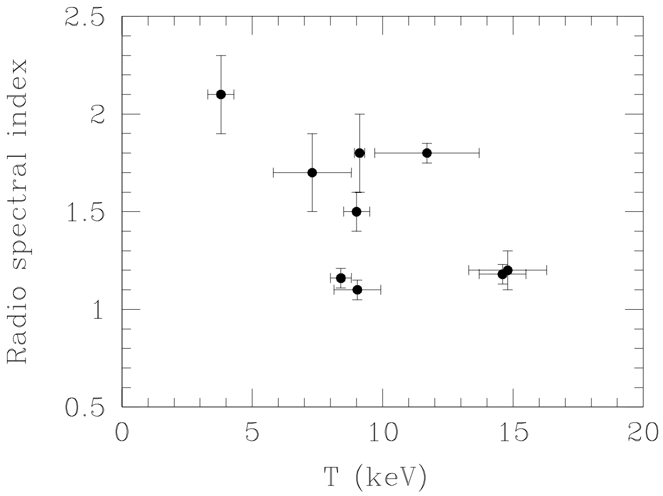

Fig. 6.— Integrated spectral index of radio halos versus cluster temperature.

errors very large. This correlation, if confirmed, could be understood in the framework of the reacceleration models, since the hottest clusters, being more massive, may statistically host more violent mergers giving rise to a higher fraction of the turbulent energy per unit gas mass. Thus this correlation would provide further evidence of the connection between radio emission and cluster mergers.

V. IMPLICATIONS ON PARTICLE ACCELERATION AND CLUSTER MAGNETIC FIELD PROFILE

Since the diffusion velocity of relativistic particles is low in relation to their radiative lifetime, the radial spectral steepening detected in A665 and A2163 in the more undisturbed regions cannot be simply due to ageing of radioemitting 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 the primary reacceleration scenario the electrons are accelerated up to a maximum energy which is given by the balance between acceleration efficiency and energy losses. As a consequence a break (or cut–off) is expected in the synchrotron spectrum emitted by these electrons. The presence of spectral steepenings and flattenings implies that the frequency of such a synchrotron break is relatively close to the range 0.3–1.4 GHz for a relevant fraction of the cluster volume.

If Fermi–like acceleration processes are efficient in the cluster volume, the synchrotron break frequency $\nu_{\rm b}$ is related to the magnetic field B as:

$$\nu_{\rm b}(r) \propto \chi^2(r) \begin{cases} B(r), & \text{if } B(r) << B_{IC}; \\ B^{-3}(r), & \text{if } B(r) >> B_{IC}. \end{cases} \quad (1)$$

where $\chi(r) = \tau_{acc}^{-1}$ is the acceleration rate ($dp/dt = \chi p$), and B_{IC} is the IC equivalent magnetic field $\sim 3\mu$G.

The equipartition magnetic field in the present clusters are $\sim$ 0.5 μG, i.e. $<< B_{IC}$, thus we expect $\nu_{\rm b}(r) \propto \chi^2(r)B(r)$. Allowing for a decrease of B with r, it follows that a roughly constant acceleration efficiency results in a systematic steepening of the synchrotron spectrum with r, simply because at a given frequency higher energy electrons emit in the lower field intensity. This steepening effect would be further enhanced if the reacceleration efficiency increases toward the central regions.

The trends of the spectral index showing radial steepening (bottom right panels of Figs. 3 and 5) reflect the radial trends of the product between the magnetic field strength and the reacceleration efficiency, $B\chi^2$. In both clusters, it is derived that $B\chi^2$ decreases about a factor of 2 over the scale of the spectral index profile. Each trend of $B\chi^2$ represents the profile of the magnetic field strength in the case that the reacceleration is constant throughout the cluster.

Under the hypothesis that the magnetic field results from the compression of the thermal plasma during the gravitational collapse, we would expect $B \propto n_{th}^{2/3}$, where n_{th} is the thermal plasma density. We derive that this trend is much steeper that than that estimated by the spectral behaviour. We note, however, that in A665 and A2163 the β model approximation for the distribution of n_{th} may be significantly inaccurate owing to gas perturbations related to strong dynamical evolution. On the other hand, detailed MHD numerical simulations show that the radial behaviour of the magnetic field may diverge from the prediction of a frozen–in B model, resulting in flatter spectra in the central regions, and steeper in the external regions (Dolag et al. 1999, 2002).

The radial profile of the Coma cluster magnetic field, derived in the same way by modeling the spectral steepening (Brunetti et al. 2001), shows a decline with the distance which is not too different from that expected by the frozen–in B model. This is also the case of the magnetic profile in A119, obtained using the Rotation Measure of the cluster radio galaxies (Dolag et al. 2001). In general, we could argue that the ongoing violent mergers in A665 and A2163 are likely to play a crucial role in determining the conditions of the radiating particles and the magnetic field in these clusters.

We finally remark that the hypothesis of constant reacceleration efficiency in the cluster volume may not be valid, according to the following arguments: i) first results from numerical simulations (Norman & Bryan 1999) indicate that the injection of turbulence in clusters is not homogeneous and occurs on very different spatial scales in different regions; ii) detailed calculations of particle acceleration due to Alfvèn waves show that, under reasonable assumptions, the acceleration efficiency slightly increases with distance from the cluster center (Brunetti et al. 2004); iii) the radiative losses of electrons in the innermost cluster regions may be strongly increased if the magnetic field is larger than the equipartition value, in particular if it is of the order of B_{IC} (e.g Kuo et al. 2003).

VI. CONCLUSIONS

The link between radio halos and cluster merger processes is confirmed by the halo spectral behaviour. Spectral index maps obtained for the two clusters A665 and A2163 with an angular resolution of the order of $\sim 1'$, show a clumpy distribution with significant variations, which are indication of a complex shape of the radiating electron spectrum. This is supportive of halo models invoking the reacceleration of relativistic particles. Regions of flatter spectra appear to trace the geometry of recent merger activity as suggested by X-ray maps. These results prove that radio emitting electrons are gaining energy from the merger event. There is no evidence of spectral flattening at the location of the hot shock detected in A665 (Markevitch & Vikhlinin 2001). This favours the scenario that cluster turbulence might be the major mechanism responsible for the electron reacceleration.

A plot of the halo total spectral index versus the cluster temperature indicates that hotter clusters tend to host halos with flatter spectra. This may be understood in the framework of the reacceleration models, since hottest clusters, being more massive, may host more violent mergers.

In the undisturbed cluster regions of A665 and A2163, the spectrum steepens with the distance from the cluster center. This is interpreted as the result of the combined effect of a radial decrease of the cluster magnetic field strength and of the spatial distribution of the reacceleration efficiency. The profile of the product between the cluster magnetic field and the reacceleration efficiency, $B\chi^2$, derived under simple assumptions is flatter than that predicted in the case of a constant reacceleration and magnetic field frozen to the cluster thermal gas. The ongoing violent mergers may play a crucial role in determining the conditions of the radiating particles and of the magnetic fields in clusters.

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