SF2A 2011
G. Alecian, K. Belkacem, R. Samadi and D. Valls-Gabaud (eds)

NON-THERMAL PHYSICS OF GALAXY CLUSTERS

C. Ferrari [1]

Abstract. Deep radio observations of galaxy clusters have revealed the existence of diffuse radio sources related to the presence of relativistic electrons and weak magnetic fields in the intracluster volume. Non-thermal intracluster phenomena are reviewed, together with the importance for this research field of joint radio, mm, X- and Gamma-ray observations of galaxy clusters.

Keywords: galaxies: clusters: general, radio continuum: galaxies

1 Introduction

Galaxy clusters are complex gravitationally bound astrophysical objects, whose huge masses ($M_{cl} \approx 10^{13} - 10^{15}\ M_\odot$) are principally made of dark matter ($\sim 80\%\ M_{cl}$). Their dominant baryonic component is a hot and tenuous intracluster medium (ICM) that we observe in X-rays ($\sim 15\%\ M_{cl}$). Radio observations have pointed out that the volume in between cluster galaxies may also host a non-thermal component, i.e. weak magnetic fields ($\approx \mu$Gauss) and relativistic particles ($\approx$ GeV). At present, non-thermal emission has been detected in approximately 10% of known clusters, in particular in massive major mergers (Ferrari et al. 2008).

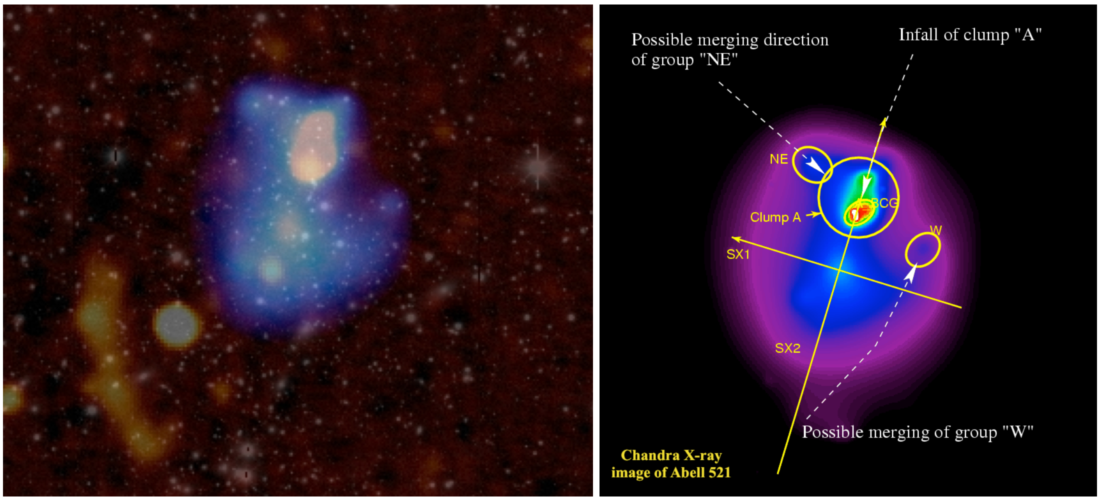

Fig. 1. Left: composite image of the galaxy cluster Abell 521, observed in optical (*ESO*, white), X-rays (*Chandra*, blue) and radio (*VLA*, brown). (Adapted from Ferrari et al. 2003, 2006). **Right**: multiple merging scenario for Abell 521 reconstructed by comparing optical and X-ray observations of the cluster (from Ferrari et al. 2006).

Actually, in agreement with the expectation of the hierarchical scenario of structure formation emerging from the concordant cosmological model, the comparison of X-ray and optical observations with results coming from numerical simulations has now clearly proven that galaxy clusters form through merging of less massive systems (e.g. Maurogordato et al. 2011, see also right panel of Fig. 1)).

---

[1] Université de Nice Sophia Antipolis, CNRS, Observatoire de la Côte d'Azur, Laboratoire Cassiopée, Nice, France

2 Detection of the non-thermal intracluster component

2.1 Radio observations

In 1959 Large et al. mapped for the first time the Coma cluster at radio wavelengths. Despite the very low resolution of their observations ($\sim 40 \times 56$ arcmin^2), they discovered the presence of a resolved and thus extended source at the cluster centre. The nature of this diffuse radio emission remained unclear until 1970, when Willson confirmed its detection and pointed out that the extended source was related to intergalactic emission rather than integrated radiation from unresolved radio galaxies. Since then extended radio sources permeating the central volume of clusters are usually referred as “radio halos” or as “radio mini-halos”, depending on their size ($\gtrsim$ 1 Mpc *vs.* $\lesssim$ 500 kpc). Elongated radio sources in the cluster periphery are known as “radio relics”. These sources are generally characterized by steep synchrotron spectra, indicative of aging of relativistic particles (bottom left panel of Fig. 2).

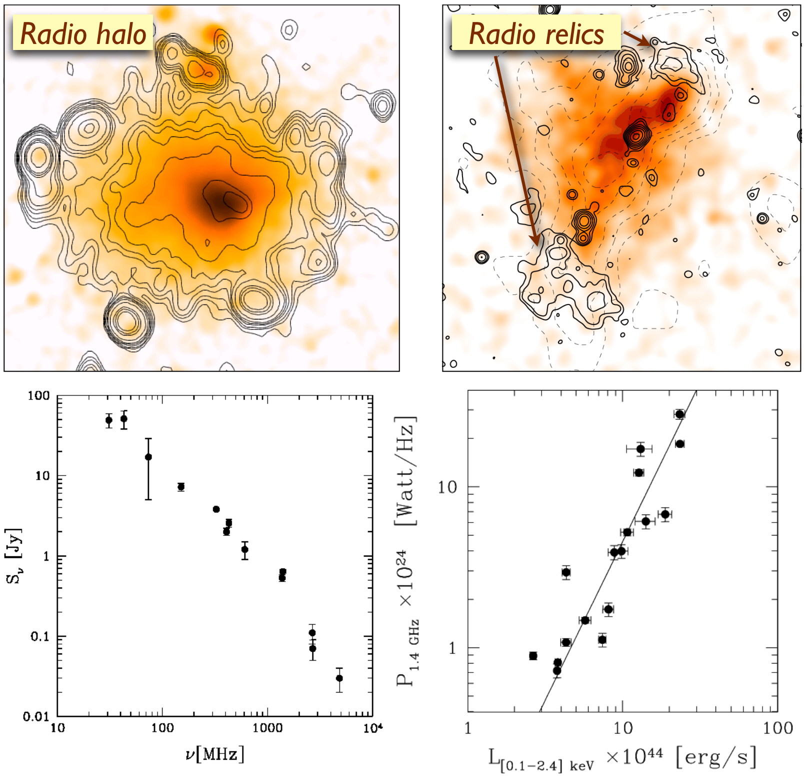

Fig. 2. Top: Radio contours overlaid on the X-ray image of Abell 2163 (*left*) and ZwCl 2341.1+0000 (*right*) (adapted from Feretti et al. 2001; Bourdin et al. 2011; van Weeren et al. 2009). **Bottom**: Spectrum of the radio halo in the Coma cluster (*left* – adapted from Thierbach et al. 2003). Radio power at 1.4 GHz of radio halos *vs.* cluster X-ray luminosity (*right* – adapted from Cassano et al. 2006).

Up to now Mpc-scale intracluster radio sources have been detected only in merging galaxy clusters. Their radio power generally correlates with the X-ray luminosity of the host clusters (see bottom right panel of Fig. 2). Recent results claim however the detection of a few systems lying outside the expected radio *vs.* X-ray correlation. These clusters are under- or over-powerful at radio wavelengths with respect to their X-ray luminosity (Russell et al. 2011; Giovannini et al. 2011).

2.2 Hard X-ray and Gamma-ray observations

If, as detailed in previous sections, X-ray and radio observations have revealed the presence of a highly ionized thermal plasma as well as of relativistic electrons and magnetic fields in the intracluster volume, galaxy clusters are also expected to host relativistic protons and ultra-relativistic electrons (e.g Brunetti et al. 2009). Besides synchrotron radio emission from GeV electrons and intracluster magnetic fields, non-thermal emission from galaxy clusters is thus expected in other bands of the electromagnetic spectrum (Ferrari et al. 2008; Brunetti et al. 2009, and references therein):

- Hard X-rays (HXR) from inverse Compton (IC) scattering of CMB photons by GeV electrons or from synchrotron emission of TeV electrons;

- Gamma-rays from IC scattering of CMB photons by TeV electrons or from inelastic collision of cosmic ray protons with the ions of the CMB. Some gamma-ray emission is also expected from interactions of relativistic electrons and protons with MHD intracluster turbulence.

Evidence of non-thermal (IC) HXR emission from several clusters hosting diffuse radio sources has been obtained mostly through the X-ray satellites *Beppo-SAX* and *RXTE* (Fusco-Femiano et al. 1999; Rephaeli et al. 1999). The detection and nature (thermal or non-thermal) of the HXR excess in galaxy clusters is however strongly debated (Ferrari 2009, and references therein). Up to now, only upper-limits have been derived for the Gamma-ray emission of galaxy clusters (e.g. Ackermann et al. 2010), which imply a cosmic-ray energy density less than 5-20% of the thermal cluster energy density.

3 Open questions and perspectives

The origin of the intracluster non-thermal component observed at radio wavelengths is one of the main open questions of current cluster studies.

Magnetic fields at the observed intensity level ($\approx 1\ \mu$Gauss) could result from amplification of seed fields through adiabatic compression, turbulence and shear flows associated to the hierarchical structure formation process. Seed fields could fill the entire volume of the universe, having been created by primordial processes or through different physical mechanisms (such as the "Biermann battery" effect in merger and accretion shocks, or the outflow from AGN and starburst galaxies in proto-clusters at $z \approx 4 - 6$. See Dolag et al. 2008, for a review).

Different mechanisms can produce cosmic-rays in galaxy clusters. Primary relativistic electrons can be accelerated by processes internal to cluster galaxies and then ejected into the intracluster volume. The expected diffusion velocity of relativistic particles being of the order of the Alfvén speed ($\sim$ 100 km/s), cosmic rays need $\gtrsim$10 Gyr to propagate over radio halo and relic extensions. The radiative lifetime of relativistic electrons is however much shorter ($\lesssim$0.1 Gyr) due to IC and synchrotron energy losses[*]. Cosmic-ray electrons, thus, cannot simply be ejected by active galaxies and propagate over the cluster volume, but they have to be continuously (re-)accelerated *in situ* (see Ferrari et al. 2008, and references therein). Electrons can be (re-)accelerated by shocks and turbulence generated in the ICM by major cluster mergers (Ensslin et al. 1998; Brunetti et al. 2001), or they could have a secondary origin, resulting from hadronic collisions between relativistic protons and ions of the ICM (Dennison 1980). Current radio observational results are mostly in agreement with the first hypothesis (e.g. Brunetti et al. 2008). In particular, intracluster electron re-acceleration would be related to shocks in the case of radio relics, or turbulence in the case of halos and mini-halos. Since most of Mpc-scale radio sources have been detected in luminous merging systems, the energy required to produce radio emitting cosmic-rays would come most likely from the huge gravitational energy released during cluster mergers ($\approx 10^{64}$ ergs). In the case of mini-halos it has been suggested that a population of relic electrons ejected by a central AGN are most likely re-accelerated by MHD turbulence within the central cold cluster region (Gitti et al. 2002).

In a recent work, we have shown for the first time the importance of combining radio and mm studies of galaxy clusters in order to understand the physical mechanisms lying behind electron acceleration (Ferrari et al. 2011). A high-pressure region in the ICM of the galaxy cluster RX J1347-1145 has been pointed out by mm *MUSTANG* observations through the Sunyaev-Zel'dovich effect (Mason et al. 2010). This galaxy cluster was known to host a radio mini-halo, whose cosmic-ray electron origin was attributed to ICM turbulence at the center of the cluster (Gitti et al. 2007). Our low-frequency (240 MHz and 610 MHz) *GMRT* observations point out the existence of an excess radio emission corresponding to the high pressure region of the ICM (see Fig. 3), which is in turn most likely associated to a shock front resulting from a cluster merger (Ferrari et al. 2011).

This result indicates that the diffuse radio source at the center of RX J1347-1145 presents intermediate properties between classical radio mini-halos and relics. The acceleration of electrons in this system results from the combination of different physical mechanisms, suggesting that, if up to now we have observed the "tip of the iceberg" of non-thermal cluster emission, joint multi-wavelength studies of clusters through new radio, mm and X-ray instruments (e.g. *LOFAR*, *Planck*, *NuSTAR* ...) will probably allow us to get a clearer characterization of the physics driving non-thermal intracluster phenomena. Traditional classifications of diffuse intracluster radio sources will lead to a more general view of multi-scale, complex radio emission, deeply connected to the thermo-dynamical history of each cluster.

I acknowledge financial support by the "*Agence Nationale de la Recherche*" through grant ANR-09-JCJC-0001-01.

---

[*] Note that, compared to electrons, cosmic ray protons have much longer lifetimes, comparable to the Hubble time.

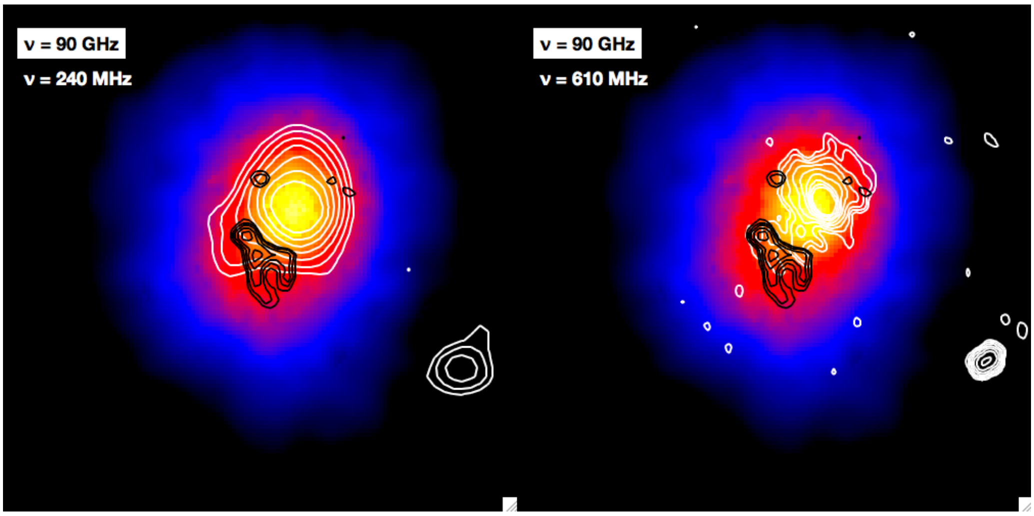

Fig. 3. X-ray image of RXJ1347-1145 with *MUSTANG* 90 GHz contours in black, indicating the presence of a high-pressure ICM region, possibly related to hot shocked gas (Mason et al. 2010). GMRT 240 MHz (*left*) and 610 MHz (*right*) contours are also superimposed (in white). The first radio contours is at 5σ level (with 0.9 and 0.1 mJy/beam noise level at 240 and 610 MHz, respectively). (Adapted from Ferrari et al. 2011).

References

Ackermann, M., Ajello, M., Allafort, A., et al. 2010, ApJ, 717, L71

Bourdin, H., Arnaud, M., Mazzotta, P., et al. 2011, A&A, 527, A21

Brunetti, G., Blasi, P., Cassano, R., & Gabici, S. 2009, in American Institute of Physics Conference Series, Vol. 1112, American Institute of Physics Conference Series, ed. D. Bastieri & R. Rando, 129–137

Brunetti, G., Giacintucci, S., Cassano, R., et al. 2008, Nature, 455, 944

Brunetti, G., Setti, G., Feretti, L., & Giovannini, G. 2001, MNRAS, 320, 365

Cassano, R., Brunetti, G., & Setti, G. 2006, MNRAS, 369, 1577

Dennison, B. 1980, ApJ, 239, L93

Dolag, K., Bykov, A. M., & Diaferio, A. 2008, Space Sci. Rev., 134, 311

Ensslin, T. A., Biermann, P. L., Klein, U., & Kohle, S. 1998, A&A, 332, 395

Feretti, L., Fusco-Femiano, R., Giovannini, G., & Govoni, F. 2001, A&A, 373, 106

Ferrari, C. 2009, in American Institute of Physics Conference Series, Vol. 1126, American Institute of Physics Conference Series, ed. J. Rodriguez & P. Ferrando, 277

Ferrari, C., Arnaud, M., Ettori, S., Maurogordato, S., & Rho, J. 2006, A&A, 446, 417

Ferrari, C., Govoni, F., Schindler, S., Bykov, A. M., & Rephaeli, Y. 2008, Space Sci. Rev., 134, 93

Ferrari, C., Intema, H. T., Orrù, E., et al. 2011, ArXiv e-prints

Ferrari, C., Maurogordato, S., Cappi, A., & Benoist, C. 2003, A&A, 399, 813

Fusco-Femiano, R., dal Fiume, D., Feretti, L., et al. 1999, ApJ, 513, L21

Giovannini, G., Feretti, L., Girardi, M., et al. 2011, A&A, 530, L5

Gitti, M., Brunetti, G., & Setti, G. 2002, A&A, 386, 456

Gitti, M., Ferrari, C., Domainko, W., Feretti, L., & Schindler, S. 2007, A&A, 470, L25

Large, M. I., Mathewson, D. S., & Haslam, C. G. T. 1959, Nature, 183, 1663

Mason, B. S., Dicker, S. R., Korngut, P. M., et al. 2010, ApJ, 716, 739

Maurogordato, S., Sauvageot, J. L., Bourdin, H., et al. 2011, A&A, 525, 79

Rephaeli, Y., Gruber, D., & Blanco, P. 1999, ApJ, 511, L21

Russell, H. R., van Weeren, R. J., Edge, A. C., et al. 2011, MNRAS, L297

Thierbach, M., Klein, U., & Wielebinski, R. 2003, A&A, 397, 53

van Weeren, R. J., Röttgering, H. J. A., Bagchi, J., et al. 2009, A&A, 506, 1083

Willson, M. A. G. 1970, MNRAS, 151, 1