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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 γ >>1000 and magnetic fields of the order of μG) 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 ΛCDM model with H_0=70 km s^{-1}Mpc^{-1}, Ω_m = 0.3 and Ω_Λ = 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 Gyr to propagate over radio halo extensions. Radiative timescales are longer than the Hubble time for CR protons (CR*p*s). 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 CR*p*s in clusters. Hadronic CRs can subsequently produce Gamma-rays and secondary relativistic electrons through inelastic collisions with the ions of the ICM (e.g. Aharonian et al. 2009).

The radiative lifetime of relativistic electrons (CR*e*s) is instead much shorter ($\lesssim$0.1 Gyr) than their cluster crossing time due to in-

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verse Compton (IC) and synchrotron energy losses. Therefore CR*e*s 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 α[1] distribution in radio halos show hints of a possible increase of α as a function of radius and of frequency (e.g Thierbach et al. 2003), as expected in the case of primary models. A possible anticorrelation between α and the ICM temperature (i.e. flatter spectra in hotter regions) has also been pointed out in a few cases (e.g. Orrú 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 CR*e*s 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 multiwavelength 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 nonthermal 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 (e.g. 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-

[1] $S_\nu \propto \nu^{-\alpha}$

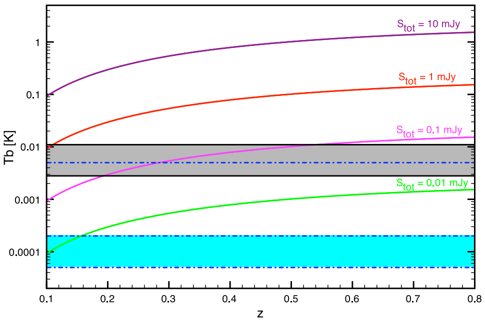

Fig. 1. Brightness temperature at $\sim$ 1.3 GHz as a function of redshift expected for radio halos of a given total flux and of 0.5 Mpc radius. Possible limits for the *ASKAP* EMU Survey and for 50% of the *SKA* with 1 hour integration time are indicated (shaded areas delimited by solid and dot-dashed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

ity halo tail will appear at low-frequency radio observations. That's the huge potential of *LOFAR* in the study of diffuse cluster radio sources. Radio maps resulting from the *LOFAR* Surveys[2] (Tier-1 Wide, Tier-2 Deep, Tier-3 Ultra Deep) are expected to provide a catalog of several hundreds candidates of galaxy clusters hosting diffuse radio sources (e.g. Cassano et al. 2010).

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)[3], the Australian Square Kilometre Array Pathfinder (*ASKAP*, 70–1800 MHz)[4], the Karoo Array Telescope (*MeerKAT*, 0.58–15 GHz)[5]. 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)[6]. Multi-frequency radio surveys of the sky will be available that will unveil statistical samples of hundreds candidate diffuse cluster radio source (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 ($\sim$ 10 μJy rms; 1130 – 1430 MHz) covering the entire Southern sky and part of the Northern sky ($\delta \lesssim 30°$) with the *ASKAP* telescope. Fig. 1 shows the brightness temperature at $\approx$ 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 3 σ 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 variating from 40 to 80 arcsec. Our estimates for the EMU survey are here compared to the $T_b \sim$ 5mK sensitivity limit of 50% of the *SKA* collecting area. This 3σ sensitivity level (indicated by a dot-dashed line in Fig. 2) 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 3 σ 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 $\gtrsim$ 300 halos at any redshift with EMU (i.e. halos in $\gtrsim 2\pi$ sterad with S_{tot} > 1 mJy) and several thousands ($\gtrsim$ 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 go down to $S_{tot} \approx 10\mu$Jy at any redshift. Note

[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.ska.ac.za/meerkat/
[6] http://www.skatelescope.org/

that, in addition, EMU could detect several tens higher redshift ($\gtrsim$ 0.3) halos with $S_{tot} > 0.1$ 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):

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

where ξ indicates the fraction of the total flux of the source at $r = \eta R_h$ (thus $\xi \leq 1$ and $\eta \leq 1$), B_ν is in Jy/arcsec^2, $L_{1.4GHz}$ in W/Hz, ν in MHz and R_h (=0.5) in Mpc. In our estimates a radio halo is considered to be detected when $B_\nu(\eta R_h) \geq$ 5-10 $\mathrm{rms_{EMU}}$ and $\xi = 0.5$. The EMU detection limits for radio halo luminosities have finally be 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 3σ 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 σ 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; Goto 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 well 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 Wide survey. *eROSITA*[7] detection limits should

[7] http://www.mpe.mpg.de/heg/www/Projects/EROSITA/main.html

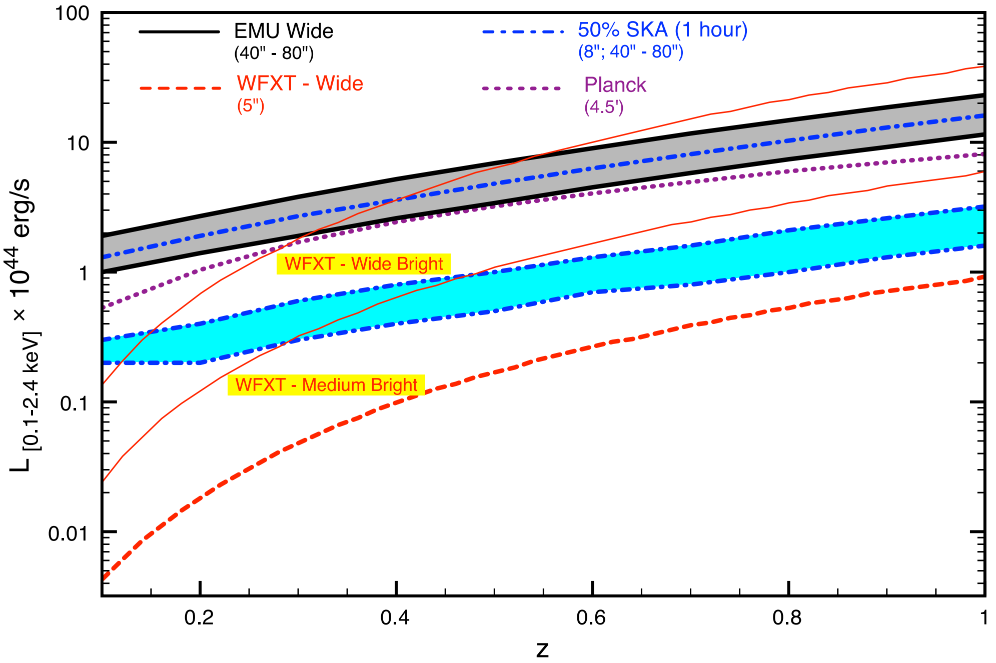

Fig. 2. Evolution with redshift of the X-ray luminosity limit of clusters whose diffuse radio emission can be detected: **a) (shaded area delimited by solid lines)** at 5-10 σ significance level with the *ASKAP* telescope down to the sensitivity limit of the EMU-Wide survey and at 40 to 80 arcsec resolution (Sect.3.1); **b) (dot-dahsed line)** at 10 σ 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 σ 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).

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): $\sim 3 \times 10^6$ detected clusters (out of which $\approx 98\%$ at $z < 1$[8]), and $\sim 2 \times 10^4$ 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 in Sartoris et al. (2010)). 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

[8] For $z \gtrsim 1$ the lifetime of CR*e*s whose synchrotron emission peaks at 1.4 GHz $\tau \lesssim 10$ Myr due to IC energy losses.

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 $\gtrsim$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 α and of the ICM brightness and temperature (Sect. 2). This could be done on several hundred clusters at z <0.5 by combinining 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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