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Magnetic field in galaxy clusters from depolarization of radio sources

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Abstract. We present a new approach to investigate the average properties of the magnetic field in the intra-cluster medium (ICM), and to search for possible correlations with the thermal properties of the ICM and cluster radio emission. We have selected a sample of 33 massive galaxy clusters from the HIghest X-ray FLUx Galaxy Cluster Sample, and used Northern VLA Sky Survey data to analyze the fractional polarization (F_p) of radio sources out to 10 core radii from the cluster centers. We detect a trend of F_p versus the projected distance from the cluster center. Such a trend can be reproduced by a magnetic field model with central values of a few μG. The logrank statistical test indicates that there are no differences in the depolarization trend observed in clusters with and without radio halo, while the same test indicates significant differences in depolarization trend of sources in clusters with and without cool core. Although the role of the gas density should be better accounted for, these results are important for establishing a link between cluster magnetic fields, cool cores and radio halos.

Key words. Galaxy: clusters, general – Methods: observational, statistical – Intergalactic medium – Magnetic fields – Non-thermal

1. Introduction

In the last decade increasing attention has been devoted to the presence, strength and structure of magnetic fields in galaxy clusters (see e.g. Ferrari et al. 2008). Our current knowledge on cluster magnetic fields comes mainly from radio observations. Diffuse radio emission not obviously associated with any particular galaxy is observed in an increasing number of galaxy clusters (e.g. Venturi, this conference). These radio sources are wide (∼ Mpc-sized), have low surface brightness (∼ 1 μJy/$arcsec^2$ at 1.4 GHz), and steep spectra[1] (α >1). They can be found either at the cluster center, permeating the cluster volume (radio halos), and at the cluster periphery, possibly tracing large-scale shocks (radio relics, see van Weeren, this conference). These radio sources reveal the presence of magnetic fields in the ICM, but since the energy spectrum of the emitting particles is still poorly known, estimates of the magnetic field from the observed

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[1] We define the radio spectrum as $S(\nu) \propto \nu^{-\alpha}$.

radio emission are subject to crucial assumptions.

Estimates of the volume-averaged magnetic field strength can be obtained in clusters with radio halos by studying the Inverse Compton (IC) Hard X-ray emission (see e.g. Wik et al, this conference). So far these estimates have lead to detections or upper limits of approximately a fraction of μG over the cluster volume (Fusco-Femiano 2004; Wik et al. 2009).

Another possibility to investigate the ICM magnetic field properties comes from the study of Faraday rotation of sources located both behind and within galaxy clusters. Synchrotron radiation from radio galaxies which crosses a magneto-ionic medium is subject to Faraday rotation. The direction of the polarization plane, Ψ_{int}, is rotated by a quantity that in the case of a purely external Faraday screen is proportional to the square of the wavelength:

$$\Psi_{obs}(\lambda) = \Psi_{int} + RM\lambda^2 \tag{1}$$

$$RM \propto \int_0^L B_{//} n_g dl, \tag{2}$$

here $B_{//}$ is the magnetic field component along the line of sight, n_g is the ICM gas density and L is the distance along the line of sight. With the help of X-ray observations, which provide information about the thermal gas distribution, RM studies give an additional set of information about the magnetic field in the ICM. Recent works have investigated several aspects of the magnetic field, such as its power spectrum, central strength and radial decline (e.g. Bonafede et al. 2010; Vogt & Enßlin 2005; Laing et al. 2008; Vacca et al., this conference). These studies, however, require deep and multi-frequency observations of several sources located at different projected distances from the cluster center, and so far have been performed on a small number of clusters only. Owing to the sensitivity limits of current radio telescopes, studies of a large number of galaxy clusters with many RM probes per cluster are still unfeasible. Hence, in order to obtain general information on magnetic fields in galaxy clusters without focusing on single objects, a different strategy is required.

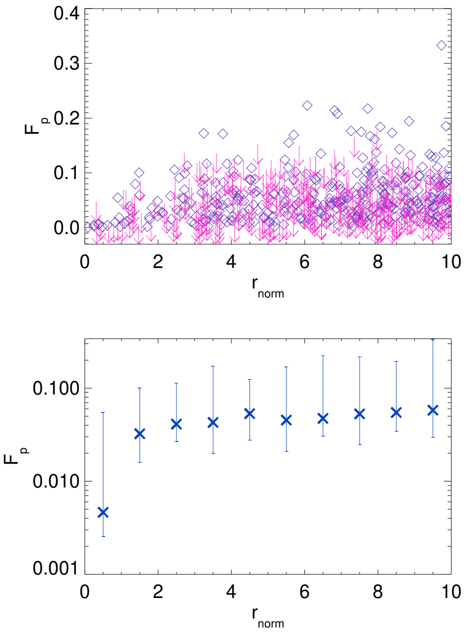

Fig. 1. Upper panel: Fractional polarization for the sources belonging to the cluster sample as a function of the projected distance from the cluster center normalized by the core radius. The arrows indicate upper limits. Lower panel: the median of the KM estimator (see Sect. 2 in every bin is shown, error bars refer to the 16th and 84th percentile of the KM distribution.

2. Depolarization from radio sources

When synchrotron emission arising from a cluster or background source crosses the ICM, regions with similar Ψ_{int}, going through different paths, will be subject to differential Faraday rotation. If the magnetic field in the foreground screen is tangled on scales much smaller than the observing beam, radiation with similar Ψ but opposite orientation will be averaged out, and the observed degree of polarization will be reduced (beam depolarization). In the central region of a cluster, B and n_g are higher, hence resulting in a higher value of RM, and lower fractional polarization F_P. Sources at larger radii, instead, are subject to less depolarization, since their emission is affected by lower RM.

At the aim of investigating the fractional polarization trend of radio sources as a function of the distance from the cluster center, we have selected a sample of massive galaxy clusters from the HIghest X-ray FLUx Galaxy Cluster Sample (Reiprich & Böhringer 2002). We have used the Northern VLA Sky Survey data to analyze the polarization properties of radio-sources out to 10 core radii, r_c, from the cluster centers (Bonafede et al., submitted). The sample consists of 33 clusters, with $L_x[0.1 - 2.4\text{keV}] \geq 1.5 \times 10^{44}$erg/s. We have normalized the distance of the sources to the cluster core radius, defining $r_{norm} = r/r_c$. In the upper panel of Fig. 1, the fractional polarisation as a function of r_{norm} is reported for all the sources in our sample.

Since our sample is highly affected by the presence of upper-limits, i.e. sources that are detected in total intensity but not in polarization, we used the Kaplan Meier (KM) estimator (Kaplan & Meier 1958) to derive the distribution function of F_p in bins having size of one r_{norm} each. In the lower panel of Fig. 1 the median of the distribution function in each bin is reported. A trend is detected in the F_P going from the cluster center to the cluster outskirts. This confirms, as already found by Clarke (2004) and Johnston-Hollitt et al. (2004), that magnetic fields are ubiquitous in galaxy clusters.

3. Magnetic field properties from F_P trend.

The observed trend of F_P versus the projected distance from the cluster center can be used to constrain the magnetic field properties. We have used 3D simulations of random magnetic fields, performed with the FARADAY code (Murgia et al. 2004) to analyze the polarization trend resulting from different magnetic field configurations. We have adopted a Kolmogorov power-spectrum, and a magnetic field profile scaling with the thermal gas density according to $\langle B(r)\rangle \propto \langle B_0\rangle \left(\frac{n_g(r)}{n_g(r=0)}\right)^{0.5}$. We have inspected how different magnetic field models, having different auto-correlation length, Λ_B , and magnetic field central intensity $\langle B_0\rangle$ affect the depolarization of radio sources (Fig. 2). The model that best reproduces the observed trend of F_P, among those considered here, has $\langle B_0\rangle = 5\mu$G, for every choice of Λ_B (Fig. 2).

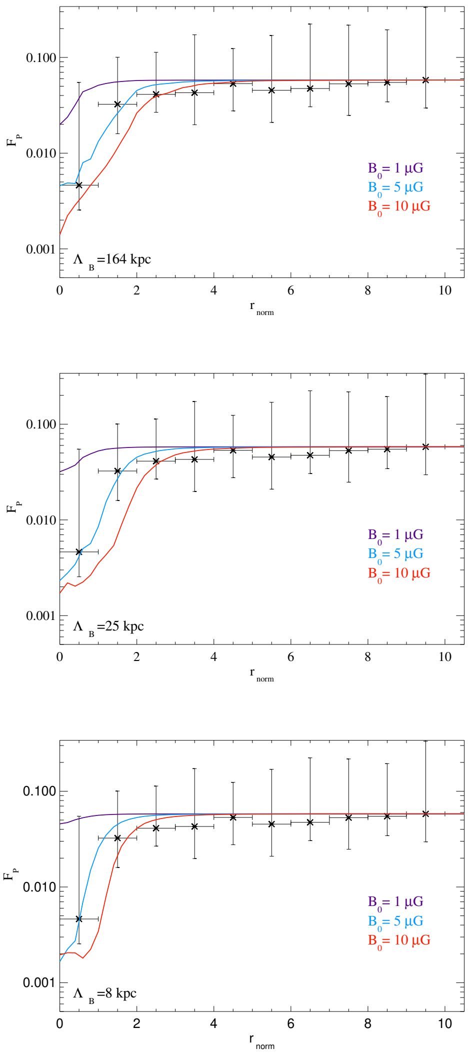

Fig. 2. Simulated (lines) and observed (crosses) depolarization trends for models with different Λ_B. Different lines refer to different magnetic field strengths, decreasing from top to bottom, as reported in the figures.

4. F_p and ICM thermal/non-thermal properties

The sample of clusters we have selected comprises both clusters that host radio halos and clusters that are radio quiet, as well as clusters with and without a cool-core.

- We searched for possible differences in the magnetic field properties in clusters with and without radio halos by comparing the depolarization trend for the two sub-samples. We performed the logrank statistical test, that is a non-parametric test, widely used in astronomy when censored populations have to be compared. The logrank statistical test indicates that the two samples (halos and non-halos) very likely belong to the same intrinsic population (with a probability P=0.83). Since there are no significant differences in the gas density for the two samples of clusters, this result indicates that ICM magnetic fields are likely to share the same properties regardless of the presence of radio emission from the ICM. This result poses problems for the "hadronic-models" for the origin of radio halos, that requires a difference in magnetic field strengths in clusters with and without radio halos (e.g. Dolag & Enßlin 2000; Pfrommer & Enßlin 2004), while it is in agreement with the re-acceleration scenario (see Brunetti, this conference).
- Following the same approach, we searched for possible differences in the magnetic field properties in clusters with and without cool core. The logrank test indicates that the F_P distribution observed in clusters with and without cool cores is likely to be different (the null hypothesis of the two samples belonging to the same population has a low significance: P=0.15). This is expected by recently proposed models that explain the cool core and non cool core bimodality as due to different magnetic field configurations in clusters with and without cool-core (e.g. Parrish et al. 2010; Ruszkowski et al. 2010). However, the results obtained here must be treated with cautions since the role of the different gas densities in the two samples is not easy to quantify, and could play a crucial role. Deeper radio observations would be required to properly test these models.

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