Mem. S.A.It. Vol. 82, 507

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The magnetic field power spectrum in galaxy clusters from observations of polarized radio sources

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Abstract. Our knowledge on the properties of the intra-cluster magnetic field has advanced over the past decade thanks to new radio observations and to the development of more sophisticated interpretative models. I will shortly review some of the recent progresses in this subject. Especially I will describe how it is possible to constrain the intra-cluster magnetic field power spectrum from studies of the Faraday rotation effect based on observations of polarized radio sources located inside or behind galaxy clusters.

Key words. Galaxies: cluster: general – Magnetic fields – Polarization – Cosmology: large-scale structure of Universe

1. Introduction

The presence of μG-level magnetic fields associated with the intra-cluster medium in clusters of galaxies is now widely acknowledged (Carilli & Taylor 2002; Govoni & Feretti 2004; Vallée 2004; Ferrari et al. 2008). The study of cluster magnetic fields is relevant to understand the dynamical and physical conditions of the intra-cluster medium. Cluster magnetic fields provide an additional term of pressure and may be used to probe cluster dynamics. They are able to inhibit transport processes like heat conduction, spatial mixing of gas, and propagation of cosmic rays. In addition, magnetic fields couple cosmic ray particles to the intra-cluster gas and they are essential for the production of the diffuse synchrotron radiation observed in an ever growing number of galaxy clusters. Moreover, understanding the origin and evolution of the intra-cluster magnetic fields is relevant per se. They could have a primordial origin or they could have been injected into the intergalactic medium by winds and out-flows from primeval galaxies (see Dolag et al. 2008). In both cases, explaining the magnetic fields that we observe in the local Universe should be a requirement for the numerical simulations of the formation of galaxy clusters. For all these reasons, it would, of course, be highly desirable to measure both the intensity and the structure of the intra-cluster magnetic fields and know how they eventually vary inside and among galaxy clusters. Intra-cluster magnetic fields have been investigated using a variety of techniques, including observations of inverse Compton scattering, minimum energy estimates, cold fronts, and, obviously, Faraday rotation studies based on observations of polarized radio sources located inside or behind galaxy clusters.

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2. The Faraday rotation effect in galaxy clusters

The Faraday rotation effect arises during the propagation of electromagnetic waves in a magnetized plasma. These conditions are met in the intra-cluster medium, where magnetic fields are mixed with the thermal plasma. The presence of a magnetic field in an ionized plasma creates a difference in the phase velocities for left versus right circularly polarized radiation. A linearly polarized wave can be decomposed into opposite-handed circularly polarized components. As a consequence, the polarized emission from a radio source propagating through the magneto-ionic medium experiences a phase shift between the two components. Therefore, traveling along the cluster, the intrinsic polarization angle ψ_0 will be rotated by an amount

$$\Delta\psi = \psi - \psi_0 = \lambda^2 RM, \tag{1}$$

where λ is the radiation wavelength while RM is the so-called rotation measure. The rotation measure is given by the integral

$$RM = 812 \int_0^L n_e B_z dl \;\; (\mathrm{rad/m^2}) \tag{2}$$

where n_e is the thermal electron density in $\mathrm{cm^{-3}}$, B_z is the magnetic field component along the line-of-sight in μG, and L is the path length through the cluster in kpc (Burn 1966). If we perform multi-frequency observations of a radio source embedded or placed behind a galaxy cluster, then by a linear fit of the λ^2-law in Eq.1 we can estimate the RM along that direction. By knowing the RM and given a model for the distribution of the thermal electrons (e.g. from X-ray observations) we can infer the intra-cluster magnetic fields. However, because of the random and turbulent nature of the intra-cluster magnetic fields, inverting Eq.2 is not straightforward even in the cases of simple electron density distributions.

Detailed RM images of extended radio sources sitting at the center of galaxy clusters have been obtained (see e.g. Taylor & Perley 1993; Feretti et al. 1999a; Eilek & Owen 2002). The RM distributions seen across these sources are not uniform (see e.g. left panel of Fig.1). Rather, they present an alternation of positive and negative patches whose statistics is, in first approximation, Gaussian-like with dispersions up to several hundred (and even thousand) rad/m^2. The observed RM fluctuations indicate that the intra-cluster magnetic field is not regularly ordered but turbulent on scales much smaller than ~100 kpc, which is the typical linear size of these radio sources.

The early interpretation of this finding was that the intra-cluster magnetic field is composed by uniform cells of size Λ_C with random orientation in space. In this "single-scale" model, the Faraday rotation from a physical depth $L \gg \Lambda_C$ is expected to be a Gaussian with zero mean and dispersion given by:

$$\sigma^2_{RM} = 812\Lambda_C \int_0^L (n_e B_z)^2 dl \;\; (\mathrm{rad^2/m^4}), \tag{3}$$

(e.g. Lawler & Dennison 1982; Feretti et al. 1995; Felten 1996).

For the very simple case where the electron density is constant,

$$\sigma_{RM} = 812 n_e \sqrt{\Lambda_C}\sqrt{L}\,\sigma_{B_z} \;\; (\mathrm{rad/m^2}). \tag{4}$$

Thus, by measuring the dispersion of the RM we can estimate the magnitude of the magnetic field fluctuations provided that the cell size Λ_C is known. The question is then what exactly is Λ_C and how can we find it.

The issue was investigated theoretically and in numerical tests by different authors (Enßlin & Vogt 2003; Vogt & Enßlin 2003; Murgia et al. 2004; Vogt & Enßlin 2005), who determined that the correct value for Λ_C is the field autocorrelation length, Λ_B, which can be calculated if the power spectrum of the magnetic field fluctuation is known.

For an isotropic divergence-free random field, it can be shown that Λ_B is related to the magnetic field power spectrum[1], $|B_\mathrm{k}|^2$, by

$$\Lambda_\mathrm{B} = \frac{3\pi}{2}\frac{\int_0^\infty |B_\mathrm{k}|^2 k dk}{\int_0^\infty |B_\mathrm{k}|^2 k^2 dk}, \tag{5}$$

[1] Note that the power spectra are expressed as vectorial forms in k-space. The one-dimensional forms can be obtained by multiplying by $4\pi k^2$ and $2\pi k$ respectively the three and two-dimensional power spectra.

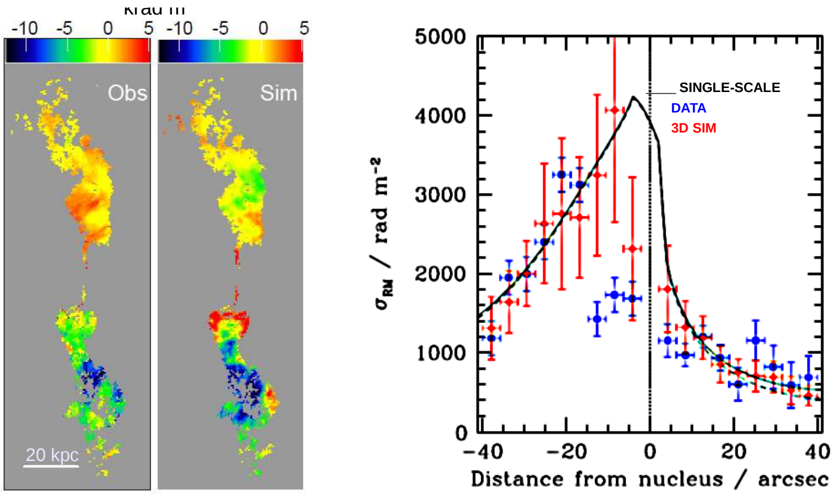

Fig. 1. Hydra-A. Left panels: observed and simulated *RM* images. Right panel: *RM* profile across the source. Diamonds and circles represent the 3-dimensional simulations and the data, respectively. The line is the best fit of the single-scale model. Adapted from Laing et al. (2008).

where $k = 2\pi/\Lambda$ is the wave number. Note that, in general, the *RM* and magnetic field scales are different, $\Lambda_{RM} \neq \Lambda_B$. Hence, if we want to determine the strength of the magnetic field we ultimately need to determine the power spectrum of its fluctuations.

3. Numerical approaches to Faraday rotation modeling

According to Eq.2, the *RM* images we observe can be viewed as a 2-dimensional projection of the 3-dimensional magnetized volume of the cluster in front of the radio source and, for an isotropic random field, the *RM* and the magnetic field power spectra are proportional

$$|RM_{\rm k}|^2 \propto n_e L\,|B_{\rm k}|^2. \qquad (6)$$

Although it is impossible to recover the exact 3-dimensional configuration of the intra-cluster magnetic field in space, we can at least reconstruct its power spectrum from a careful analysis of the observed *RM* fluctuations.

The set-up of an ideal *RM* experiment is straightforward in principle:

i) We obtain a *RM* image from multi-frequency, polarization sensitive, radio observations;
ii) From this, we derive the power spectrum and the autocorrelation length of the intra-magnetic field fluctuations;
iii) We model the distribution of the thermal electrons from X-ray observations and, finally, we derive the field strength.

However, there is a number of difficulties that complicates this approach. The most serious one is the strong window function imposed by the relatively small projected area of the cluster covered by the *RM* image. The *RM* fluctuations comparable or larger than the size of the radio source are poorly sampled. As a result, the statistical variance of the field generally dominates over the formal uncertainty on the observed *RM*. Second, the angular cut-off imposed by the finite resolution of the *RM* images does not permit to observe the small-scale fluctuations of the field and causes a drop of the polarized signal (beam depolarization) which complicates the fit of the λ^2–law. Furthermore, determining the geometry of the problem is not trivial too. In fact, it could be difficult to know the exact position and orientation of the radio lobes with respect to the observer for the radio galaxies embedded in the intra-cluster medium.

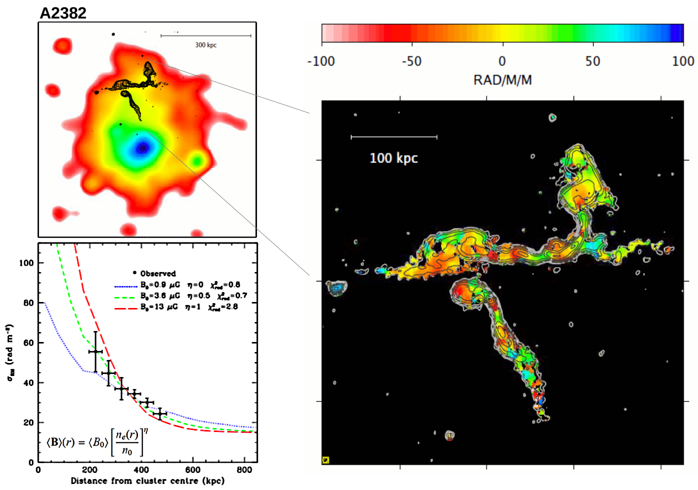

Fig. 2. *RM* analysis of two tailed radio sources in Abell 2382. Right-panel: *RM* image of the two radio sources. Top-left panel: the total intensity radio contours are overlaid to the X-ray emission of the cluster. Bottom-left panel: the azimuthally averaged radial profile of σ_{RM} is compared with the expected trends for three magnetic field models characterized by different central strengths B_0 and radial slopes η, see text. Adapted from Guidetti et al. (2008).

Dedicated software tools have been developed to attempt to solve these problems and to constraint the magnetic field power spectrum parameters and their uncertainties (see e.g. Murgia et al. 2004; Laing et al. 2008). These codes have been designed to produce, starting from 3D magnetic field models, synthetic polarization images which include the effects of window functions, noise, etc., and that can be directly compared with the observations. To limit the degrees of freedom and the computational burden, in many of these simulations the magnetic field power spectrum is assumed to be a power-law of the form $|B_k|^2 \propto k^{-n}$. However in some cases high-order terms in the curvatures have been also explored (Laing et al. 2008; Guidetti et al. 2010). Another more general method, relying on a semi-analytical approach and Bayesian inference have been also developed (Enßlin & Vogt 2003; Kuchar & Enßlin 2009). The power spectrum normalization has a similar scaling with gas density, but its shape it is decomposed with multiple spectral basis components and it is free to assume, in principle, any form required by the data.

In both cases, it is assumed that the power spectrum normalization scales as a function of the gas density such that $B \propto n_e^{\eta}$, where the index η is in the range 0.5−1.0 (Dolag et al. 2001).

4. Results on cluster sources

The Faraday rotation modeling described above has been applied to interpret the *RM* images of single radio galaxies at the center of galaxy clusters, like e.g. the case of Hydra-A shown in Fig.1. The modeling is based on the assumption that the Faraday rotation is occurring entirely in the intra-cluster medium and that any possible local *RM* enhancement occurring at the interface between the radio lobes and the surrounding medium is negligible compared to the total *RM* across the cluster (but see Rudnick & Blundell (2003) for a contrary viewpoint). These radio sources are clearly located at the center of the cluster and some of them present strong *RM* asymmetries between the jets and lobes at the opposite side of the nucleus. This is the Laing-Garrinton effect: the farthest lobe suffers a higher Faraday rotation due to the largest amount of intervening material (Laing 1988). Indeed, at least for these sources, we know that the observed *RM* must originate mostly in the foreground magnetized intra-cluster medium.

Radio sources at the center of dense cool-core clusters, like Hydra-A, probe magnetic fields as high as 10−30 μG (Laing et al. 2008; Kuchar & Enßlin 2009). The *RM* analysis of radio sources in the less dense environments of galaxy groups, such us 3C31 or 3C449 (Laing et al. 2008; Guidetti et al. 2010), indicates lower central magnetic field strengths in the range 3−10 μG. The intra-cluster magnetic field autocorrelation length is generally found to be of the order of a few kpc.

Determining the detailed shape of the magnetic field power spectrum it is not trivial because of the degeneracy existing between its slope and the outer scale of the fluctuations, Λ_{max} (Murgia et al. 2004). In fact, the same *RM* images can be explained either by a flat power spectrum with a large Λ_{max} or by a steeper power spectrum with a lower Λ_{max}. Given the limited spatial dynamic range of the current *RM* images, it's still not easy to break the degeneracy. According to Kuchar & Enßlin (2009), the slope of the magnetic field power spectrum is close to the Kolmogorov index in Hydra-A while other authors report a flatter slope (Laing et al. 2008).

Another important degeneracy exists between the central magnetic field strength B_0 and the index η, which describes the scaling of B with the gas density. The two parameters are correlated. Indeed, the same *RM* levels can be explained either by a higher B_0 with a rapid radial decrease (high η) or by a lower B_0 with a flatter radial profile. The degeneracy can be solved if *RM* images of different radio sources at different impact parameters (i.e. projected distances) from the cluster center are available. In Fig.2 it is presented the case of two tailed sources in Abell 2382 (Guidetti et al. 2008). In this cluster, the power spectrum of the *RM* fluctuation is compatible with the Kolmogorov index. The observed σ_{RM} decreases in the cluster outskirts and can be explained if $B_0 \simeq 3.5$ μG and $\eta = 0.5$. But it is also marginally compatible with a flat magnetic field profile with $B_0 \simeq 0.9$ μG or with a higher central magnetic field strength of $B_0 \simeq 13$ μG which decreases with radius following the thermal gas density, $\eta = 1$ (see bottom-left panel of Fig.2).

In a few other Abell clusters, the *RM* of radio sources at different impact parameters have been obtained, see e.g. the cases of Abell 119 (Feretti et al. 1999b; Murgia et al. 2004) and Abell 2255 (Govoni et al. 2006). In Abell 119, the *RM* analysis indicates a central magnetic field strength of $B_0 \simeq 5.5$ μG which decreases with radius roughly following the gas density. The case of Abell 2255 is particularly interesting since this cluster hosts a Mpc-scale radio halo. By analyzing the *RM* of three different radio sources, Govoni et al. (2006) found a central magnetic field strength of about 2 μG for $\eta = 0.5$. These results would imply that the magnetic field strength in clusters with or without a diffuse halo is indeed very similar.

This finding is corroborated by the results on the Coma cluster, one of the best studied objects so far. Bonafede et al. (2010) studied seven radio sources to sample different lines-of-sight in the Coma cluster and to constraint the magnetic field profile. The magnetic field radial profile was investigated through a series of 3D simulations. By comparing the observed and simulated $\sigma_{\rm RM}$ values these authors found that the best models are in the range (B_0=3.9 μG; $\eta = 0.4$) and (B_0=5.4 μG; $\eta = 0.7$). These values correspond to models where the magnetic field energy density scales as the gas energy density, or the magnetic field is frozen into the gas, respectively. This is expected since the energy in the magnetic component of the intra-cluster medium is a tiny fraction of the thermal energy. It is important to note that the average magnetic field intensity over a volume of ∼1 Mpc^3 is ∼2 μG. Indeed, the model derived from *RM* analysis gives an average estimate that is compatible with the minimum

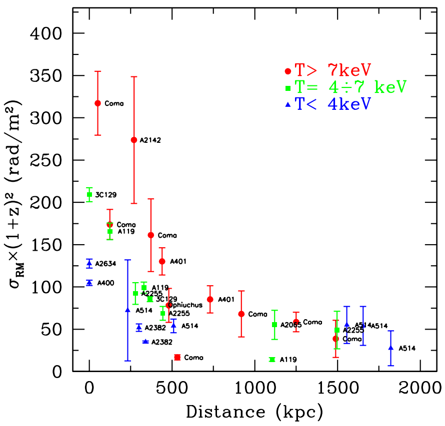

Fig. 3. Radial profile of σ_{RM} for a sample of cluster radio sources with high-quality *RM* images (adapted from Govoni et al. 2010).

energy condition in the radio halo. A direct comparison with the magnetic field estimate derived from the IC emission is more difficult since the hard-X detection is debated. The field strength derived from *RM* analysis gives a magnetic field estimate that is consistent with the present lower limits obtained from hard X-ray observations while it is still a bit higher when compared with the estimate given by Fusco-Femiano (2004).

To summarize, *RM* studies seem to indicate that magnetic fields could be common in galaxy clusters. For a statistical analysis, Clarke et al. (2001) analyzed the average *RM* values as a function of source impact parameter for a sample of 16 Abell clusters, selected to be free of radio halos and widespread cooling flows. They found a clear increase in the width of the *RM* distribution toward smaller impact parameter implying that magnetic fields could be present in all galaxy clusters, i.e. independently of the presence of a diffuse radio halo. A similar correlation has been found by Govoni et al. (2010). They formed a sample of 12 galaxy clusters for which high-quality *RM* data are available. They included only those clusters hosting radio sources for which high-resolution, extended *RM* images are available. In Fig. 3 the trend of σ_{RM} as a function of distance from the cluster X-ray center is shown. The different symbols represent different cluster temperature. It is evident a clear broadening of the σ_{RM} toward small projected distances, consistently with an excess of Faraday rotation due to the magnetized intra-cluster medium. These studies are still restricted to a few radio sources per cluster, but suggest that magnetic fields could be present in all galaxy clusters, i.e. independently of the presence of a diffuse radio halo or a cooling core.

5. Radio halo (de)polarization studies

Typically, rotation measure images of cluster radio galaxies permit investigating the fluctuations of the intra-cluster magnetic field below a spatial scale of about 50 ÷ 100 kpc. On the other hand, radio halo images reveal that the intra-cluster magnetic field is spread over Mpc scales. Thus, it would be of paramount importance to investigate the magnetic field turbulence over such a large volume of space. Unfortunately, radio halos are typically unpolarized. Only in A2255 (Govoni et al. 2005) and MACS J0717.5+3745 (Bonafede et al. 2009), a polarized signal associated (in projection) to the radio halo has been detected. In fact, due to their faintness, radio halos have been observed so far at low angular and spectral resolution. These instrumental effects, combined with the differential Faraday rotation across the cluster, lead to a strong depolarization of the radio halo emission. Vacca et al. (2010) presented a study of the magnetic field power spectrum in the galaxy cluster A665, which contains a Mpc-scale radio halo. Information on the cluster magnetic field can be derived from detailed images of the radio halo, since the halo brightness fluctuations and the polarization level are strictly related to the intra-cluster magnetic field power spectrum (Tribble 1991; Murgia et al. 2004). For example, lack of polarization and a smooth and regular surface brightness may indicate that the cluster magnetic field is tangled on smaller scales than the resolution of the radio images, while a disturbed radio morphology and the presence of polarization could be related to a magnetic field ordered on larger scales than

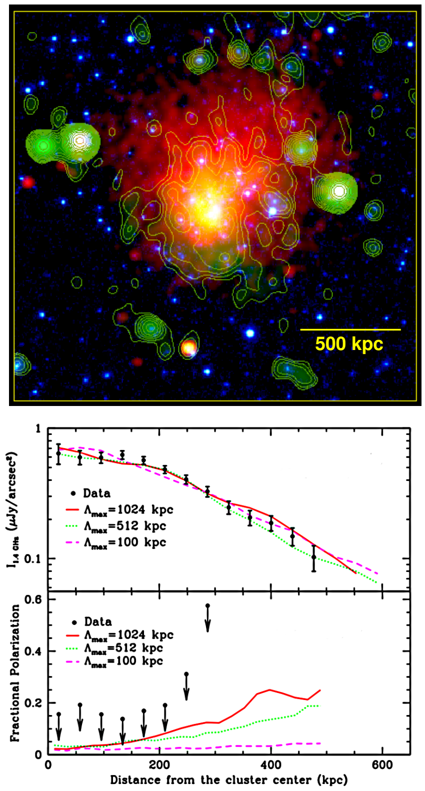

Fig. 4. The radio halo in Abell 665. Top: VLA contours are overlaid on the Chandra X-ray and on the DSS optical images. Bottom: Modeling of total intensity and fractional polarization emission (Vacca et al. 2010).

the observing beam. The modeling by Vacca et al. (2010) has proven successful in reproducing the observed total intensity fluctuations in Abell 665 and suggests that radio halos can be effectively polarized, but because of their faintness, detecting this polarized signal is a very hard task with the current radio interferometers (see Fig.4). More importantly, this study showed how very tight constraints could be potentially obtained by detecting the radio halo polarization fluctuations, not just total intensity fluctuations. In fact, the ratio of two former quantities, i.e. the fractional polarization, is a very robust indicator of the intra-cluster magnetic field power spectrum, because it only marginally depends on the energy spectrum of the synchrotron electrons. Therefore, it would be very important to improve the sensitivity of the future observations in order to detect polarized signal in the most radio halos possible. This is a science case for the new generation of instruments in radio astronomy. The high sensitivity provided by the incoming radio instrumentation will make possible to observe the polarized signal in narrow frequency channels over large bandwidths and hence to exploit the *RM* synthesis at its best. Pizzo et al. (2011) showed that this powerful technique is very effective to study the polarized emission of both the discrete sources and the diffuse emission in a comprehensive way. It is likely that in the next future we will be able to perform the *RM* synthesis of many radio halos and to obtain a clearer picture of the power spectrum of the magnetic field fluctuations over the entire volume of the cluster.

6. Summary

I shortly reviewed some of the recent progresses in the study of magnetic fields in galaxy clusters. Thanks to new radio observations and to the development of more sophisticated interpretative models, our understanding of this concealed component of the intracluster medium has advanced significantly. The results presented in this review are summarized in what follows.

The power spectrum of the intra-cluster magnetic field can be constrained if detailed *RM* measure images of radio galaxies located inside or behind galaxy clusters are available.

These studies are still restricted to a few radio sources per cluster, but suggest that magnetic fields could be present in all galaxy clusters, i.e. independently of the presence of a diffuse radio halo.

There are also evidences that the magnetic field decreases following the gas density, and hence volume-averaged magnetic field strengths could be much lower in these cases. This is relevant when the field strength derived from the *RM* analysis are compared with that obtained from the observation of the inverse Compton radiation from giant radio halos.

The magnetic field power spectrum can be approximated with a power law with the slope close to the Kolmogorov index in some clusters but shallower indexes are also observed.

It is likely that in the next future we will be able to perform the *RM* synthesis of many radio halos and to obtain a clearer picture of the power spectrum of the magnetic field fluctuations over the entire volume of the cluster.

Acknowledgements. I wish to thank my close collaborators Federica Govoni, Luigina Feretti, Gabriele Giovannini, Annalisa Bonafede, Valentina Vacca, Klaus Dolag, and Greg Taylor.

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