

## RADIO RELICS IN CLUSTERS OF GALAXIES

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### ABSTRACT

In this paper we review the observational results on Relic radio sources in clusters of galaxies. We discuss their observational properties, structures and radio spectra. We will show that Relics can be divided according to their size, morphology, and location in the galaxy cluster. These differences could be related to physical properties of Relic sources. The comparison with cluster conditions suggests that Relics could be related to shock waves originated by cluster mergers.

*Key words* : cluster of galaxies – non-thermal emission – radio relic

### I. INTRODUCTION

An increasing number of clusters of galaxies is known to contain large-scale diffuse radio sources whose origin is not related to the activity of Active Galactic Nuclei (AGN) in cluster galaxies, but to the intracluster medium. These sources are classified in two groups, radio halos and Relics, according to their location with respect to the cluster center: radio halos show a regular emission around the cluster center, Relics are not located at the cluster center and in most cases are in peripheral cluster regions and have an irregular, elongated shape (see e.g. Giovannini & Feretti 2002).

The existence of Relic sources reveal the presence of cluster wide magnetic fields of about 0.1 - 1  $\mu\text{G}$  and of relativistic electrons of  $\sim \text{Gev}$  energies in large regions where the number of galaxies is scarce and the density of the hot Intra Cluster Medium (ICM) is low (peripheral regions).

Several studies of radio halos and their hosting clusters have been recently published, thus our knowledge of their characteristics and physical properties has largely improved (see e.g. Feretti 2003, 2004). About radio Relics instead, the available data and knowledge are still poor and the number of well studied sources is limited. Many Relics have not yet been studied or observed in detail and deep high resolution radio maps are still missing, therefore their reported size and radio flux density could be under-estimated. Most radio spectra have been obtained with a poor frequency coverage and very few spectral index images have been published. Moreover many Relics, being at the cluster periphery, are in the external regions or outside of the available X-ray images. In these cases a comparison between radio and X-Ray data is difficult or not possible.

In this paper we will present the general properties of this puzzling class of radio sources to improve our

understanding of the diffuse non thermal emission in clusters of galaxies.

To estimate intrinsic parameters we use a cosmology with  $H_0 = 70 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_m = 0.3$  and  $\Omega_\Lambda = 0.7$ .

### II. GENERAL PROPERTIES

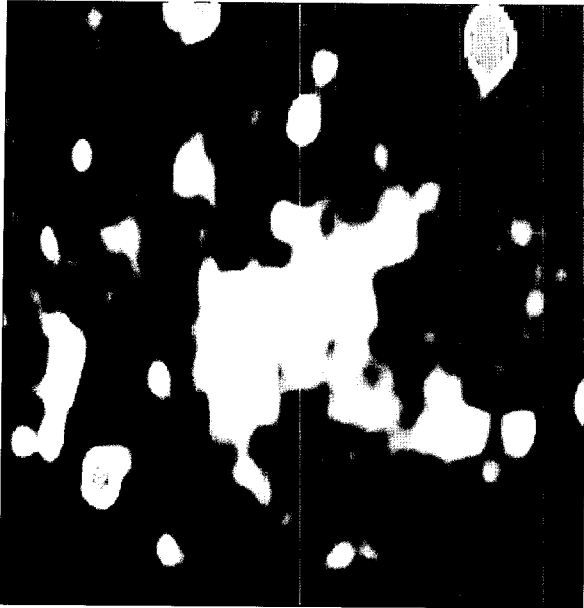
We define a Relic as an extended diffuse synchrotron emission not located at the cluster center and not identified with the activity of one or more cluster galaxies. In most cases Relics show an elongated structure, a steep spectrum ( $\alpha > 1$ , assuming  $S_\nu \propto \nu^{-\alpha}$ ), and are linearly polarized at a level of  $\sim 10 - 30 \%$ .

Currently we know  $\sim 30$  clusters of galaxies where at least one Relic source is present. Most of them are rich Abell clusters, but a Relic source is present in a X-Ray selected cluster (RXS J1314236-251521, Valtchanov et al. 2002), and one belongs to a poor cluster (S0753, Subrahmanyam et al. 2003).

Kempner et al. (2004) suggested a physical classification scheme for Relics, and distinguished three different types of Relic sources. Here, we prefer to present the properties of Relics simply according to their observational structures and location, without relating them to physically different classes. We can group known Relics as discussed in the following sub-sections.

#### (a) Classic Elongated Relics

We include in this class elongated and peripheral diffuse radio sources. The prototype source of this class is the Relic 1253+275 in the Coma cluster (see Giovannini et al. 1991 and Fig. 1). Other similar Relics are e.g. in A2255, A2744, A1367 and A115. We note that the Relic in A115 (Govoni et al. 2001a) apparently starts at the main cluster center and is elongated towards the cluster periphery. Present data do not allow to understand if it really starts in the central cluster region or if this peculiarity is due to projection effects.

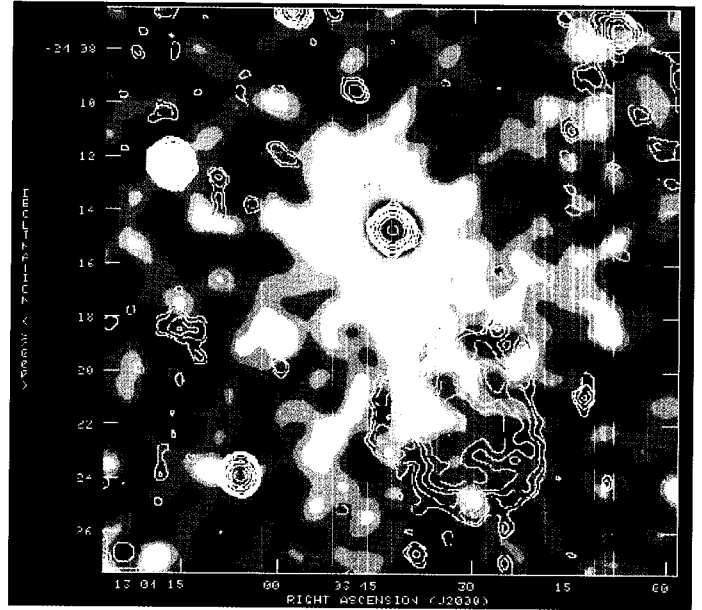


**Fig. 1.**— Colour image of the Relic source 1253+275 in the Coma cluster observed with the VLA at 90 cm (Giovannini et al. 1991). The strong point like source on the top is 3C 277.3 (Coma-A)

Most of these Relics are quite extended, with the linear size ranging from 400 to 1500 kpc. They show an asymmetric transversal profile, with a sharp edge and a flatter spectral index in the external side and a smooth edge in the side near to the cluster center. The radio emission is usually polarized. These characteristics and the presence in a few clusters of double Relic sources (see Sect. III) have suggested the link to models where cluster mergers produce shock waves that propagate in both directions along the line that connects the centres of the initial pre-merger clusters. These merger shock waves can revive fossil radio plasma present in cluster regions or to accelerate electrons from the thermal plasma (Kempner et al. 2004).

#### (b) Circular Peripheral Relics

Two clusters (A548b and A1664) host a Relic radio source which is clearly at the cluster periphery, but shows an extended mostly circular shape (Feretti et al. in preparation and Govoni et al. 2001a). In Fig. 2 we report the superposition of X-Ray and NVSS (Condon et al. 1998) radio data for A1664. This peculiar morphology could suggest that the elongated Relics might be extended disk-like Relics seen in projection. However, this is not the case because of the too large number of Relics with elongated structure. Moreover, we note that the Relic in A1664 when observed at higher resolution shows evident substructures (Govoni et al. 2001a).



**Fig. 2.**— Radio image (contours) of the radio Relic in the cluster A1664 (Govoni et al. 2001a) from NVSS data, overimposed to the cluster ROSAT X-ray image (colour)

#### (c) Relic Sources near the First Ranked Galaxy

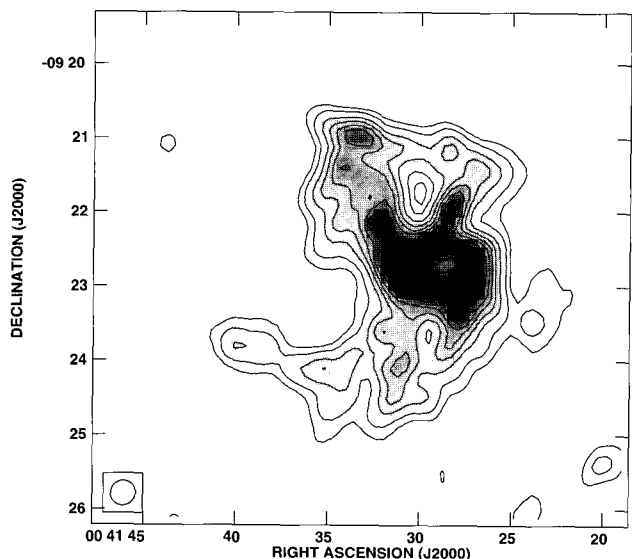
In some clusters an extended diffuse emission is located near the central First Ranked Galaxy (FRG, usually a cD galaxy), but not coincident with it. We classify these sources as Relics even if they are not located at the cluster periphery, since their connection to the activity of the FRG is not clear (but see Fujita et al., 2002 for A133). The distances of these Relic sources from the cluster center are in the range from  $\sim 50$  to  $\sim 350$  kpc. We note that if these diffuse sources were old lobes of a previous activity of the central galaxy we should expect to see in most cases an almost symmetric double structure centered on the galaxy, whereas in all these clusters only one diffuse emission is present.

These sources can be very small ( $< 100$  kpc in A133, A2063, A4038) but also quite large: the Relic in A85 is  $\sim 360$  kpc in size and that in A13 is  $\sim 650$  kpc. They have a very steep spectrum ( $\alpha > 1.5 - 2.0$ ) with evidence of high frequency steepening. The radio emission is strongly polarized and shows a regular shape with evident filaments inside (see Slee et al. 2001 and Fig. 3).

#### (d) Relics at Large Distance from the Cluster Center

In this sub-class we include two Relic radio sources very far from the cluster center: 0917+75 (Fig. 4) tentatively identified with A786 and the Relic probably associated with A2069.

0917+75 is an extended elongated diffuse emission (Dewdney et al. 1991, Harris et al. 1993, Giovannini and Feretti 2000) located at  $\sim 3.8$  Mpc from the nearest rich cluster of galaxies; the Relic source in A2069 (Gio-



**Fig. 3.**— Relic source in the cluster A85 from VLA radio data at 90 cm (Giovannini and Feretti, 2000)

vannini et al. 1999) is at  $\sim 4.6$  Mpc from the cluster center.

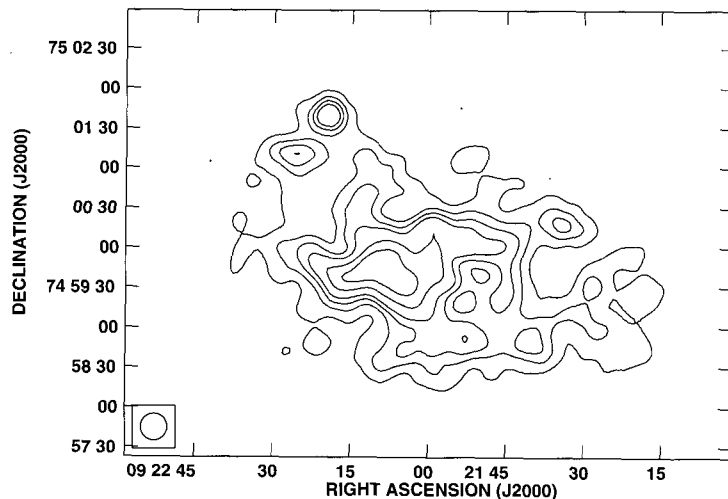
These distances are so huge that a connection between the Relic radio emission and the cluster is not straightforward. In these cases the radio activity could be related to a possible filamentary structure in a super-cluster structure (see next sub-section).

### (e) Filaments

Radio emission has been detected in some cases from regions in between clusters of galaxies (filaments). Probably, these features should not be considered Relic sources, because they may have a different origin and evolution.

Relic sources are detected in cluster peripheral regions. Can we expect the presence of radio emission in even less dense regions as filaments in between rich cluster of galaxies? A suggestion of a possible radio emission in filaments comes from the bridge of radio emission visible in the region between Relics and halos in a few clusters as Coma, A2255, and A2744. In particular, in the Coma cluster a bridge of radio emission about 1 Mpc in size is present between the central halo Coma C and the peripheral Relic source 1253+275 (Kim et al. 1989, Giovannini et al. 1990). We note that this elongated radio emission is oriented in the same direction as the Coma-A1367 supercluster. Also the two Relics at large distance from the cluster center (see previous Sub-Section) could be related to the radio activity in a filament region.

Moreover, Bagchi et al. (2002) found a radio emission coincident with the filament of galaxies ZwCl



**Fig. 4.**— Relic source 0917+75 tentatively associated with A786. The image is from VLA data at 1.4 GHz with a HPBW =  $20''$  (Giovannini and Feretti, 2000)

2341.1+0000, 2.5 Mpc in size. The possible detection of radio emission in filaments would imply the existence of faint magnetic fields in super-cluster regions and will raise questions about the origin of relativistic particles.

## III. CLUSTERS WITH MULTIPLE DIFFUSE SOURCES

### (a) Double Relics

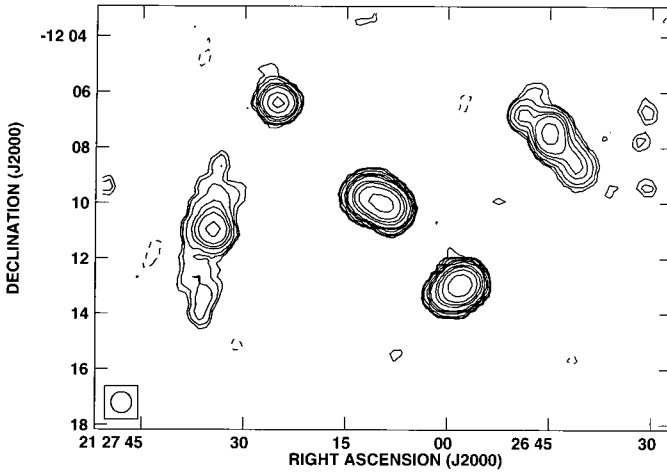
In 6 clusters of galaxies, radio images show two Relic radio sources located in the peripheral regions, and symmetric with respect to the cluster center (see e.g. A2345 in Fig. 5; Giovannini et al. 1999). In most cases these Relic sources show a classical elongated structure. In the parent clusters, no central extended halo source has been detected. The prototype and best studied cluster with two symmetric Relics is A3667 (Rottgering et al. 1997, Johnston-Hollitt et al. 2002, 2003).

These structures suggest that Relics are related to the presence of shock waves originated by mergers between clusters with approximately equal masses. In this scenario, it is expected that Relics should often come in pairs and be located on opposite sides of the cluster along the axis merger, with the extended radio structures elongated perpendicularly to this axis.

### (b) Halo plus Relic

In 7 cases, a cluster shows both a Relic and a halo radio emission. In most cases the Relic emission is elongated and at the cluster periphery and it can be connected to the halo source by a bridge of radio emission (e.g. Coma cluster, A2255 and A2744, see Fig. 6), but complex structures can also be present as in A2256.

The connection between halo sources and cluster



**Fig. 5.**— Double Relics in the cluster A2345. Radio image is from the NVSS survey at 1.4 GHz; see Giovannini et al. (1999).

mergers has been discussed in many papers (see e.g. Feretti 2004 and references therein). A recent major merger process is suggested to supply the energy necessary to reaccelerate the relativistic electrons in the central radio halo. The same merger could be the origin of shock waves which supply the energy to the peripheral Relics. In this scenario, however, the origin of the bridge of radio emission connecting the halo to the Relic source in some clusters has still to be clarified.

#### IV. DISCUSSION

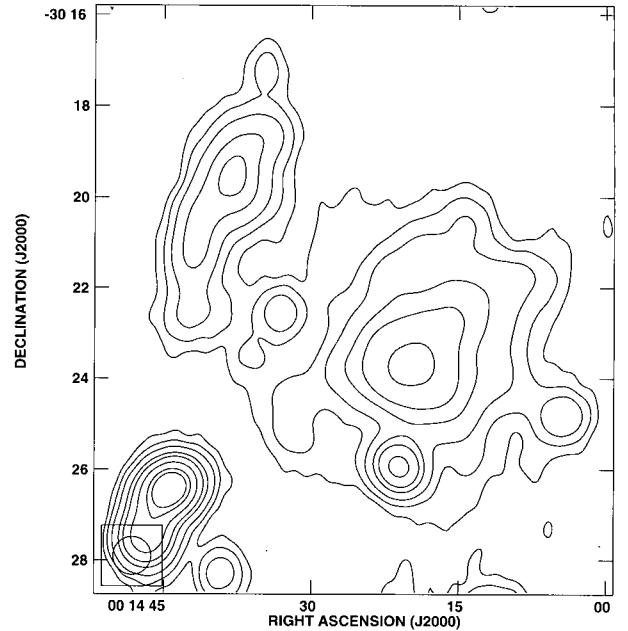
##### (a) Redshift Distribution

In fig. 7 we show the redshift distribution of clusters of galaxies where at least a Relic source has been found. We could have missed Relic sources at very low redshift because nearby Relics could have a too large angular extension to be detected in interferometric observations, due to missing short uv spacings. However, thanks to the irregular and elongated structure of most Relics, this observational problem is not as strong as in the more regular and diffuse halo sources. In Fig. 8 we plot the Relic radio power at different redshifts. The selection effect of the radio power with the distance is well visible. If we consider only Relics with a radio power larger than  $10^{24}$  W/Hz (visible at all distances) we can conclude that the Relic distribution is homogeneous up to  $z \sim 0.3$ .

##### (b) Radio Spectra

Important information on the evolution and properties of Relics can be derived from radio spectra, which reflect the energy distribution of relativistic electrons.

The total radio spectra of Relic sources are steep ( $\alpha > 1$ ). These are typical spectra of old radio sources



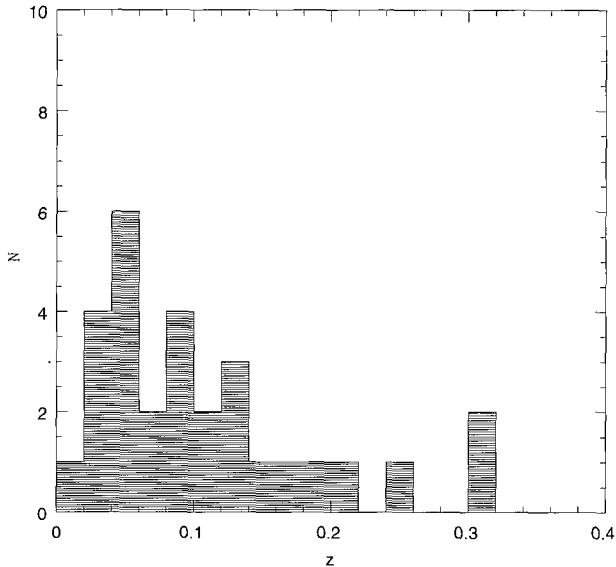
**Fig. 6.**— Halo and Relic source in the cluster A2744. The image is from VLA data at 1.4 GHz; see Govoni et al. (2001a)

where the radiative lifetime of relativistic electrons, taking into account radiative and Inverse Compton losses, is of the order of  $10^8$  years. All small size Relics near the cluster brightest galaxy have very steep ( $> 2$ ) and curved radio spectra (see Slee et al. 2001). On the contrary, the Relic in the Coma cluster and that in A786 show a straight moderately steep ( $\sim 1.2$ ) radio spectrum. The number of Relics with accurate flux density measurements at different frequencies is too small to derive useful considerations.

The spectral index distribution is known only in a few sources as A3667 (Rottgering et al. 1997), 1253+275 in the Coma cluster (Giovannini et al. 1991) and S0753 (Subrahmanyan et al. 2003). The external side, i.e. the more distant side from the cluster center, is always sharper and characterized by a flatter spectrum, consistent with the presence of electron reacceleration in an expanding merger shock, but more data on more Relics are necessary to investigate this point.

##### (c) Models

Enßlin and Gopal-Krishna (2001) proposed a scenario where fossil relativistic particles from no more visible radio sources can gain energy during adiabatic compression by shock waves produced by a merger event. Hoeft et al. (2004) found that cluster-wide shock fronts can revive old radio ghosts when the thermal pressure is much higher than the magnetic field pressure. In this model a much higher occurrence of radio



**Fig. 7.**— Distribution in redshift ( $z$ ) of clusters with at least a Relic radio source

Relics in peripheral locations is expected because in the cluster center the radio plasma ages faster (higher magnetic field) and shock waves are weaker. In the hotter cluster center we have weak shock waves which steepen when they pass the cooler outer regions of the cluster where the compression shock factor increases (Hoefl et al. 2004).

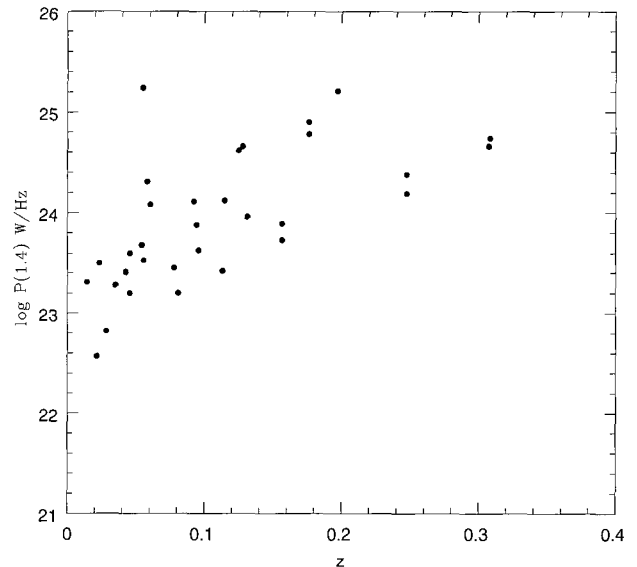
Alternatively, Relic radio emission could be due to electrons directly accelerated from the thermal plasma in shocks (Kempner et al. 2004). This mechanism could explain double Relics and very extended elongated sources, which are more difficult to relate to the fossil electrons supplied by single radio sources.

Tests of these models are difficult because of the very low X-ray brightness of the peripheral cluster regions. Data are presently available for A754, where the radio Relic (Kassim et al. 2001, Bacchi et al. 2003) is found to be at the same position of the hot region found by Markevitch et al. (2003), which indicates the presence of a shock wave.

Finally we need to understand why in many clusters with a merger activity, we do not see Relics.

#### (d) Radio – X-Ray Comparison

Studies of several radio halos permeating the cluster centers have been recently published improving our knowledge of this class of radio sources. In particular it has been found that the radio power correlates with the cluster X-ray luminosity (Bacchi et al. 2003) and that in well resolved clusters a point-to-point spatial correlation is observed between the X-ray and radio brightness (Govoni et al. 2001b).



**Fig. 8.**— Relic radio power at 1.4 GHz in W/Hz versus cluster redshift ( $z$ )

Relics are mostly in peripheral regions, thus we do not expect similar strong correlations to be present between relativistic electrons and hot gas, however a comparison between Relic and X-Ray is important to test the energy origin of Relic radio sources.

For this reason we have compared the Relic total radio power at 1.4 GHz with the parent cluster X-Ray luminosity. Despite of the low radio data quality for some Relic sources, the data show a clear correlation:

$$P_{1.4GHz} \propto 10^K L_{Xbol}$$

where the slope  $K$  is in the range from 0.8 to 2.2. We note that this slope is in agreement with the slope (1.68) found by Bacchi et al. (2003) for the central halo sources, although there is a much larger dispersion. The large dispersion of the data may be due to the lack of homogeneous and deep radio data for many Relic sources, but may also indicate that the connection between the thermal and relativistic plasma in Relics is weaker than in halos. The existence of a correlation is nevertheless very important and could be explained by the link between Relics and cluster mergers.

To support this result we note that all clusters of galaxies which exhibit a Relic source, and which have been analyzed in detail in the optical and/or X-Ray domain, are characterized by the presence of merger events (e.g. A754, Coma, A2256, A3667, etc.). In a few clusters (e.g. A85, A115, A133), also a cooling core is present, probably because the merger event is not strong enough (off-axis merger, or merger between sub-clusters of very different masses) to destroy the central cluster cooling flow. Therefore, also a merger event which is not able to strongly influence the cluster cen-

ter (in these cases no halo source is expected and the cooling flow is not destroyed) seems to be able to re-accelerate particles in cluster peripheral regions and to give origin to peripheral Relic sources.

## V. CONCLUSIONS

1) The number of known Relics is increasing, however, better data are necessary for many of them to allow a proper study.

2) Different Relic morphologies and distances from the cluster center could be correlated with different Relic properties and origin. Elongated Relics are located in peripheral regions, are polarized and show straight spectra. Relics located near a FRG have smaller size and very steep curved spectra. They show a filamentary polarized structure. In some clusters two Relics located symmetrically with respect to the cluster center are present. These structures suggest that Relics are tracers of shock waves. The presence of a halo and a Relic radio source in the same cluster confirms the correlation between cluster mergers and the presence of diffuse emission.

3) A correlation is found between the Relic radio power and the cluster X-Ray luminosity. Although it shows a large dispersion, it is in agreement with the correlation found for halo radio sources.

4) Some Relics are present in clusters showing a central cooling core. This suggests that Relics may originate not only from strong mergers, but also from minor or off-axis mergers, which do not destroy the cooling flow.

5) The presence of radio emission in extended filaments is proved by the radio emission in the Coma cluster and in the galaxy filament ZwCl 2341.1 +0000.

6) The next generation of radio telescopes (LOFAR, LWA and SKA) is necessary to properly study Relics and filaments.

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