The main component of the intracluster medium (ICM) in clusters of galaxies is represented by the X-ray emitting thermal plasma. In addition, the presence of relativistic electrons and large-scale magnetic fields in a fraction of galaxy clusters is demonstrated by the detection of large-scale synchrotron radio sources, which have no optical counterpart and no obvious connection to the cluster galaxies. Observational results provide evidence that these phenomena are related to cluster merger activity, which supplies the energy for the reacceleration of the radio emitting particles. The investigation of the halo-merger connection is of great importance to the knowledge of the formation and evolution of clusters of galaxies.

1 Introduction

Clusters are formed by hierarchical structure formation processes. In this scenario, smaller units formed first and merged to larger and larger units in the course of time. The merger activity appears to be continuing at the present time, and explains the relative abundance of substructures found from X-ray and optical studies, and the gas temperature gradients detected in rich clusters from X-ray observations. The ICM in merging clusters is likely to be in a violent or turbulent dynamical state. It is found that a fraction of clusters which have recently undergone a merger event show diffuse radio sources, thus leading to the idea that these sources are energized by turbulence and shocks in cluster mergers. In this paper, the link between diffuse radio sources and cluster merger processes is discussed, with particular emphasis on the observational aspect.

2 Radio halos and relics

The Coma cluster is the first cluster where a radio halo (Coma C) and a relic (1253+275) have been detected (Willson 1970, Ballarati et al. 1981). The radio halos are permeating the cluster...
central regions, with a brightness distribution similar to that of the X-ray gas (Govoni et al. 2001) and a typical extent of $\gtrsim 1$ Mpc. They are characterized by steep radio spectrum. Limits of a few percent have been derived for their polarized emission. Relic sources are similar to halos in their low surface brightness, large size and steep spectrum, but they are typically found in cluster peripheral regions. Unlike halos, relics are highly polarized ($\sim 20 - 30\%$).

The number of clusters with halos and relics is presently around 50. Examples of radio images of cluster halos and relics are given in Fig. 1. Their properties have been recently reviewed by Giovannini & Feretti (2002, 2004) and Feretti (2005). From radio data, under equipartition conditions, the minimum energy content in halos and relics is of about $10^{60} - 10^{61}$ erg, with minimum non-thermal energy densities of $10^{-14} - 10^{-13}$ erg cm$^{-3}$. The last values are about 1000 times lower than values of the energy density of the thermal X-ray gas. Thus, the non-thermal components are not contributing to a significant fraction of the mass or energy of a cluster. However, the presence of relativistic particles and large-scale magnetic fields are important for a comprehensive physical description of the ICM in galaxy clusters.

3 Connection to cluster merging processes

All clusters hosting halos and relics are characterized by dynamical activity related to merging processes. These clusters indeed show: i) substructures and distortions in the X-ray brightness distribution (Schuecker et al. 2001); ii) temperature gradients (Govoni et al. 2004) and gas shocks (Markevitch et al. 2003a); iii) absence of a strong cooling flow (Schuecker et al. 2001); iv) values of spectroscopic $\beta$ on average larger than 1 (Feretti 2002); v) core radii significantly larger than those of clusters classified as single/primary (Feretti 2002); vi) large distance from the nearest neighbours compared to clusters with similar X-ray luminosity (Schuecker & B"ohringer 1999); the latter fact supports the idea that recent merger events lead to a depletion of the nearest neighbours. Buote (2001) derived a correlation between the radio power of halos and relics and the dipole power ratio of the cluster two-dimensional gravitational potential. Since power ratios are closely related to the dynamical state of a cluster, this correlation represents the first attempt to quantify the link between diffuse sources and cluster mergers.

The link between cluster merger processes and the presence of radio halos and relics indicates a physical connection between the thermal and non-thermal ICM components. However, not all clusters showing merging processes are known to host halos and/or relics. This could be due to the limited sensitivity of current radio telescopes. Indeed it is found that the most powerful radio
halos and relics are detected in the most X-ray luminous clusters (see e.g. Feretti 2005). For halos, this trend is reflected in the correlation of the radio brightness versus X-ray luminosity, presented in Fig. 2. The upper limits shown in the plot are consistent with the correlation suggesting that clusters of low X-ray luminosity might host faint diffuse sources. On the other hand, it is possible that giant halos are only present in the most X-ray luminous clusters, i.e. above a threshold of X-ray luminosity (see discussion in Bacci et al. 2003). This would be expected in the framework of electron reacceleration models (Cassano et al. 2006). Future radio data with next generation instruments (LOFAR, LWA, SKA) will allow the detection of low brightness/low power large halos, in order to clarify if halos are present in all merging clusters or only in the most massive ones.

4 Spectral index distribution of radio halos

A direct confirmation that the cluster merger supplies energy to the radio halo can be obtained from maps of the radio spectral index and their comparison to the X-ray properties. The radio spectral index is related to the energy and ageing of relativistic electrons, and to the strength of the magnetic field in which they emit. These parameters are both influenced by a cluster merger. Thus, 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 the large scale (e.g. radial spectral index trends).

Feretti et al. (2004) obtained maps of the radio spectral index between 0.3 and 1.4 GHz in A 665 and A 2163, and found that regions characterized by flatter radio spectra appear to trace the geometry of recent merger activity. A similar behaviour is derived in A 2744 (Orrú et al. 2006). Since regions of flatter spectra are indication of the presence of more energetic
radiating particles, the above results support the idea that the merger process supplies energy to the radio emitting electrons. In particular, one can compute that in regions of identical volume and same brightness at 0.3 GHz, a flattening of the spectral index from 1.3 to 0.8 implies an amount of energy of the electron population larger by a factor of \( \sim 2.5 \). The difference in the spectral index can also be understood in terms of electron ageing, i.e. by considering that a flatter spectrum generally reflects a spectral cutoff occurring at higher energies. The implication is that the electrons in the flat spectrum regions would have been reaccelerated more recently.

The above results prove that the radio spectral index can be a powerful tracer of the current physical properties of clusters, and confirm the importance of cluster merger in the energetics of relativistic particles responsible for the halo radio emission.

5 Origin of radio halos

The relativistic particles radiating in halos are likely to originate from AGN activity (quasars, radio galaxies, etc.), or from star formation (supernovae, galactic winds, etc.), or from the thermal pool during violent processes connected to the cluster dynamical history. Because of radiation losses, the radiating particles have short lifetimes, of the order of 0.1 Gyr. This implies that they can travel a maximum distance of \( \sim 100 \text{ kpc} \) during their lifetime. Given the large size of the radio emitting regions, the relativistic particles need to be reaccelerated by some mechanism, acting with an efficiency comparable to the energy loss processes (Petrosian 2001). It is found from observational results that a cluster merger plays a crucial role in the energetic of radio halos. Energy can be transferred from the ICM thermal component to the non-thermal component through two possible basic mechanisms: 1) acceleration at shock waves (Keshet et al. 2004); 2) resonant or non-resonant interaction of electrons with MHD turbulence (Brunetti et al. 2001, Fujita et al. 2003).

Shock acceleration is a first-order Fermi process of great importance in radio astronomy, as it is recognized as the mechanism responsible for particle acceleration in the supernova remnants. The acceleration occurs diffusively, in that particles scatter back and forth across the shock, gaining at each crossing and recrossing an amount of energy proportional to the energy itself. The acceleration efficiency is mostly determined by the shock Mach number. Based on observational evidences, it seems difficult to associate giant halos to merger shocks, since the shocks are localized while the radio emission of halos is generally much more extended. In addition, Gabici & Blasi (2003) argue that only shocks of high Mach number (\( \gtrsim 3 \)) are suitable for the electron reacceleration, whereas shocks detected so far with Chandra at the center of several clusters have inferred Mach numbers in the range of \( \sim 1 - 2.5 \) (see e.g. Markevitch et al. 2003a). Finally, the radio spectral index distribution in A 665 (Feretti et al. 2004) shows no evidence of radio spectral flattening at the location of the hot shock detected by Chandra (Markevitch & Vikhlinin 2001).

Therefore, although it cannot be excluded that shock acceleration may be efficient in some particular regions of a halo (e.g. in A 520, Markevitch et al. 2005), current observations globally favour the scenario that turbulence following a cluster shock, rather than a shock itself, might be the major mechanism responsible for the supply of energy to the electrons radiating in radio halos. Numerical simulations indicate that mergers can generate strong fluid turbulence on scales of 0.1 - 1 Mpc. The time during which the process is effective is of \( \sim 10^8 \) years, so that the emission is expected to correlate with the most recent or ongoing merger event. The emerging scenario is that turbulence reacceleration is the likely mechanism to supply energy to the radio halos. Recent theoretical developments of this aspect can be found in Blasi 2004, Brunetti et al. (2004), Cassano & Brunetti (2005).
Figure 3: Results of hydrodynamical simulations of a symmetric off-center merger by Ricker & Sarazin (2001). The colors show the temperature, while the contours represent the X-ray surface brightness. A shocked region is initially at the cluster center, then shocks propagate to the outer part of the cluster.

6 Origin of radio relics

Current theoretical models predict that relativistic particles radiating in radio relics are powered by energy dissipated in shock waves produced in the ICM during the cluster formation history. This picture is supported by numerical simulations on cluster mergers (Ricker & Sarazin 2001, Ryu et al. 2003), which predict that shocks forming at the cluster center at the early stages of a cluster merger further propagate to the cluster periphery (Fig. 3).

Two models have been proposed for the origin of the relic radio emission. It could result from Fermi-I diffusive shock acceleration which produces relativistic electrons from the ICM electrons, or it could be due to fossil radio bubbles, related to former active radio galaxies, that are compressed by the passing shock wave and thus induced to emit observable synchrotron emission again (Ensslin & Gopal-Krishna 2001, Ensslin & Brüggen 2002, Hoeft et al. 2004). In both case, because of the electron short radiative lifetimes, radio emission is produced close to the location of the shock waves. This is consistent with the relic elongated structure, almost perpendicular to the merger axis.

The detection of shocks in the cluster outskirts is presently very difficult because of the very low X-ray brightness in these regions. The X-ray data for radio relics are indeed very scarce. The Chandra data of A 754 (Markevitch et al. 2003b) indicate that the easternmost boundary of the relic (see Fig. 1) coincides with a region of hotter gas. From XMM data of the same cluster, Henry et al. (2004) show that the diffuse radio sources (halo + relic) appear to be associated with high pressure regions.

A recent study of the region of the radio relic 1253+275 in the Coma cluster has been performed by Feretti & Neumann (2006) using XMM-Newton data. X-ray emission is detected at the location of the radio relic (Fig. 4) and is found to be of thermal origin, connected to the sub-group around NGC 4839. The best-fit gas temperature in the region of the relic and in its vicinity is in the range 2.8 – 4.0 keV, comparable to the temperature of the NGC 4839
sub-group. No gas of higher temperature, resulting from a possible shock in the region of the Coma relic, is detected. Therefore, the connection between relics and cluster shocks seems to be disproved by these data on the Coma cluster. The authors suggest that turbulence may be the major mechanism responsible for the energy of particles. In particular, during its infall onto the Coma cluster, the sub-group around NGC 4839 encounters a region of relativistic particles and magnetic fields. The interaction between the ionized moving plasma and the magnetic field would imply energy transfer from the ICM to the relativistic particles. Data on more objects will be crucial to test the models and fully understand the relic phenomenon.

7 Conclusions

Massive clusters of galaxies showing strong dynamical activity and merger processes can host diffuse radio emission, which demonstrates the existence of relativistic particles and magnetic fields in the ICM. From the comparison between radio and X-ray emission there is evidence that recent merger phenomena would provide the energy for the relativistic electron reacceleration, thus allowing the production of a detectable diffuse radio emission. A question which is still unanswered is whether all merging clusters have cluster-wide radio halos. This will be answered by systematic deep studies with future instruments.

Spectral index maps of the halos in A 665, A 2163 and A 2744 show that spectra are flatter in regions more directly influenced by the merger activity, confirming that electrons are likely gaining energy from the merger process. Observational results favour a scenario where cluster turbulence might be the major responsible for the electron reacceleration in radio halos.

Theoretical models predicting a connection between cluster shocks and radio relics need to be tested through X-ray observations of cluster peripheral regions. In the Coma cluster, no clear shock is detected at the location of the radio relic. More data on a significant number of clusters, however, are needed to draw firm conclusions.
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References

1. Bacchi M., Feretti L., Giovannini G., Govoni F., A&A 400, 465 (2003)
2. Ballarati B., Feretti L., Ficarra A., Giovannini G., Nanni M., Olori C., Gavazzi G., A&A 100, 323 (1981)
3. Blasi P., Jour. Kor. Astr. Soc. 37, 483 (2004)
4. Brunetti G., Setti G., Feretti L., Giovannini G., MNRAS 320, 365 (2001)
5. Brunetti G., Blasi P., Cassano R., Gabici S., MNRAS 350, 1174 (2004)
6. Buote D.A., ApJ 553, L15 (2001)
7. Cassano R., Brunetti G., MNRAS 357, 1313 (2005)
8. Cassano R., Brunetti G., Setti G., MNRAS 369, 1577 (2006)
9. Enßlin T.A., Gopal-Krishna, A&A 366, 26 (2001)
10. Enßlin T.A., Brüggen M., MNRAS 331, 1011 (2002)
11. Feretti L., Fusco-Femiano R., Giovannini G., Govoni F., A&A 373, 106 (2001)
12. L. Feretti, in: The Universe at low radio frequencies, IAU Symp. 199, ASP Conference Series, Vol. 199, p. 133 (2002)
13. Feretti L., Orrú E., Brunetti G., Giovannini G., Kassim N., Setti G., A&A 423, 111 (2004)
14. Feretti L., AdSpR 36, 729 (2005)
15. Feretti L., Schuecker P., Böhringer H., Govoni F., Giovannini G., A&A 444, 157 (2005)
16. Feretti L., Neumann D.M., A&A 450, L21 (2006)
17. Fujita Y., Takizawa M., Sarazin C.L., ApJ 584, 190 (2003)
18. Gabici S., Blasi P., ApJ 583, 695 (2003)
19. Giovannini G., Feretti L., in: Merging Processes of Galaxy Clusters, ASSL, Kluwer Ac. Publish., p. 197 (2002)
20. Giovannini G., Feretti L., Jour. Kor. Astr. Soc. 37, 323 (2004)
21. Govoni F., Enßlin T.A., Feretti L., Giovannini G., A&A 369, 441 (2001)
22. Govoni F., Markevitch M., Vikhlinin A., VanSpeybroeck L., Feretti L., Giovannini G., ApJ 605, 695 (2004)
23. Henry P.J., Finoguenov A., Briel U.G., ApJ 615, 181 (2004)
24. Hoeft M., Brüggen M., Yepes G., MNRAS 347, 389 (2004)
25. Keshet U., Waxman E., Loeb A., ApJ 617, 281 (2004)
26. Markevitch M., Vikhlinin A., ApJ 563, 95 (2001)
27. Markevitch M., Vikhlinin A., Forman W.R., in: Matter and energy in clusters of galaxies, ASP Conference Series Vol. 301, p. 37 (2003a)
28. Markevitch M., Mazzotta P., Vikhlinin A., ApJ 586, L19 (2003b)
29. Markevitch M., Govoni F., Brunetti G., Jerius D., ApJ 627, 733 (2005)
30. Orrú E., Feretti L., Govoni F., Murgia M., Giovannini G., Brunetti G., Setti G., AN 327, 565 (2006)
31. Petrosian V., ApJ 557, 560 (2001)
32. Ricker P.M., Sarazin C.L., ApJ 561, 621 (2001)
33. Ryu D., Kang H., Hallman E., Jones T.W., ApJ 593, 599 (2003)
34. Schuecker P., Böhringer H., in: Diffuse thermal and relativistic plasma in galaxy clusters, MPE Report 271, p. 43 (1999)
35. Schuecker P., Böhringer H., Reiprich T.H., Feretti L., A&A 378, 408 (2001)
36. Willson M.A.G, MNRAS 151, 1 (1970)