Non-thermal emission from galaxy clusters

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Abstract. The relevance of non-thermal cluster studies and the importance of combining observations of future radio surveys with WFXT data are discussed in this paper.

Key words. Cosmology: large-scale structure – Galaxies: clusters: general – Radiation mechanisms: non-thermal

1. Introduction

The discovery of diffuse radio sources in a few tens of merging galaxy clusters has pointed out the existence of a non-thermal component (i.e. relativistic particles with Lorentz factor \( \gamma \gg 1000 \) and magnetic fields of the order of \( \mu \text{G} \)) in the intracluster volume (e.g. Ferrari et al. 2008). Through non-thermal studies of galaxy clusters we can estimate the cosmic-ray and magnetic field energy budget and pressure contribution to the intracluster medium (ICM), as well as get clues about the cluster dynamical state and energy redistribution during merging events. Non-thermal analyses can elucidate non-equilibrium physical processes whose deep understanding is essential to do high-precision cosmology using galaxy clusters (Pfrommer 2008).

In the following, we will give an overview of the main open questions about the non-thermal intracluster component (Sect. 2). The perspectives that will be opened in this field by a new generation of radio telescopes will also be addressed (Sect. 3.1). We will focus in particular on the study of clusters with similar X-ray and radio morphologies, i.e. clusters hosting diffuse radio sources that are called “radio halos”. The importance of an X-ray facility such as WFXT will be discussed (Sect. 3.2). The \( \Lambda \)CDM model with \( H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1} \), \( \Omega_m = 0.3 \) and \( \Omega_\Lambda = 0.7 \) has been adopted.

2. Open questions

The origin of intracluster cosmic rays (CRs) is matter of debate. CRs, gyrating around magnetic field lines which are frozen in the ICM, have typical diffusion velocity of the order of the Alfvén speed (~ 100 km/s). They thus need \( \gtrsim 10 \text{ Gyr} \) to propagate over radio halo extensions. Radiative timescales are longer than the Hubble time for CR protons (CRps). They thus can be continuously accelerated (directly in the ICM or inside active galaxies and then ejected), resulting in an effective accumulation of relativistic and ultra-relativistic CRps in clusters. Hadronic CRs can subsequently produce Gamma-rays and secondary relativistic electrons through inelastic collisions with the ions of the ICM (e.g. Aharoonian et al. 2009).

The radiative lifetime of relativistic electrons (CREs) is instead much shorter (< 0.1 Gyr) than their cluster crossing time due to in-
verse Compton (IC) and synchrotron energy losses. Therefore CRs have to be continuously re-accelerated in situ. Two main classes of models have been proposed to explain intracluster electron acceleration: primary and secondary models. The former predict the acceleration of fossil radio plasma or directly of thermal electrons of the ICM through shocks and/or MHD turbulence generated by cluster mergers. Secondary models predict instead that non-thermal electrons in clusters are the secondary product of hadronic interactions between relativistic protons and the ions of the thermal ICM (e.g. Ferrari et al. 2008).

Current observational results are in favour of primary models. The very few detailed analyses of the radio spectral index $\alpha$ distribution in radio halos show hints of a possible increase of $\alpha$ as a function of radius and of frequency (e.g. Thierbach et al. 2003), as expected in the case of primary models. A possible anti-correlation between $\alpha$ and the ICM temperature (i.e. flatter spectra in hotter regions) has also been pointed out in a few cases (e.g. Orru et al. 2007). The hottest ICM regions are usually associated to shock and/or turbulence induced by cluster collisions. The fact that these regions host younger CRs is thus in agreement with primary models. A unique prediction of the turbulence re-acceleration models is the existence of ultra-steep radio halos, not associated to major cluster mergers, but to less energetic merging events. Recently Brunetti et al. (2008) claimed the detection of the first ultra-steep radio halo in the multiple merging cluster A521. At the moment, the most striking observational evidence in favour of primary models is the fact that diffuse cluster sources have been detected only in merging clusters.

Deeper statistical analyses of the correlation between diffuse radio sources and the physical properties of their host clusters are required to refine the physical models for CR acceleration. For instance, we know that diffuse radio sources have been detected in $\leq 10\%$ of known clusters, while about 40\% of clusters show a disturbed dynamical state: why cluster mergers seem to be a necessary but not sufficient condition for the acceleration of intracluster relativistic particles? The answer could be related to the cluster mass, since a correlation between radio and X-ray cluster luminosity has been pointed out (e.g. Buote 2001). This suggests that only the most massive merging clusters are energetic enough to produce diffuse radio emission at power levels observable with current radio observations (see also the discussion in Sect. 3.1).

Even more debated are the origin and properties of intracluster magnetic fields (Dolag et al. 2008). The different methods available to measure intracluster magnetic fields (equipartition assumption, rotation measures, Compton scattering of CMB photons, X-ray study of cooling-cores in the ICM) show quite discrepant results (see Table 3 of Govoni & Feretti 2004). Different reasons can explain this discrepancy (e.g. Ferrari 2010). Again, higher statistics is required for magnetic field measurements. For instance, we need deeper multi-wavelength radio observations of radio galaxies per cluster for rotation measure (RM) estimates, combined to detailed modeling of the ICM X-ray brightness profile (Govoni et al. 2001b).

3. Perspectives

3.1. A new generation of radio telescopes

Huge perspectives in the study of the non-thermal intracluster component will be open by the Low Frequency Array (LOFAR, Röttgering et al. 2006). A steepening of the synchrotron spectrum of radio halos is expected in the framework of stochastic particle acceleration by MHD turbulence and it has been observed in several halos (see Ferrari et al. 2008). Cassano et al. (2010) have introduced a characteristic frequency $\nu_s \sim 7\nu_B$, at which the steepening become extremely severe. Basically, surveys at frequency $\nu > \nu_s$ cannot detect radio halos. Since the lower is the radio luminosity of the halo, the lower is the expected break frequency, high-frequency ($\nu \approx 1.4$ GHz) surveys are sensitive only to high-luminosity halos, while most of the faint radio luminos-
will unveil statistical samples of hundreds candidates of diffuse cluster radio sources (Feretti et al. 2004). As detailed above, wide and deep complementary cluster catalogs at other wavelengths will be necessary in order to answer the open questions about non-thermal cluster physics.

After LOFAR, the following survey project very important for non-thermal cluster studies will probably be EMU (“Evolutionary Map of the Universe”, project leader: R. Norris). It will be a deep radio survey (∼10 µJy rms; 1130 – 1430 MHz) covering the entire Southern sky and part of the Northern sky (δ ≤ 30°) with the ASKAP telescope. Fig. 1 shows the brightness temperature at ∼1.3 GHz as a function of redshift expected for radio halos of a given total flux and of 0.5 Mpc radius. The shaded area delimited by solid lines indicates an approximate 3σ sensitivity level of the EMU survey. We have taken into account that the exact observing strategy of EMU is under discussion. The best resolution of the survey will be of ∼10 arcsec, but lower resolutions radio maps will also be produced in order to increase the sensitivity to diffuse radio sources (see Sect. 3.5.1 in Johnston et al. 2008). We have assumed here and in the following (see also Fig. 2) an rms sensitivity of 10-20 µJy/beam, with beam sizes varying from 40 to 80 arcsec. Our estimates for the EMU survey are here compared to the T_b ∼ 5mK sensitivity limit of 50% of the SKA collecting area. This 3σ sensitivity level (indicated by a dot-dashed line in Fig. 1) has been estimated by Feretti et al. (2004) assuming an integration time of 1 hour. The shaded area delimited by dot-dashed curves correspond to the 3σ sensitivity limit of 50% SKA at the same resolution limits that we have adopted for EMU (from 40 to 80 arcsec).

Based on the results in Fig. 1 and on the radio halo luminosity function derived by Enßlin & Röttgering (2002) (see also Table 1 in Feretti et al. 2004) we can expect to detect ≥ 300 halos at any redshift with EMU (i.e. halos in ≥ 2π sterad with S_{tot} > 1 mJy) and several thousands (≥ 6000) halos with the low-resolution 50% SKA observations (1h integration time), among which about one third at z > 0.3. In such a case, in fact, our SKA estimates indicate that we can

Fig. 1. Brightness temperature at ∼1.3 GHz as a function of redshift expected for radio halos of a given total flux and of 0.5 Mpc radius. Possible limits for the ASKAP EMU Survey and for 50% of the SKA with 1 hour integration time are indicated (shaded areas delimited by solid and dot-dashed lines respectively).

The full international LOFAR telescope should be operational by early 2011. Other new generation radio telescopes will follow in the next few years, such as the Long Wavelength Array (LWA, 10–80 MHz), the Australian Square Kilometre Array Pathfinder (ASKAP, 70–1800 MHz), the Karoo Array Telescope (MeerKAT, 0.58–15 GHz). All these instruments will indeed play an important role for the study of non-thermal cluster physics and, more generally, will be crucial scientific and technical pathfinders for the Square Kilometre Array (SKA, 0.10–25 GHz). Multi-frequency radio surveys of the sky will be available that

2 http://www.lofar.org/astronomy/surveys-ksp/surveys-ksp
3 http://lwa.unm.edu/
4 http://www.atnf.csiro.au/SKA/
5 http://www.skatelescope.org/meerkat/
6 http://www.skatelescope.org/
go down to $S_{\text{snr}} \approx 10 \mu$Jy at any redshift. Note that, in addition, EMU could detect several tens higher redshift ($\gtrsim 0.3$) halos with $S_{\text{snr}} > 0.1$ mJy.

We have then refined our estimates to evaluate the evolution with redshift of the X-ray luminosity limit of clusters whose diffuse radio emission can be detected by the EMU Survey (shaded are delimited by solid curves in Fig. 2). We have considered radio halos of 1 Mpc size with radio luminosities $L_{1.4GHz} \gtrsim 5 \times 10^{20}$ W/Hz and a typical brightness profile as a function of radius has been adopted (Govoni et al. 2001a):

$$B_{v}(\eta R_{h}) = \frac{\xi L_{1.4GHz}(1400/\nu)^\alpha(1 + z)^{-3+\alpha}}{1.5 \times 10^{31}(\eta R_{h})^2}$$

where $\xi$ indicates the fraction of the total flux of the source at $r = \eta R_{h}$ (thus $\xi \leq 1$ and $\eta \leq 1$), $B_{v}$ is in Jy/arcsec$^2$, $L_{1.4GHz}$ in W/Hz, $\nu$ in MHz and $R_{h} (=0.5)$ in Mpc. In our estimates a radio halo is considered to be detected when $B_{v}(\eta R_{h}) \geq 5-10 \text{mJy}_{\text{EMU}}$ and $\xi = 0.5$. The EMU detection limits for radio halo luminosities have finally been converted to X-ray luminosities of the host clusters following Eq. (1) in Cassano et al. (2006). Increased inverse Compton energy losses on the CMB at higher redshift and the consequent decrease in the intrinsic radio halo luminosity have also been taken into account (Enßlin & Röttgering 2002).

Note that the EMU limits shown in Fig. 2 concern the Wide EMU survey described above. The possibility to perform deeper ASKAP surveys, in particular at lower frequencies (~850 MHz) that are more favorable to radio halo detection, is currently considered within the EMU project (Johnston-Hollitt, private communication). In such a case, complementary cluster catalogs could provide excellent targets for deeper radio follow-ups, thus helping in selecting the regions of the sky to be observed with ASKAP, MeerKAT or any other radio facility. Fig. 2 also shows the detection limit expected with 50% of the SKA collecting area at a resolution of ~8, 40 and 80 arcsec, assuming a bandwidth of 0.5 GHz and an integration time of 1 hour. As before, a 3$\sigma$ level brightness sensitivity of $T_{b} \sim 5$ mK has been adopted for these estimates (Feretti et al. 2004). We have converted this radio brightness sensitivity to X-ray luminosity limits as a function of redshift by adopting exactly the same method of our previous EMU estimates. The detection limits are here at 10 $\sigma$ level. Much deeper sensitivity limits can of course be reached with the full SKA and longer integration times.

3.2. Importance of WFXT surveys

In order to be able to test current models about the origin of the non-thermal intracluster component we need both statistical studies of the fraction of observed clusters hosting diffuse radio sources as a function of the cluster mass and $z$, and detailed analyses of how the correlation between the radio emission and the physical properties of clusters ($L_{X}$, $T_{X}$, mass, dynamical state...) evolve with $z$. The newly identified candidates of radio emitting clusters described in Sect. 3.1 will thus have to be cross-matched with cluster catalogs in other wave bands, which will be needed for the cluster identification and physical characterization.

On short timescales, existing or incoming optical, IR, sub-mm and X-ray surveys will provide an important set of complementary data for the identification of potential clusters detected by LOFAR (among others: Ebeling et al. 1998; Böhringer et al. 2000; Ebeling et al. 2001; Böhringer et al. 2001; Góto et al. 2002; van Breukelen et al. 2006; Olsen et al. 2007). In Ferrari (2010) we have compared the cluster X-ray luminosity detection limits of Planck and LOFAR. Our estimates indicate that the Tier-1 Wide LOFAR survey will provide a galaxy cluster catalog through diffuse radio source detection that will match the expected Planck cluster detection at $z \lesssim 0.3$. At higher redshift, all the systems detected by LOFAR will have an X-ray luminosity above the Planck detection limit. Fig. 2 shows that the cluster detection limits of Planck will also be perfectly suited for the comparison with the list of diffuse radio surveys resulting from the EMU.
Fig. 2. Evolution with redshift of the X-ray luminosity limit of clusters whose diffuse radio emission can be detected: a) (shaded area delimited by solid lines) at 5-10 $\sigma$ significance level with the ASKAP telescope down to the sensitivity limit of the EMU-Wide survey and at 40 to 80 arcsec resolution (Sect. 3.1); b) (dot-dashed line) at 10 $\sigma$ significance level with 50% of the SKA collecting area assuming an integration time of 1 hour and a resolution of 8 arcsec (Feretti et al. 2004); c) (shaded area delimited by dot-dashed lines) at 10 $\sigma$ significance level with 50% of the SKA collecting area assuming an integration time of 1 hour and 40 to 80 arcsec resolution. The cluster detection limits expected for the Planck (dotted line; courtesy of A. Chamballu and J. Bartlett) and WFXT-Wide (dashed line; courtesy of B. Sartoris) surveys are also shown. The thinner curves, finally, correspond to the bright sample limits of the WFXT Wide and Medium surveys (Sartoris et al. 2010).

Wide survey. eROSITA $^7$ detection limits should match well the radio halo cluster detection limits with EMU presented here (Reiprich, private communication). Based on our estimates radio observations with the SKA will instead require deeper complementary surveys for cluster cross-identification.

The projected WFXT surveys will provide two kinds of cluster catalogs (Giacconi et al. 2009; Sartoris et al. 2010): ∼ $3 \times 10^6$ detected clusters (out of which ≈ 98% at $z < 1$), and ∼ $2 \times 10^4$ clusters (the so called “bright sample”), which, with a flux limit 30 times brighter than the detection flux limit, will have robust measures of mass proxies, as well as of ICM surface brightness and temperature profiles.

Most of the cluster detections will come from the all-sky WFXT Wide Survey, while the “bright sample” at $z < 1$ is mainly due to the Medium WFXT survey, which would cover 3000 square degrees (see Table 1 and Fig. 3).

$^7$ http://www.mpe.mpg.de/heg/www/Projects/EROSITA/main.html

For $z \gtrsim 1$ the lifetime of CRs whose synchrotron emission peaks at 1.4 GHz $\tau \lesssim 10$ Myr due to IC energy losses,
In Fig. 2 we have plotted the X-ray luminosity detection limits of the WFXT Wide survey as a function of \( z \) (red dashed curve), as well as the X-ray luminosity limits for the bright samples resulting from the Wide and Medium WFXT surveys (thin red curves). Fig. 2 shows that the comparison between possible WFXT and radio surveys could provide:

- an all-sky cluster catalog (WFXT Wide, dashed thick line in Fig. 2) deep enough for the identification of \( \geq 6000 \) candidate clusters hosting diffuse radio emission coming from SKA observations (see Sect. 3 and Fig. 1). This sample will offer the unique opportunity to study in a fully statistical way the cluster radio vs. X-ray luminosity correlation (Sect. 2);

- the possibility to compare radial profiles of the radio spectral index \( \alpha \) and of the ICM brightness and temperature (Sect. 2). This could be done on several hundred clusters at \( z < 0.5 \) by combining radio surveys data (LOFAR, ASKAP, SKA in Fig. 2) with the bright samples deriving from WFXT Wide and Medium surveys (thin red lines in Fig. 2);

- interesting targets for deeper LOFAR, ASKAP, MeerKAT or SKA follow-ups.

WFXT will provide X-ray surveys with the necessary sensitivity to match those achievable in future radio surveys of galaxy clusters.

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