Part 3

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Observational Properties of Diffuse Halos in Clusters

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Abstract. The number of known diffuse radio sources 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. This is indication of a link between the diffuse relativistic and thermal plasma in clusters of galaxies.

1. Introduction

It is well established that an important component of the intergalactic medium (IGM) in clusters and groups of galaxies is the hot gas, observed in X-rays and characterized by temperatures in the range ~5-10 keV, by a central density of $\sim 10^{-3}$ cm^{-3} and by a density distribution approximated by a beta model (Cavaliere & Fusco-Femiano 1981). In addition, magnetic fields are wide spread in clusters (e.g. Eilek 1999), as deduced by Rotation Measure arguments, and relativistic electrons may be common (Sarazin & Lieu 1998). These two non-thermal components can be directly revealed in some clusters by the presence of diffuse extended radio sources, which are related to the intergalactic medium, rather than to a particular cluster galaxy. However, diffuse sources seem not to be a general property of the IGM.

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 diffuse cluster sources and of their host clusters are outlined. Intrinsic parameters are calculated with $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$.

2. Classification and radio properties

The diffuse source Coma C in the Coma cluster (Fig. 1, left panel), discovered 30 years ago (Willson 1970), is the prototypical example of a cluster *radio halo.* The radio halo 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). Another example of cluster-wide halo, associated with the cluster A 2255, is shown in the right panel of Fig. 1. An additional diffuse source, 1253+275, is detected at the Coma

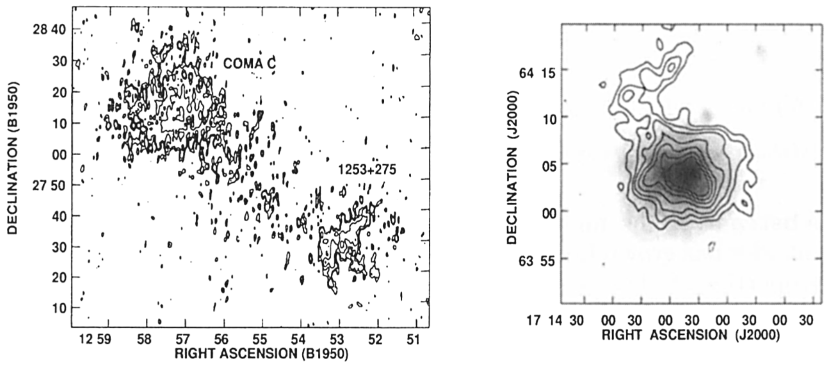

Figure 1. Examples of diffuse sources in clusters, after subtraction of the discrete sources. *Left panel:* Radio map of Coma at 90 cm, with angular resolution of 55″ × 125″ (HPBW, RA × DEC). Contour levels are 2.5, 4, 8 16 mJy/beam. The two diffuse sources are easily visible. *Right panel:* Radio image of the diffuse emission in A 2255 at 90 cm (contours) superimposed on the greyscale X-ray ROSAT image. Contour levels are -4, 4, 7 , 10, 15, 20 25, 30 mJy/beam, with HPBW=89″ ×84″(@6°).

cluster periphery, which might be connected to the cluster halo by a very low-brightness radio bridge (Giovannini *et al.* 1991). This source and similar diffuse sources located in peripheral cluster regions are referred to as *radio relics* in the literature. This name may be misleading, since it can also be used to indicate dying radio galaxies, without active nucleus, as B2 1610+29 in A 2162 (Parma et al. 1986). I would suggest *peripheral halos*, whereas Ron Ekers suggested *radio flotsam*. Since the interpretation of these sources is still unclear, I will use here the name *relics*, for homogeneity with the literature.

Radio halos and relics show low surface brightness ($\sim \mu$Jy/arcsec^2 at 20 cm) and steep radio spectrum. Their detection is limited by the surface brightness sensitivity coupled with the high resolution needed to separate such sources from the embedded discrete sources. Because of their steep spectrum, they are better detected at lower frequencies.

Until recently, the number of halos and relics was small, thus these sources were considered to be rare. This is no longer true. Thanks to the better sensitivity of radio telescopes and to the existence of deep surveys, more than 30 clusters hosting diffuse sources are known today. For 18 of them (see Table 1) the presence of diffuse radio emission is well established and good radio data are available either from the literature or from new observations (Govoni *et al.* in preparation). It is remarkable the existence in some clusters of more than one diffuse source.

Table 1. Clusters with well studied halos and relics

Cluster	z	$P_{1.4}$	L.S. Mpc	L_{Xbol}	T keV	Dist Mpc	Class
A85	0.0555	6.26	0.48	19.52	5.1	0.54	R
A115	0.1971	255.5	1.88	31.09	4.9	0.93	R
A520	0.2030	62.1	1.08	37.35	8.5	-	H
A610	0.0956	7.65	0.57	-	-	0.71	R
A665	0.1818	66.5	2.13	41.72	8.5	-	H
A773	0.2170	22.3	0.83	35.10	8.6	-	H
A1300	0.3071	92.4	0.58	47.63	10.5	-	H
		92.4	0.95	47.63	10.5	0.80	R
A1367	0.0216	0.71	0.29	2.87	3.5	0.83	R
A1656	0.0232	15.0	1.09	20.42	8.2	-	H
		7.03	1.17	20.42	8.2	2.72	R
A2163	0.2080	306.2	2.60	132.91	14.2	-	H
A2218	0.1710	12.2	0.52	21.96	6.9	-	H
A2255	0.0809	12.6	1.23	12.42	5.4	-	H
		3.51	0.98	12.42	5.4	1.23	R
A2256	0.0581	37.3	1.11	18.39	7.5	0.59	R
		4.48	1.19	18.39	7.5	-	H
A2319	0.0555	20.8	1.41	39.74	9.7	-	H
A2744	0.3080	241.6	1.81	62.44	11.0	-	H
		74.3	1.84	62.44	11.0	1.91	R
A3667	0.0552	323.1	2.63	22.70	7	2.45	R
CL0016+16	0.5545	89.6	1.11	28.13	8.2	-	H
1E0658-56	0.296	312.0	1.96	140	14.5	-	H

Caption. Col. 1: cluster name Col. 2: redshift Col. 3: radio power of the diffuse source at 1.4 GHz (10^{23} W Hz^{-1}) Col. 4: largest linear size of the diffuse source Col. 5: X-ray bolometric luminosity (10^{44} erg s^{-1}) Col 6: cluster temperature obtained by averaging values in the literature Col. 7: projected distance of the diffuse source from the cluster center Col. 8: source classification, H=halo, R=relic.

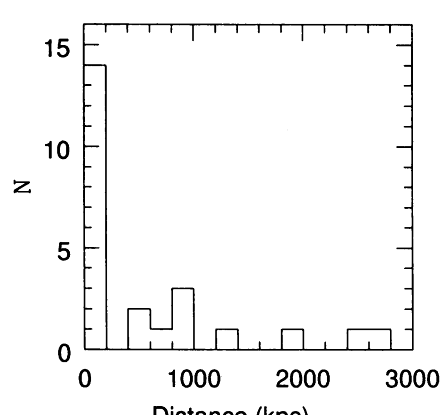

Figure 2. Distribution of projected distances of the diffuse sources from the cluster center.

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The sizes of halos are typically larger than 1 Mpc. Peripheral relics are elongated in shape, and the distribution of their largest sizes is not statistically different from that of halos on a Kolmogorov-Smirnov (KS) test.

The distribution of projected distances from the cluster center (Fig. 2) demonstrates that the diffuse sources are not located at random positions in the clusters, i.e. central halos are likely to be really at the cluster center and not simply projected onto it.

Radio powers are of the order of 10^{24}-10^{25} W Hz^{-1} at 1.4 GHz. In a radio size-radio power diagram, the diffuse radio sources follow the same correlation of the radio galaxies (e.g. Ledlow *et al.* 2000), lying in the upper part of the plot.

Minimum energy densities in diffuse sources 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 can be compared with independent estimates from Rotation Measure arguments and from Inverse Compton X-ray emission, to determine if these radio sources are at the equipartition.

3. Occurrence

To derive the frequency of radio halos and relics we need systematic radio information on complete samples of clusters. Giovannini *et al.* (1999) used the NRAO Vla Sky Survey (NVSS) to search for diffuse sources associated with clusters of galaxies from the sample of Ebeling *et al.* (1996). This sample is complete down to an X-ray flux of $5\ 10^{-12}$ erg cm^{-2} s^{-1} in (0.1-2.4) keV, for redshifts <0.2 and for galactic latitude $|b|>20°$. Moreover, it contains some clusters at higher redshift and at lower galactic latitude.

The total detection rate of clusters with halos + relics in the complete sample is of 5% to 10%, and the relative occurence of halos and relics is similar (taking into account the uncertain detections). The detection rate increases with the X-ray luminosity (Giovannini *et al.* 2000), being of $\sim$40% in clusters with X-ray luminosity larger than 10^{45} erg s^{-1}. In particular, the detection rate of central radio halos is more strongly dependent on the X-ray luminosity.

The clusters hosting a diffuse source have a significantly higher X-ray luminosity than clusters without a diffuse source (> 99.9% confidence level with a KS test). The detection rate in the high redshift sample is fully consistent with the previous results. These results are consistent with those of Owen *et al.* (1999).

4. Properties of the host clusters

An important property derived in the previous section is that the clusters hosting diffuse sources are more X-ray luminous and consequently they have a high temperature and a large mass. Values larger than $1.5\ 10^{14}\ M_{\odot}$ are found for the total (gravitating) mass within 0.5 Mpc, with gas fraction ranging from 10% to 20%. This is consistent with the serendipitous detection of halos observed

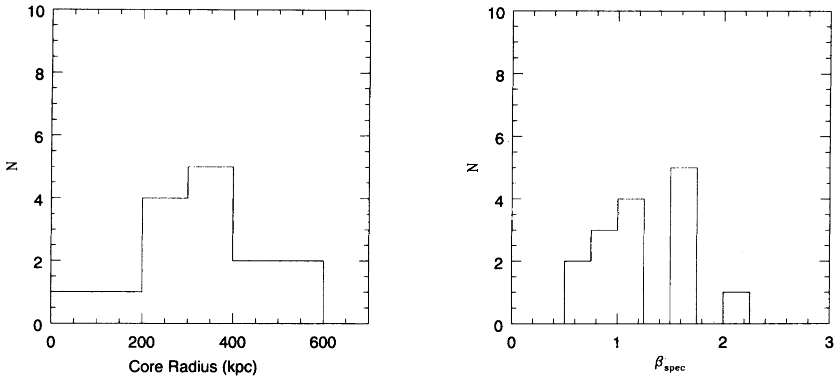

Figure 3. *Left panel:* Distribution of X-ray core radii of clusters with halos and relics. *Right panel:* Distribution of spectroscopic β of clusters with halos and relics.

during the attempts to detect Sunyaev-Zeldovich effect in massive high redshift clusters.

In previous studies (e.g. Feretti 1999), radio halos have been found to be often associated with clusters showing indication of merger processes from X-ray and optical structure, and from X-ray temperature gradients. This is confirmed by statistical studies, according to the following arguments:

- X-ray images of clusters with halos and relics show the presence of substructures and distortions in the brightness distribution (Schuecker & Böhringer 1999), which can be interpreted as the result of subclumps interaction;
- clusters with halos do not have a strong cooling flow (e.g. Feretti 1999). This is further indication that a cluster has undergone a recent merger, as cooling flow and irregular cluster structure tend to be anticorrelated (Buote & Tsai 1996) and a strong merger process is expected to disrupt a cooling flow (Peres *et al.* 1998);
- the X-ray core radii of clusters with halos/relics in Table 1 (see Fig. 3, left panel) are significantly larger (>99% level using a KS test) than those of clusters classified as single/primary by Jones anf Forman (1999). According to the last authors, the large core radius clusters are multiple systems in the process of merging and hotter clusters tend to have larger core radii;
- for the clusters of Table 1 with optical and X-ray information, the values of spectroscopic β are on average larger than 1 (Fig 3, right panel), indicating the presence of substructure (Edge & Stewart, 1991);
- clusters with halos and relics have larger distances to their next neighbours compared to ordinary clusters with similar X-ray luminosity, i.e. similar cluster mass (Schuecker and Böhringer 1999). The fact that they appear more isolated gives additional support to the idea that recent merger events in halo clusters lead to a depletion of the nearest neighbours.

In conclusion, there seems to be convincing evidence that diffuse sources are preferentially associated with high X-ray luminosity clusters with mergers. To our knowledge, however, not all the X-ray luminous merging clusters host a diffuse source, but this point needs further investigation.

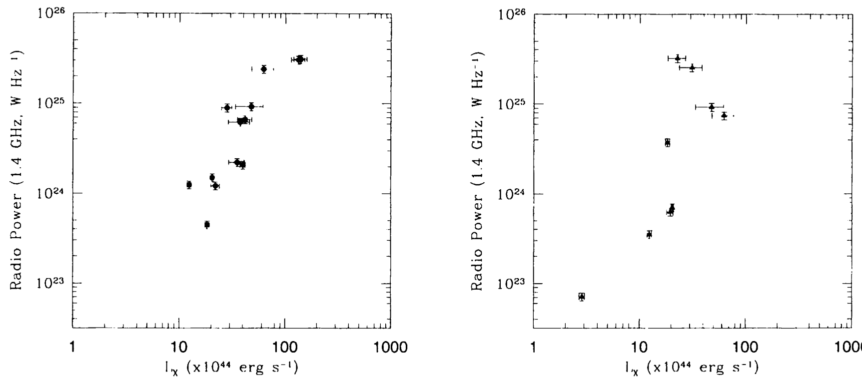

Figure 4. Monochromatic radio power versus cluster bolometric X-ray luminosity for halos (left panel) and relics (right panel).

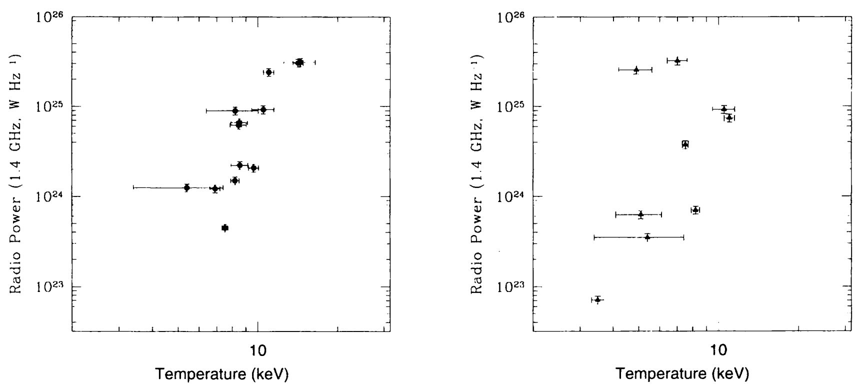

Figure 5. Monochromatic radio power versus cluster temperature for halos (left panel) and relics (right panel).

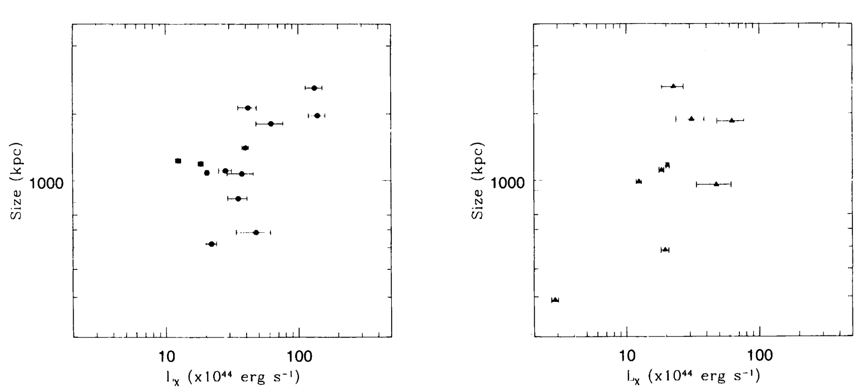

Figure 6. Radio largest linear size versus cluster bolometric X-ray luminosity for halos (left panel) and relics (right panel).

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5. Link between relativistic and thermal plasma

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. An example is given in Fig. 1 (right panel), which shows that the central radio halo in A 2255 is elongated in the E-W direction as the X-ray gas. Other examples are the radio halos in A 665, A 1300, A 2218, A 2319 (see Feretti 1999 for comments on individual clusters) and in 1E0658-56 (Liang 1999).

The correlation visible between the monochromatic radio power at 1.4 GHz and the bolometric X-ray luminosity for the clusters of Table 1 (Fig. 4) implies a correlation between radio power and cluster temperature (Fig. 5), also derived by Liang (1999). 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 mass. The correlations must be taken into account in model of radio halo formation. It is of particular interest to understand whether the formation of a diffuse source is affected by the high cluster temperature or by the large cluster mass.

A correlation seems to exist also between the largest radio size of diffuse sources and the cluster X-ray luminosity (Fig. 6), and goes in the direction of more X-ray luminous clusters hosting larger diffuse sources. All the correlations are more evident for radio halos than for relics.

Another link between radio and X-ray is represented by the detection of hard X-ray emission produced by the IC scattering of relativistic electrons with the microwave background photons. The hard X-ray emission detected in the Coma cluster (Fusco-Femiano *et al.* 1999) and in A 2256 (Fusco-Femiano *et al.* 2000) has been interpreted in this way.

6. Discussion and Conclusions

It is evident from the observational results that central halos are strictly related to the presence of recent mergers. The cluster merger can provide energy for the electron reacceleration and magnetic field amplification. However, also the high X-ray luminosity is relevant for the formation of halos. This seems to imply that the dynamical history of the cluster, i.e. the formation process of a massive hot cluster is crucial to trigger a halo. This scenario would explain why not all merging clusters host a halo (at least 50% of clusters show mergers, Jones & Forman 1999, while less than 5% of clusters show central halos).

Brunetti *et al.* (2000) suggested a two-phase model, successfully applied to Coma C, which includes: i) a phase of injection of relativistic electrons in the cluster volume from starburst galaxies, AGNs, and strong shocks during the cluster formation; ii) a phase of particle reacceleration by recent mergers. The Brunetti *et al.* model can be generalized to the other halos, and it would account for the presence of halos in X-ray luminous clusters, since the hot massive clusters should have had a more efficient injection phase.

It still debated if radio halos and relics have a common origin and evolution, or if they should be considered as different classes of sources. Several clusters host both a central and a peripheral halo, thus favouring a common origin and nature. Peripheral relics, like halos, are associated with merging clusters. However, the clusters are less luminous in X-ray and the radio-X-ray correlations are weaker. A current hypothesis is that radio relics have a different nature, and may be reaccelerated by shock waves of an ongoing merger event, or from shocks during the structure formation of the Universe (Ensslin 2000).

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