PROCEEDINGS OF SCIENCE

Galaxy cluster magnetic fields from radio polarized emission

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The presence of magnetic fields in the intra-cluster medium of galaxy clusters is now well estabilished. It is directly revealed by the presence of cluster-wide radio sources: radio halos and radio relics. In the last years increasing attention has been devoted to the intra cluster magnetic field through the study of polarized radio emission of radio galaxies, radio halos and radio relics. Recent radio observations have revealed important features of the intra-cluster magnetic field, allowing us to constrain its main properties and to understand the physical processes taking place in the intra-cluster medium. I will review the newest results on galaxy cluster magnetic fields, both focusing on single objects and aimed at describing the magnetic field general properties. The up-coming generation of radio telescopes, EVLA and LOFAR, will shed light on several problematics regarding the cluster magnetic fields and the related non-thermal emission.

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1. Introduction

In recent years the presence of magnetic fields in galaxy clusters has been unambiguously proved. Magnetic fields are thought to play an important role in the development of large-scale structure in the Universe, but despite their importance, the origin and evolution of magnetic fields are still open problems in fundamental physics and astrophysics. The magnetic fields that we observe in the Local Universe probably owe their strength to dynamo amplification of an initial seed. The smaller the object is the shorter is the time required for the dynamo to amplify the original seed. The magnetic fields on large scales are thus the most challenging. The dynamical scale for large objects are in fact long, and the amplification is correspondingly slow. This indicates the need for a seed field whose strength is not predicted by present theories (see *e.g.* Rees 2006).
According to the standard scenario of structure formation, galaxy clusters are built-up by gravitational merger of smaller units, such as groups and sub-clusters. They are composed of hundreds galaxies in Mpc-size region, and the Intra Cluster Medium (ICM) is filled with hot and rarefied gas - emitting in the soft-X ray domain through optically thin bremsstrahlung - magnetic fields and relativistic particles. Magnetic fields in the ICM are investigated through synchrotron emission of cluster-wide radio sources and from the study of the Rotation Measure of radio galaxies. I will discuss in this proceeding the most recent results that we have obtained so far on the ICM magnetic field strength and structure.

2. Why should we care about magnetic field in the ICM?

Several models have been proposed to explain the origin of magnetic field in the Universe. It could be either primordial (see Grasso & Rubinstein 2001 for a review) or injected in the proto-cluster region by AGN and galactic winds ejecta (*e.g.* Völk & Atoyan 2000). Whatever the origin of the initial seed, some amplification mechanisms are required to account for its strength in the local Universe. Cosmological MHD simulations predict magnetic field strength of the order of μG spread over the cluster volume (*e.g.* Dolag et al. 2005), in agreement with radio observations (*e.g.* Govoni & Feretti 2004). Cosmological simulations indicate that the amplification of the magnetic field resulting by pure adiabatic contraction of the gas falling into the cluster potential well, can explain only 1% of such magnetic field strength, so that other amplification mechanisms are required. Merger events and accretion of material onto galaxy clusters are supposed to drive significant shear-flows and turbulence within the ICM. These processes can amplify the magnetic field up to at least μG values (see Dolag et al. 2008 and references therein). A detailed knowledge of the fundamental ICM magnetic field properties, like *e.g.* its power spectrum and radial decline, can help to understand if it is amplified by processes related to merger events. The presence of magnetic field in the ICM of galaxy clusters may also affect the thermal conduction: typical values for the thermal electron gyro-radius ($\sim 10^8$ cm for T= $10^{8\circ}$K and B= 1μG) are much smaller than any scale of interest in clusters, and in particular than the particle mean free path due to collisions ($\sim$20 kpc). It follows that the effective mean free path for diffusion perpendicular to the magnetic field lines is reduced, and being the magnetic field tangled in the ICM, it is crucial to have information at least on the magnetic field coherence length to understand how the magnetic field inhibits the thermal conduction.

In addition, a precise knowledge of the ICM magnetic fields is also important to clarify the origin of the relativistic particles which are responsible for the synchrotron diffuse radio halos and relics detected in an increasing number of galaxy clusters (see Secs. 4 and 5).

3. Power spectrum and radial profile of the ICM magnetic field

There are several indications that the magnetic field intensity declines with radius with a rough dependence on the thermal gas density. This is predicted by both cosmological simulations (*e.g.* Dolag et al. 2005, Dolag et al. 1999, Brüggen et al. 2005) and by the comparison between thermal and radio brightness profiles (Govoni et al. 2001). It is then reasonable to assume that the magnetic field declines from the center outwards according to:

$$B(r) = B_0 \left[1 + \frac{r^2}{r_c^2}\right]^{-\frac{3}{2}\mu} = B_0 \left[\frac{n_e}{n_0}\right]^{\eta} \tag{3.1}$$

with n_e being the gas density distribution, and r_c the cluster core radius.
Faraday Rotation Measures (RM) images have often revealed patchy structure, with RM fluctuations over a large range of spatial scales. This indicates that the magnetic field itself fluctuates over a range of spatial scales, and that its power spectrum has to be considered. One of the simplest approaches is to consider that the magnetic field fluctuations are Gaussian and that their power spectrum can be approximated by a power-law of the form:

$$|B_\Lambda|^2 \propto \Lambda^n \tag{3.2}$$

in a range of scales going from Λ_{min} to Λ_{max}.

4. Magnetic fields and radio halos

The most spectacular and direct evidence that the ICM is magnetized comes from observations of radio halos. They are wide synchrotron emitting sources, whose emission arises directly from the ICM. Radio halos permeate the central region of galaxy clusters, and have typical sizes of ~ 1 Mpc at 1.4 GHz. Their emission has been mainly studied at frequencies $\nu \sim$ GHz, and only recently observations at lower frequencies have been performed (*e.g.* van Weeren et al. 2009,Venturi et al. 2008). In this frequency range, they are characterized by low surface brightness (~ 1 μJy/arcsec^2 at 1.4 GHz) and steep radio spectrum[1], with $\alpha \geq 1$ between 300 MHz and 1 GHz (Giovannini et al. 2009). The presence of radio emission on such large scales poses some questions about the origin of the emitting electrons. Because of synchrotron and Inverse-Compton losses, particles that emit around ~ 1 GHz in a μG magnetic field have a life-time of $\approx 10^8$ yr. During this timescale they can only diffuse for a few tens of kpc, which is very small compared with the observed $\sim$ Mpc scale common for Radio Halos. This indicates that they need to be continuously injected or accelerated across the entire cluster volume. Two main classes of models have been proposed in the literature:
• *primary or re-acceleration models*: in which electrons are re-accelerated *in situ* through second-order Fermi mechanism by ICM turbulence developing during cluster mergers (*e.g.* Jaffe 1977;

[1] We define the spectrum as $S(\nu) \propto \nu^{-\alpha}$, with $S(\nu)$ being the flux density at the frequency ν

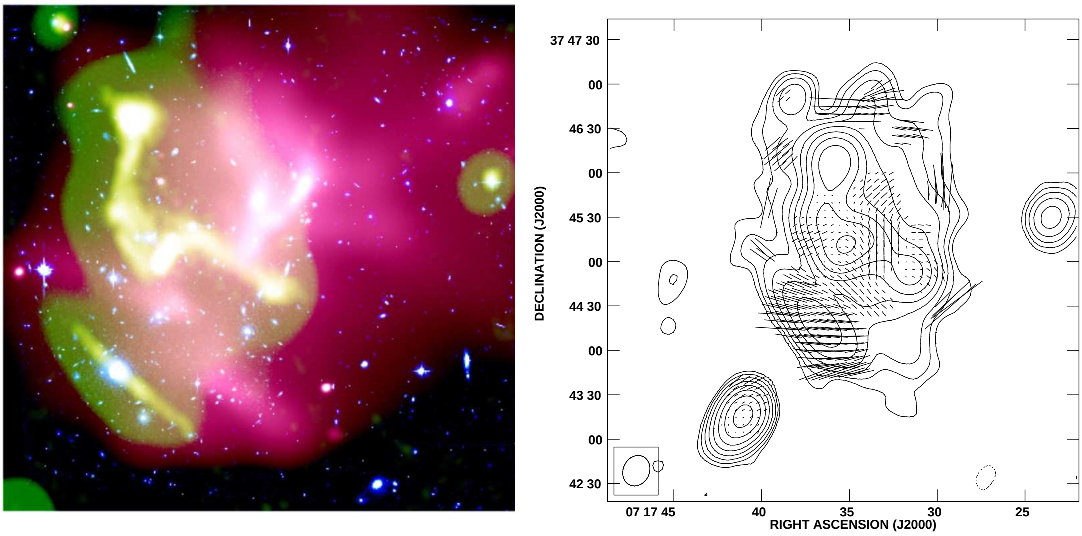

Figure 1: The most powerful radio halo known so far in MACS J0717+3745 Left panel: Optical emission from HST in blue, X-ray emission from Chandra (0.5-7 keV band) in magenta and radio emission (VLA at 1.4 GHz) in green. X-ray and optical images are courtesy of C.J. Ma. Right panel: Contours show to the total-intensity emission (beam is $21'' \times 18''$) starting at 3σ, and spaced by factors of 2. Lines refer to the E vectors. Their orientation represents the projected E-field. Their length is proportional to the fractional polarization: $1''$ corresponds to 13% (Fig. from Bonafede et al. (2009a)) .

Brunetti et al. 2001; Petrosian 2001);
• *secondary or hadronic models*: in which electrons originate from hadronic collisions between the long-living relativistic protons in the ICM and thermal ions (*e.g.* Dennison 1980).
We refer to Brunetti (this conference) for a more complete analysis. However, because of the nature of the synchrotron radiation, it is not easy to measure the energetic of the relativistic electrons and that of the magnetic field using solely observations of radio halos. The minimum energy calculation is problematic and the detections of non-thermal inverse Compton radiation in the Hard X-ray band are difficult and limited to few clusters. Indeed, an independent method to estimate the magnetic field properties in the ICM is required (see Sect.6).
Radio halos are usually found to be un-polarized. This could be due to the low resolution that is often needed to properly image their emission, causing beam depolarization, and/or to internal depolarization caused by differential Faraday Rotation (see Sec. 4.2). In the Coma cluster upper limits to the fractional polarization are $\sim$10% at 1.4 GHz, and lower values ($\sim$6% and 4%) have been found for two other powerful halos in Abell 2219 and Abell 2163 (see Govoni & Feretti 2004 and references therein). Polarized emission from radio halos has been observed so far in the cluster Abell 2255 (Govoni et al. 2005, see also Pizzo 2010) and MACS J0717+3745 (Bonafede et al. 2009a).

4.1 Polarized emission from radio halos

Detecting polarized emission from cluster radio halos would be extremely important for the

study of the magnetic field power spectrum and morphology. Murgia et al. (2004) developed the FARADAY code to simulate 3D magnetic fields in galaxy clusters. They investigated how different magnetic field power spectra affect the shape and the polarization properties of radio halos (see Fig. 6 of that paper). When single power-law power spectra are considered, models with $n > 3$ and $\Lambda_{max} > 100$ kpc (see Eq. 3.2) result in magnetic fields whose energy is larger on the large spatial scales, thus giving rise to filamentary and polarized radio halos. Models with $n < 2$, instead, having most of the magnetic field energy on small spatial scales, will give rise to halos with a more regular morphology, and very little polarization.
By comparing simulations and observations, the detection of polarized emission from radio halos permits to put some constraints on the magnetic field power spectrum. Govoni et al. (2006) analyzed the polarized emission from the radio halo in the cluster Abell 2255. They found that a single power law cannot account for the observed polarization. A power spectrum with spectral index $n = 2$ at the cluster center and $n = 4$ at the cluster periphery is needed to produce the observed polarized emission. Comparing observations and numerical simulations Bonafede et al. (2009a) found that the magnetic field power spectrum in the cluster MACS J0717+3745 should be steeper than 3, and that its maximum scale Λ_{max} should be >100 kpc. It is interesting to note that the Kolmogorov power spectrum, in this 3-D notation, would have a slope $n = 11/3$. We note that the theory developed by Kolmogorov treats incompressible un-magnetized and uniform media, so that its application to the case of the ICM of galaxy clusters is all but obvious. Nonetheless, observational data and cosmological simulations indicate that it is a good description of the pseudo-pressure fluctuations (Schuecker et al. 2004), velocity field (Vazza et al. 2009) and magnetic field (Kuchar & Ensslin 2009, Guidetti et al. 2008, Vogt & Enßlin 2005, Bonafede et al. 2010) in the ICM. In Fig. 1 the cluster MACS J0717+3745 and the polarized emission from the radio halo are shown.

4.2 Un-polarized radio halos: internal and external depolarization

There are different possibilities to explain why polarized emission from radio halos is so rarely detected. Radio halo emission fills the central Mpc^3 of galaxy clusters. Here magnetic fields, relativistic electrons and thermal gas coexist and interact. It is reasonable to assume that the direction of the magnetic field varies from point to point in the ICM. The intrinsically polarized radiation from relativistic electrons, will then vary accordingly. In addition, when radio waves propagate through the ICM, the polarization plane is subject to the internal Faraday Rotation. The result of these effects is the well known frequency dependent depolarization of the intrinsic synchrotron emission. Furthermore, radio halos are faint and wide sources, so that low resolution observations are often required to properly image their emission. If differential Faraday rotation is occurring within the beam, *i.e.* if the minimum scale of the magnetic field power spectrum is smaller than the beam FWHM, the so-called "beam-depolarization" is expected to be particularly strong. Recent works on RM studies indicate that magnetic field may fluctuate on scales as small as few kpc, while typically radio halos are observed with a resolution of several tens to hundred kpc.
Recently, Vacca et al. (2010) have analyzed the radio halo in the cluster Abell 665, where polarized emission is not detected. By comparing observed and synthetic radio halo images the strength and structure of the intra-cluster magnetic field has been constrained. The simulated magnetic field that best reproduces the observations in Abell 665 is characterized by $B_0 = 1.3$ µG, $\eta = 0.47$. Once

a Kolmogorov power spectrum is assumed, spatial scales Λ are up to 450 kpc. The authors investigated the different causes (noise and resolution) that produce depolarization (see Fig. 3 of the paper). The simulated radio halo appears intrinsically polarized at 1.4 GHz, with fractional polarization of ∼24 %, indicating that internal depolarization alone cannot explain why the radio halo appear to be un-polarized. When the intrinsic radio emission is observed with a resolution of ∼ 15″, the polarization is reduced at ∼7%. But when noise, typical of observations performed with present instruments (∼ 15 μJy/beam) is added, the polarized emission falls below the detection level. This illustrates that the intrinsic polarization of radio halos is not completely canceled out neither by internal depolarization nor by beam effects. Radio halos would appear polarized if observed with enough sensitivity, but detecting the polarized emission is a very hard task with current interferometers. The radio halo in MACS J0717 +3745 is indeed the most powerful radio halo observed so far. The mean fractional polarization is ∼5 % at 20 cm (Bonafede et al. 2009a) that is not much below the upper limits found for other radio halos.
The new generation of radio telescopes, such as LOFAR and EVLA, will have the chance to detect polarized emission from radio halos thanks to their better sensitivity performances. As shown by Govoni (2007, contributed talk at LOFAR meeting in Emmen, NL), LOFAR will have the chance of detecting polarized emission in the higher frequency band (∼ 200 MHz).

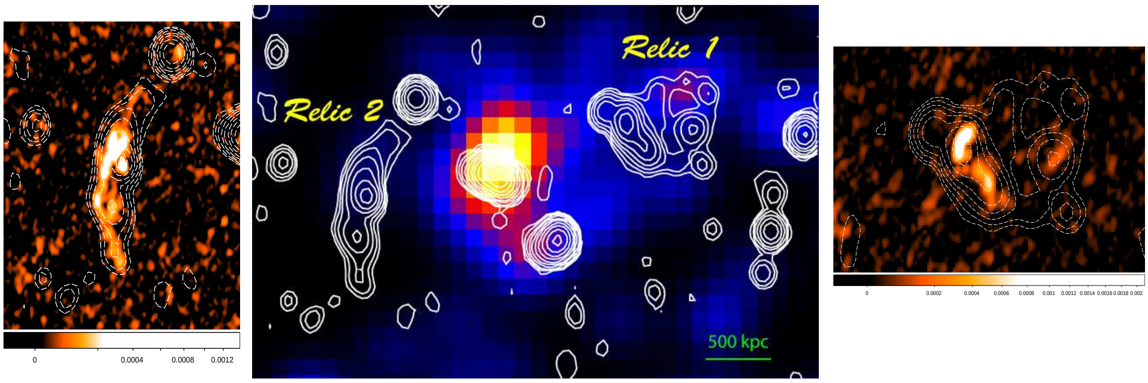

Figure 2: Center: Abell 2345 X-ray emission (colors) in the energy band 0.1-2.4 keV from RASS; contours represent the radio image of the cluster at 1.4 GHz. The beam is 50″×38″. Contours are 0.24 mJy/beam and are then spaced by a factor 2. Side panels: colors refer to the polarized emission at 1.4 GHz (beam FWHM 23″ × 16″), contours are like in the central panel.

5. Polarized emission from radio relics

Another indication that the ICM is magnetized comes from the observations of the so-called "radio relics". Their size (∼ Mpc), surface brightness, and radio spectrum have properties similar to radio halos, but they differ in morphology and polarization properties. They are located at the outskirts of the host galaxy clusters, usually at the boundary of the X-ray emission, and are strongly polarized, with linear fractional polarization at 1.4 GHz of 10-30 %, reaching values up to 50 % in some regions (see *e.g.* Bonafede et al. 2009b). Their morphology is quite various, but it is usually elongated.

The origin of their emission is still uncertain, and different models have been proposed in the literature:
• "Radio-ghost"[2]: aged radio plasma revived by merger or shock wave through adiabatic compression (see Enßlin & Gopal-Krishna 2001);
• "radio gischt": electrons are accelerated by Fermi-I process (Diffusive Shock acceleration) caused by merging or accretion shock, and the magnetic field is amplified (Ensslin et al. 1998, Hoeft & Brüggen 2007).
The "Radio-ghost" model predicts a curved radio spectrum, a filamentary or toroidal morphology and magnetic field aligned with the filamentary structure, while "radio gischt" models predict a straight radio spectrum, and an arc-like morphology of the relic, with magnetic field aligned to the relic main axis. The presence of double relics in a single cluster is particularly interesting in the "radio gischt" scenario, since the shape, morphology and properties of these extended structures strongly suggest the presence of shock waves propagating from the cluster center to the peripheral regions. A few clusters with double relics are known so far, and a detailed study of their radio properties, including all the predictions done by the models, has not been systematically performed yet.
Recently, we have analyzed the double relics in clusters Abell 1240 and Abell 2345 (Bonafede et al. 2009b), and studied their spectral index, spectral index trend and polarization properties. Double relics in Abell 1240 show radio morphology, spectral index and polarization values in agreement with radio gischt predictions in the case of merger shock waves. The values of the Mach numbers indeed ($\sim$2-3) disfavour the hypothesis of accretion shock waves. The same properties characterize also one of the two relics in Abell 2345 (relic 2 in Fig. 2). Here the polarized emission is quite spectacular, tracing the arc-like structure morphology of the relic. Relic 1 in A2345 has instead peculiar features. It shows a peculiar morphology and un-expected spectral index profile, with steeper values toward the cluster outskirts. The X-ray emission of Abell 2345 shows multiple substructures that could be galaxy groups interacting with A2345. Peculiar features of Relic 1 could be explained by a shock wave moving inward, due to the interaction of the main cluster with another group. Recently optical analysis of this region (Boschin et al. 2010) have been performed, confirming this possible scenario. Deep X-ray observations would be required to better understand this issue.

5.1 Why are relics so rare?

Despite all models agree in saying that shock waves are responsible for relic formation, yet temperature and brightness gradients induced by shock waves have been unambiguously found only in A520 (Markevitch et al. 2005), and in the Bullet cluster (Markevitch et al. 2002), while in the case of the Coma cluster, Feretti & Neumann (2006) did not find any evidence of a temperature jump near the Coma cluster relic. A few more cases are good candidates, but due to low X-ray brightness at the cluster periphery searching for shock associated to radio relics is a very hard task. Recently, Vazza et al. (2010) have performed high resolution ($\sim$ 25 kpc/h) cosmological simulations of a sample of 20 massive galaxy clusters, at the aim of studying shocks statistics in the cluster formation region (Vazza et al., in prep). They found that the occurrence of shocks with

[2] We use the nomenclature proposed by Kempner et al. (2004)

$M > 2$ within the virial radius (R_v) is a rare event, and only two clusters over 20 are interested by strong shocks inside $R_v/2$ at $z = 0$, in agreement with X-ray observations.

6. Faraday Rotation measures and ICM magnetic fields

In the last years new important results on the ICM magnetic fields have been obtained by analysing the Faraday RM of radio galaxies in/behind clusters. Synchrotron radiation from radio galaxies that crosses a magneto-ionic medium, as the ICM, is subject to the Faraday Rotation. The direction of the polarization plane: Ψ_{int} is rotated of a quantity that in the case of a purely external Faraday screen is proportional to the square of the wavelength:

$$\Psi_{obs}(\lambda) = \Psi_{int} + RM\lambda^2; RM = \int_0^L B_{//} n_e dl; \tag{6.1}$$

here $B_{//}$ is the magnetic field component along the line of sight, n_e is the ICM gas density and L is the integration path along the line of sight. With the help of X-ray observations, providing information on n_e distribution, RM studies give an additional set of information about the magnetic field in the ICM.

6.1 The Coma cluster magnetic field

We have recently analysed the RM images of 7 extended sources in the Coma cluster. Observations were performed at 4 or 5 frequencies in the range 1.4 - 8.9 GHz, with angular resolution of $\sim 1.5''$, corresponding to 0.7 kpc at the Coma redshift. The RM images we have obtained allowed us to constrain the magnetic field radial decline with unprecedent detail.
We used the approach proposed by Murgia et al. (2004) and simulated RM images for different magnetic field models with different values of B_0, going from 1 to 11 μG, and η going from -0.5 to 2.5. In Fig. 3 the χ^2 plane obtained for each combination of these parameters is shown. Due to the degeneracy between the two parameters, different models give similar χ^2. The magnetic field radial profile is better described by a model with B_0 =4.7μG and η =0.5, indicating that the magnetic field energy density follows the gas energy density. It is interesting to note that also the model with $\eta = 0.67$, expected in the case of a magnetic field frozen into the gas, lies within the 1-σ confidence level of the χ^2. Magnetic field models with a profile flatter than $\eta < 0.2$ and steeper than $\eta > 1.0$ are instead excluded at 99% confidence level, for any value of $\langle B_0 \rangle$.
The value derived here can be compared with other estimates derived from equipartition and Inverse Compton hard X-ray emission. The magnetic field model resulting from our RM analysis gives an average magnetic field strength of ~ 2 μG, when averaged over the central Mpc^3. Equipartition estimate is strongly dependent on the unknown particle energy spectrum, and a single power-law is often assumed. Although the many uncertainties and assumptions relying under this estimate, the model derived from RM analysis is compatible with the equipartition magnetic field (0.7 - 1.9 μG; Thierbach et al. 2003). A direct comparison with the magnetic field estimate derived from the IC emission is more difficult, since the Hard-X detection is debated, and depending on the particle energy spectrum, the region over which the IC emission arises may change. The model derived from RM analysis gives a magnetic field estimate that is consistent with the present lower limits obtained from Hard X-ray observations by *e.g.* Wik et al. (2009), while it is a factor four higher

than the value derived from Fusco-Femiano (2004).
The knowledge of the ICM magnetic field breaks the synchrotron degeneracy and permits to constrain the energy content of electrons that give rise to radio halo emission. Using the result of RM studies, Donnert et al. (2010) have investigated through cosmological simulations if hadronic models may account for the observed radio emission in the Coma halo. The authors found that the radial profile of the radio halo can only be reproduced with a radially increasing energy fraction within the cosmic ray proton population, reaching $>100\%$ per cent of the thermal-energy content at 1 Mpc from the cluster center, thus disfavoring the hadronic models.

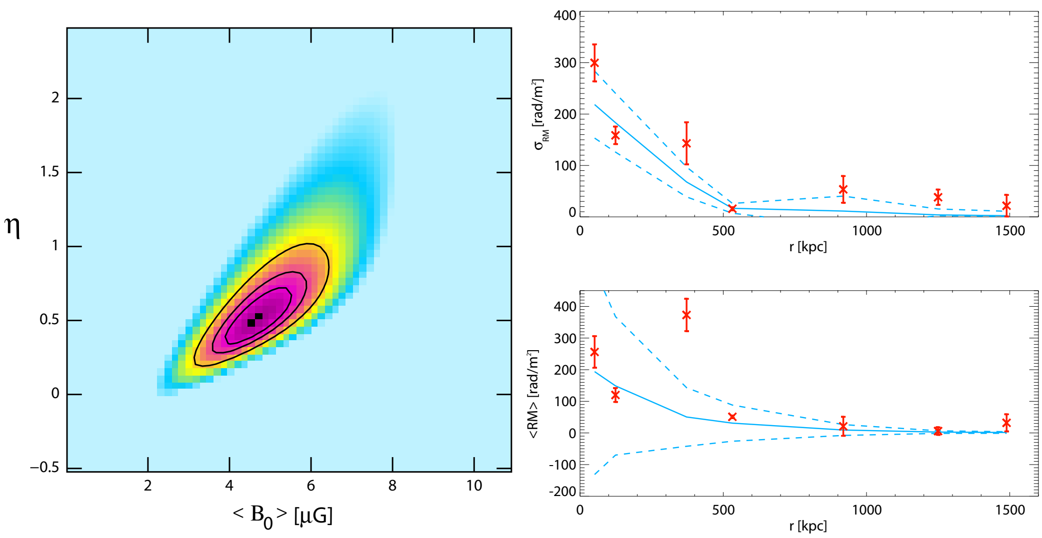

Figure 3: Figure from Bonafede et al. (2010). Left panel: χ^2 plane obtained by comparing simulated and observed RM images. Contours refer to 1,2 and 3-σ confidence levels. Right panel: RM mean and dispersion for the best-fit magnetic field model (cyan), observed points are shown in red.

6.2 Magnetic field power spectrum from Faraday RM

The intra cluster magnetic field power spectrum can be constrained starting from RM images of extended radio source, both within and behind galaxy clusters. In the cluster Abell 2255 (Govoni et al. 2006) the power spectrum has been analyzed also thanks to the detection of polarized filaments, as discussed in Sec. 4. In the Coma cluster (Bonafede et al. 2010) the power spectrum was assumed to be Kolmogorov-like, and by comparing the auto-correlation function and the structure function of simulated and observed RM images, the maximum and minimum scale of the power spectrum were constrained to be $\sim$ 2 and 34 kpc respectively. Similarly, the power spectrum of Abell 2382 is found to be consistent with a Kolmogorov-like power spectrum, with scales going from few to 30 kpc.
A different approach was adopted by Kuchar & Ensslin (2009) and Vogt & Enßlin (2005) that derived the magnetic field power spectrum through Bayesian analysis of RM images in the clusters HydraA, Abell 400 and Abell 2634. In these clusters the power spectrum is found to consistent with a Kolmogorov slope over a wide range of spatial scales.

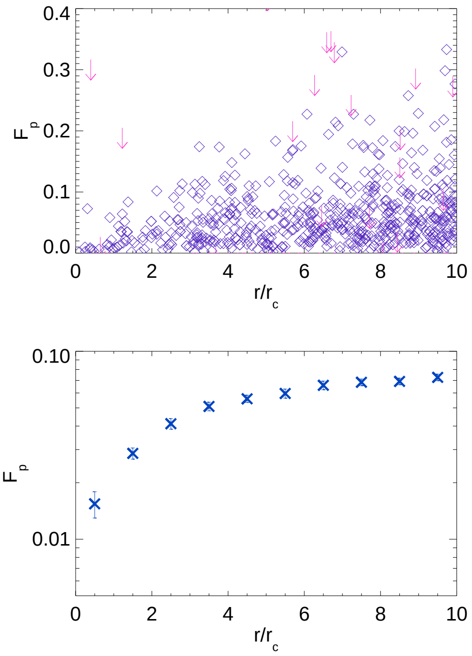

Figure 4: Fractional polarization for the whole cluster sample. Upper panel: values from single sources; lower panel: average values in bins having width of one core radius. Preliminary results from Bonafede et al. (in prep).

7. Depolarization from radio sources

The presence of ICM magnetic fields affects the polarization properties of radio galaxies. The higher RM suffered by sources in the inner regions, where both magnetic field strength and gas density are higher, causes in fact high beam depolarization. Sources at larger radii, instead, are subject to less depolarization, since their emission is affected by lower RM.

At the aim of investigating the general properties of the ICM magnetic field, we selected massive galaxy clusters from the HIghest X-ray FLUx Galaxy Cluster Sample (Reiprich & Böhringer 2002), and used Northern VLA Sky Survey data to analyze the polarization properties of radio-sources out to 10 r_c from the cluster centers (Bonafede et al., in prep). The sample consists of 33 clusters, with $L_x[0.1-2.4keV] \geq 1.5 \times 10^{44}$erg/s. In Fig. 4 the fractional polarization as a function of the distance from the cluster center is shown. We detected a clear trend of the fractional polarization, being smaller for sources close to the cluster center and increasing with increasing distance form the cluster central regions. This confirms, as already found by Clarke (2004) and Johnston-Hollitt et al. (2004) that magnetic fields are ubiquitous in galaxy clusters.

The sample of clusters we have selected comprises both clusters that host radio halos and clusters that are radio quiet. 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. The Kolmogorov-Smirnov statistical test gives high probability that the polarization trend observed in the radio-halo and radio-quiet sample are taken from the identical intrinsic population. Magnetic fields in galaxy clusters are then likely to share the same properties regardless of the presence of radio emission from the ICM. This result poses problems to the "hadronic-models" for the origin of radio halos, that requires a net difference in clusters with and without radio halos, while is in agreement with the re-acceleration scenario (see Brunetti, this conference).

8. Conclusions

Magnetic fields are now recognized to be an important component of the ICM in galaxy clusters. Our knowledge of their properties has greatly improved in the recent years thanks to both radio observations and the developments of new techniques to interpret data. We have shown that deep radio observations of both radio galaxies and cluster-wide diffuse sources permit to constrain the magnetic field radial decline slope and power spectrum. The results obtained by radio studies are fundamental to understand the process of radio halo and radio relic formation. The new generation of radio interferometers, such as LOFAR, that will open an unexplored frequency window, and as the EVLA, that will largely improve the sensitivity and polarization performances at $\nu > 1$ GHz, will allow us in the next years a step forward in the knowledge of the ICM magnetic field.

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PoS(ISKAF2010)006