Non thermal emission from clusters of galaxies: the importance of a joint LOFAR/Simbol-X view

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Abstract. Deep radio observations of galaxy clusters have revealed the existence of diffuse radio sources ("halos" and "relics") related to the presence of relativistic electrons and weak magnetic fields in the intracluster volume. I will outline our current knowledge about the presence and properties of this non-thermal cluster component. Despite the recent progress made in observational and theoretical studies of the non-thermal emission in galaxy clusters, a number of open questions about its origin and its effects on the thermo-dynamical evolution of galaxy clusters need to be answered. I will show the importance of combining galaxy cluster observations by new-generation instruments such as LOFAR and Simbol-X. A deeper knowledge of the non-thermal cluster component, together with statistical studies of radio halos and relics, will allow to test the current cluster formation scenario and to better constrain the physics of large scale structure evolution.

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INTRODUCTION

Galaxy clusters, the largest gravitationally bound virialized structures in the Universe, have been discovered at optical wavelengths as concentrations of hundreds to thousands of galaxies in regions of a few Mpc. Most of the cluster baryonic matter is made up by a hot ($T \approx 10^8$ K) and diffuse ($n \approx 10^{-3}\mathrm{cm}^{-3}$) intracluster medium (ICM), emitting in X-ray due to thermal bremsstrahlung [1]. In the last 10 years, joint detailed optical and X-ray analyses [e.g. 2] have shown that galaxy clusters form and evolve through merging of less massive systems, in agreement with the expectation of the hierarchical scenario of structure formation emerging from the concordant cosmological model (ΛCDM). It has also been proved that more than 80% of the cluster mass is in the form of dark matter, only detectable through its gravitational field. On the opposite, the last radiative component of clusters is totally negligible in terms of mass. It is made up by intracluster relativistic electrons and magnetic fields, whose origin and role within cluster physics are still matter of debate (see [3, 4] and refs. therein).

In the following, I will give an overview of our current knowledge of the non-thermal component of galaxy clusters. The perspectives that will be opened in this field by the radiotelescope LOFAR and the X-ray satellite Simbol-X will also be discussed. The ΛCDM model with H_0=70 km $s^{-1}Mpc^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$ has been adopted.

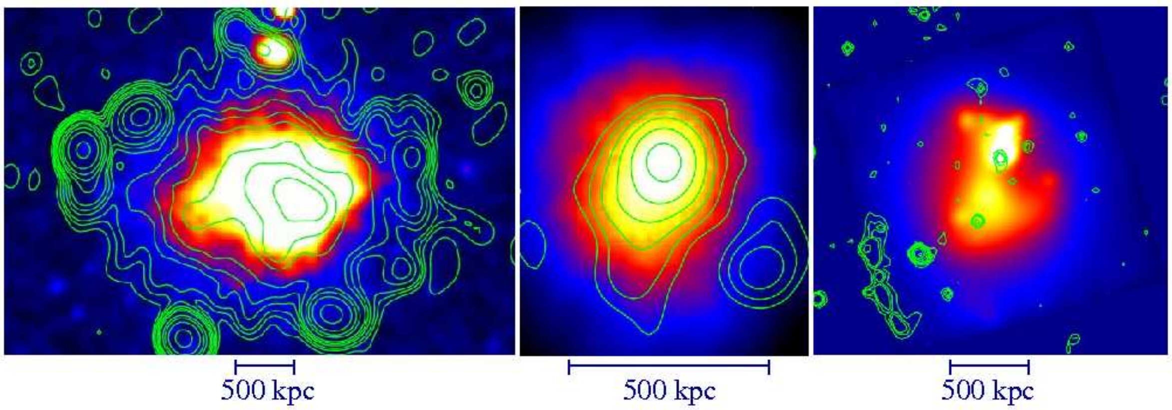

FIGURE 1. Examples of the three classes of diffuse radio sources in galaxy clusters: halos (left), mini-halos (centre) and relics (right). Radio contours are overlaid on the X-ray images of the three galaxy clusters A2163, RX J1347-1145 and A521. Radio data are from the VLA [9, 10, 2], X/ray data from XMM-Newton [11, 12] or Chandra observations [2].

THE INTRACLUSTER NON-THERMAL COMPONENT

Observational evidence

Radio Observations - Diffuse radio emission from galaxy clusters was discovered in Coma by Large et al. [5] and then confirmed by Willson [6], who suggested that the extended synchrotron radio emission was due to the presence of relativistic electrons (Lorentz factor $\gamma >> 1000$) and magnetic fields (μG) in the intracluster volume. Radio observations thus provided the first direct evidence of the presence of a non-thermal intracluster component. Statistical studies of the intracluster radio emission could start only in the 90's [e.g. 7] with the advent of continuum radio surveys such as the NVSS [8]. The surface brightness of diffuse radio sources in clusters is very low ($\sim \mu$Jy/arcsec^2 at 1.4 GHz). The detection of extended cluster radio emission is thus a challenge and, at present, only about 60 clusters are known to host diffuse radio sources. These are all characterised by steep synchrotron spectra, but can differ in their morphology and position in the host clusters (see Fig. 1). The following working definition is usually adopted a) *radio halos* are extended ($\gtrsim$1 Mpc) sources that have been detected at the centre of merging clusters; their morphology is similar to the X-ray morphology of the cluster; b) *radio mini-halos* are smaller sources ($\lesssim$500 kpc) located at the centre of cooling flow clusters; they surround a powerful radio galaxy; c) *radio relics* have extensions similar to halos and are also detected in merging clusters, but they are usually located in the cluster outskirts and have an elongated morphology.

Hard X-ray (HXR) observations - Intracluster relativistic electrons can give rise to HXR emission through Compton scattering of CMB photons [13]. The satellites Beppo-SAX and RXTE allowed to detect a non-thermal HXR excess in several clusters hosting diffuse radio sources ([14, 15] and refs. therein). However, if the radio emission from the non-thermal component is well established, the presence of an intracluster non-thermal HXR excess is at present debated. This is firstly due to the challenging detection of this kind of X-ray emission, complicated by astrophysical and instrumental backgrounds [e.g. 16, 17]. Other instruments (e.g. INTEGRAL, Swift, Suzaku) are however confirming the presence of an HXR excess in clusters hosting diffuse radio sources. The nature of the HXR excess is, in turn, debated.

Several papers agree with the *non-thermal origin* of this emission. In about 10 clusters hosting diffuse radio sources HXR data are in agreement with the Compton scattering hypothesis [e.g. the Coma cluster 18, 19, 20]. Other observations on the contrary suggest that the non-thermal HXR excess is due to a population of AGNs [e.g. 21]: since the hard X-ray instruments on both Beppo-SAX and RXTE are non imaging, contamination by very hard point sources inside the cluster cannot be excluded. Two other non-thermal hypotheses have been suggested from the theoretical point of view: the HXR excess could be due to non-thermal or supra-thermal bremsstrahlung [e.g 22, 23], or to synchrotron emission from ultrarelativistic electrons [e.g 24]. Finally, recent observational results confirm the detection of an HXR excess, but relate it to a *multi-temperature ICM emission* [e.g. 21, 25]. There are currently growing observational and numerical evidences pointing towards a non-uniform distribution of the ICM temperature in merging clusters, where diffuse radio sources have been detected and shocks can heat the ICM up to temperatures of several tens of keV [e.g. 26]. All these hypotheses need to be tested both from the theoretical and from the observational point of view through combined multi-frequency data [e.g. 27]

Main physical properties and open questions

Magnetic fields - Intracluster magnetic field intensities can be measured [28]: a) from the ratio between the synchrotron and Compton HXR fluxes, under the assumption that they are produced by the same population of relativistic electrons, b) through Faraday rotation analysis of radio sources in the background or in the galaxy clusters themselves, c) by assuming that the energy density of the relativistic plasma within the diffuse radio source is minimum (equipartition hypothesis), d) from the X-ray analysis of cold fronts. These measures give quite discrepant results, with magnetic field values ranging from $\sim$0.1 μG to $\sim$10 μG. These differences can be due to several factors, such as the various physical assumptions of the different methods, and the complicated spatial profile and structure of both the magnetic field and the gas density [4]. Variations of the magnetic field structure and strength with the cluster radius have been recently pointed out by Govoni et al. [29], stressing the need of more sophisticated studies of intracluster magnetic fields.

Relativistic particles - Due to radiative losses, the typical lifetime of relativistic electrons in the ICM is too short ($\sim$0.1 Gyr) to allow them to propagate with diffusion Alfvénic velocities over the typical Mpc scales of halos and relics. This requires *in situ* injection of relativistic electrons by physical mechanisms which are usually divided in two main classes: primary and secondary models. The former predict the (re)acceleration of fossil radio plasma or directly of thermal electrons of the ICM through shocks and/or MHD turbulence, which, in turn, can be generated either by cluster merging (in the case of halos and relics [e.g. 30, 31]), or by the central cooling-flow (in the case of mini halos

[32]). Secondary models predict that non-thermal electrons are the secondary products of hadronic interactions between relativistic protons (which have long lifetimes in clusters) and the ions of the thermal ICM [e.g. 33]. p-p collisions take place in all galaxy clusters, both relaxed and mergers, and are expected to inject also neutral pions in the ICM, which in turn decay and produce gamma-ray emission.

Most of the theoretical predictions of primary models are in agreement with current observational results, in particular concerning the spectral behaviour of radio halos and relics, and the correlation between the physical properties of these radio sources and of their host clusters (dynamical state, mass, luminosity, ...; see [4] and refs. therein). A certain number of open questions needs anyway to be addressed, such as: do all (merging) clusters host diffuse radio sources? Is the low number of known radio halos and relics related to physical or instrumental effects? What is the origin of peculiar sources and of the seed electrons for re-acceleration models? To answer this last question, hybrid models for electron acceleration (i.e. a combination of primary and secondary mechanisms) have also been proposed. These works stress the importance of the next generation of radio (e.g. LOFAR), gamma-ray (e.g. Fermi) and HXR telescopes (e.g. Simbol-X) to put essential constraints on current theoretical predictions [34, 35].

PERSPECTIVES: LOFAR AND SIMBOL-X

Enormous perspectives for the investigation of the non-thermal intracluster component will be opened by LOFAR (LOw Frequency ARray) and the Simbol-X satellite [e.g. 36]. The latter, with its imaging capabilities up to high energies ($\sim$ 80 keV), will allow to study unambiguously the presence and origin of HXR emission in clusters [e.g. 37]. LOFAR is an array of radiotelescopes that will open the low-frequency spectral window ($<$300 MHz) to deep and high-resolution observations [e.g. 38]. This low-frequency domain is optimal for the detection of high spectral index radio sources, such as radio halos, mini-halos and relics (see Fig. 7 in [4]), and about 1000 halos and relics are expected to be detected by LOFAR, of which 25% at z$\gtrsim$0.3 [38]. Statistical studies of the evolution of diffuse radio emission in clusters as a function of redshift and cluster physical properties will thus become possible. A combination of the LOFAR cluster catalogue with new X-ray and SZ cluster surveys (e.g. XMM-LSS, Planck, ...) will be suitable for a full understanding of galaxy cluster physics.

It has recently been estimated that the best targets for Simbol-X studies of the non-thermal intracluster emission are clusters at $z \lesssim$0.2 [37, 40]. Fig. 2 shows that, in the same redshift range, the LOFAR "All Sky Survey" [41] is expected to detect cluster diffuse radio sources well below current observational limits. At $z < 0.2$, joint detailed LOFAR/Simbol-X observations will thus allow to study:

- The energy spectrum of relativistic particles: it can be complementary constrained by radio and HXR observations. Actually, if the observed synchrotron radio emission and Compton HXR emission are produced by the same electron population, they share the same spectral index α ($S(\nu) \propto \nu^{-\alpha}$). This spectral index relates to the index δ of the power-law electron energy density distribution as $\delta = 2\alpha + 1$.

- Intracluster magnetic fields: their intensity and, possibly, structure will be measured

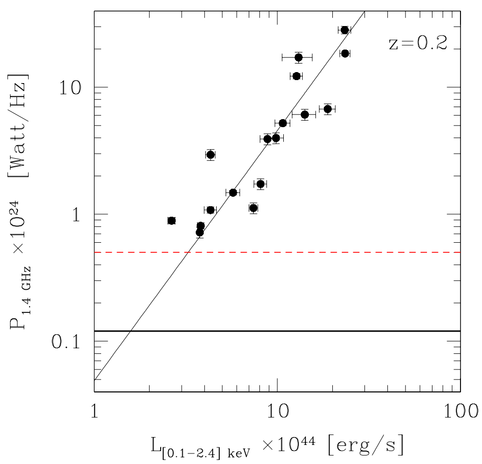

FIGURE 2: Radio power of observed halos *vs.* X-ray luminosity of their host clusters. The two quantities show a strong correlation [e.g. 39]. The horizontal dashed line indicates the approximate limit of current radio observations. The limit expected at z=0.2 in the LOFAR "All Sky Survey" for the 10σ detection of at least 50% of the flux of radio halos is indicated by the solid line. The observed correlation between radio halos' luminosities and sizes, and the X-ray luminosity of the cluster have been adopted.

with a significantly better statistics through: a) Faraday rotation measures of hundreds of embedded/background radio galaxies and joint polarisation studies of diffuse radio sources [42] (LOFAR observations); b) the ratio between the synchrotron and Compton HXR fluxes (see Eq. 13 in [4]; LOFAR + Simbol/X observations).

- The nature of radio relics: Simbol-X will be particularly suited for the study of cluster radio relics detected by LOFAR. The X-ray emissivity of the thermal ICM depends on the square density of the gas, and is thus significantly lower in the external regions of clusters (where relics are located) compared to the central parts. That is the reason why the correlation between thermal shocks and radio relics has been so poorly constrained by observations up to now [e.g. 43]. This decrease of the X-ray thermal emissivity in the cluster outskirts makes the detection of the non-thermal component over the thermal emission easier in the relic regions (for more details, see [37]).

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