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THE COMA CLUSTER MAGNETIC FIELD FROM FARADAY ROTATION MEASURES

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RESUMEN

Presentamos un nuevo trabajo en desarrollo acerca del campo magnético en el cúmulo Coma, apuntando a acotar su magnitud y estructura. Con este propósito, obtuvimos datos de polarización a 3.6 y 6 cm, y derivamos medidas de rotación de Faraday a escalas de kpcs. Simulamos campos magnéticos tridimensionales aleatorios y, suponiendo un modelo beta para la disribución de gas térmico, obtenemos imágenes sintéticas de las medidas de rotación. Comparando el modelo con observaciones obtenemos el campo magnético que reproduce mejor los datos observados. A pesar del pequeño número de fuentes, podemos poner algunas restricciones a la estructura e intensidad del campo magnético.

ABSTRACT

We present a new ongoing study on the Coma cluster magnetic field aimed at constraining its strength and structure. At this scope we obtained polarization data of 5 sources in the Coma cluster field at the Very Large Array at 3.6 and 6 cm and derived Faraday Rotation Measures at the kpc scale. We simulated random three dimensional magnetic fields and by assuming a beta model for the thermal gas distribution, we derived simulated RM images. By comparing observations with simulations, we derived the magnetic field model that best reproduces our observational data. Despite the small number of sources, we can give some constraints on the magnetic field strength and structure.

Key Words: galaxies: clusters: general — galaxies: clusters: individual (Coma-A1656) — large-scale structure of Universe — magnetic fields — polarization

1. INTRODUCTION

It is now well established that the intracluster medium (ICM) of galaxy clusters is not only composed of thermal gas emitting in the X ray energy band, but also of magnetic fields permeating the entire cluster volume. This is directly demonstrated by the detection of wide synchrotron radio sources such as radio halos and radio relics, in an increasing number of galaxy clusters (see e. g. Giovannini & Feretti 2004). In these clusters it is possible to derive an average estimate of the ICM magnetic field under the minimum energy hypothesis (equipartition magnetic field), or studying the Inverse Compton Hard X ray emission (e.g. Fusco-Femiano 2004).
The ICM magnetic field is also revealed by the analysis of polarization emission of radio sources located at different impact parameters with respect to the cluster center. The ICM, in fact, is a magneto-ionic medium and its interaction with the polarized synchrotron emission results in a rotation of the wave polarization plane (Faraday Rotation), so that the observed polarization angle, $\Psi_{\rm obs}$ at a wavelength λ differs from the intrinsic one, $\Psi_{\rm int}$ according to

$$\Psi_{\rm obs}(\lambda) = \Psi_{\rm int} + \lambda^2 \times RM, \qquad (1)$$

where RM is the Faraday Rotation Measure. This is related to the magnetic field component parallel to the line-of-sight ($B_{//}$) weighted by the thermal gas density (n_e) according to:

$$RM \propto \int_{\rm los} n_e(l) B_{//}(l) dl. \qquad (2)$$

Therefore, once we know the thermal gas density distribution from X-ray analysis, RM studies give an additional set of information about the cluster magnetic field.

The Coma Cluster magnetic field has been studied in the past following all of the three mentioned approaches. The first investigation of the magnetic field was performed by Kim et al. (1990). From RM

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analysis of 18 sources they derived a field strength of $\sim 2\ \mu$G. A further study was performed by Feretti et al. (1995) by studying in detail the polarization properties of the extended radio galaxy NGC 4869. They deduced a magnetic field of $\sim 6\ \mu$G tangled on scales of less than 1 kpc, in addition to a weaker magnetic field component of $\sim 0.2\ \mu$G , ordered on a cluster core radius scale.

From the radio emission of the Coma radio halo, assuming equipartition, a magnetic field estimate of $\sim 0.7 - 1.9\ \mu$G is derived (Thierbach et al. 2003), very similar to $\sim 0.2\ \mu$G found from the Inverse Compton Hard X-ray emission by Fusco-Femiano et al. (2004).

It must be taken into account that equipartition and IC estimates reveal the cluster volume averaged magnetic field intensity, while RM is sensitive to the local structures of both the thermal plasma and the cluster magnetic field component. Furthermore, equipartition estimate must be used with caution since it critically depends on the poorly known particle energy distribution. Radio halos, in fact, have a steep spectrum and the equipartition estimate is critically dependent on the low energy cut off of the emitting electrons.

The knowledge of cluster magnetic fields is important in order to understand the role of the magnetic field in the cosmological contest. It has been demonstrated that the intensity and the structure of the magnetic field in galaxy clusters is due to the structure formation processec (see e.g., Dolag 2006 and Donnert et al. 2009). Moreover, detailed knowledge of the magnetic field profile and power spectrum is important in order to understand the origin of non-thermal emission in galaxy clusters (see Brunetti 2009; Enßlin 2009).

In this contribution we present new Very Large Array (VLA) polarimetric observations of 5 sources in the Coma cluster field (§ 2). We used the FARADAY code developed by Murgia et al. (2004) to simulate different magnetic field models (§ 3), and present our preliminary result in § 4.

The Coma cluster is an important target for a detailed study of cluster magnetic fields. This is a nearby cluster (z=0.023) and hosts large scale radio emission (radio halo, radio relic, bridge).

We assume a ΛCDM cosmological model with $H_0 = 71$ km/s/Mpc, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$. This means that 1 arcsec corresponds to 0.460 kpc at the Coma redshift (z=0.023).

2. RADIO OBSERVATIONS AND ROTATION MEASURE FITS

We selected from Northern VLA Sky Survey (NVSS) a sample of 20 sources having a peak flux density larger than 45 mJy, located within a radius of 1° from the cluster center ($\simeq 5r_c$, where r_c is the cluster core radius), and which have indication of polarization from Kim et al. (1990). Observations have been performed, so far, of 5 sources with the VLA in B configuration. The observing time is 8h per source. The angular resolution was $\sim 1.5''$ corresponding to ~ 0.7 kpc/h_{71}. Radio observations were performed at four frequencies: 4.535 GHz, 4.935 GHz, 8.085 GHz and 8.465 GHz. Image rms noise ranges from 17 to 30 μJy/beam, close to the thermal noise level.

We derived RM fits for the observed sources using the PACERMAN algorithm (Polarization Angle CorrEcting Rotation Measure ANalysis) developed by Dolag et al. (2005). The algorithm solves the nπ ambiguity in low signal-to-noise regions exploiting the information of nearby high signal-to-noise pixels. The resulting RM maps are presented in Figure 1 overlaid into the total intensity contours at 8.465 GHz. We calculated for each source the mean value of the RM (<RM>) and its dispersion ($\sigma_{\rm RM}$).

3. SIMULATIONS

We simulated random 3-D vectorial magnetic field using the FARADAY code developed by Murgia et al. (2004). We assumed the power spectrum of the cluster magnetic field to follow a power law[6]:

$$|B_k|^2 \propto k^{-n} \propto \Lambda^n \,, \tag{3}$$

where k is the wave number associated to the magnetic field fluctuation and $\Lambda = \pi/k$. The adopted magnetic field model scales with the thermal density as (see. Dolag et al. 2001)

$$< B > (r) =< B_0 > [n_e(r)/n_0]^\eta \,. \tag{4}$$

This magnetic field model has then a total of five free parameters:

- the power spectrum slope: n
- the power spectrum maximum fluctuation scale: $\Lambda_{\rm max}$
- the power spectrum minimum fluctuation scale: $\Lambda_{\rm min}$
- the average central intensity: B_0

[6]The power spectrum is expressed as vectorial form in k-space. The one-dimensional form can be obtained by multiplying by $4\pi k^2$ the three-dimensional power spectrum. The Kolmogorov power spectrum in our notation corresponds to n=11/3.

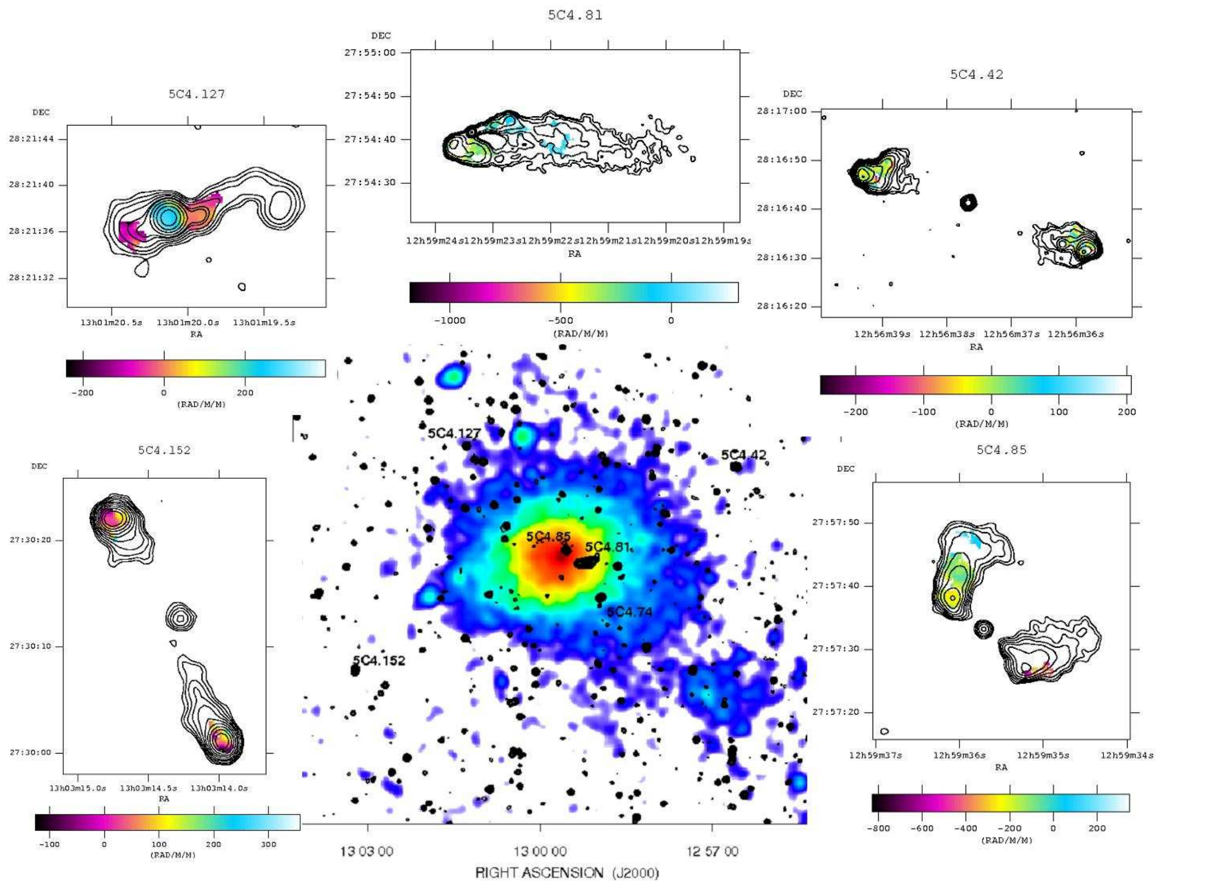

Fig. 1. Colors refer to the Coma X-ray emission in the energy band 0.1–2.4 keV (Rosat data archive). The image has been smoothed with a gaussian of $\sigma = 60''$. Black contours represent the Coma radio emission at 1.4 GHz from the Northern VLA Sky Survey. Note that the Halo emission is not visible because of the lack of short baselines. The resolution (Half Power Beam Width) is $45'' \times 45''$. Contours start at 1.5 mJy/beam and are spaced by a factor of 2. RM images of the five sources are shown asinsets.

- the radial profile slope: η.

Since we did not detect significant depolarization between 4.5 and 8.5 GHz, we assumed that we resolved the minimum scale over which the magnetic field may fluctuate and fixed $\Lambda_{\min} = 2$ kpc in the following analysis.

We obtained simulated RM images by integrating the thermal gas density obtained from X-ray observations (Briel et al. 1992) and the magnetic field intensity along the line of sight (equation 2) for different configurations of the magnetic field, i.e. varying its central strength, radial slope and power spectrum. Given the assumed power-law spectrum and the integration of the magnetic field along the line of sight, two degeneracies arise: the first one is between B_0 and η, due to the fact that the integral of a higher central magnetic field strength with a sharper radial decline is equivalent to a lower central magnetic field with a shallower radial decline. The second one in between $\Lambda_{\max}$ and n. In fact a steep power spectrum (i.e. n>3) means that the magnetic energy density is larger on the large spatial scale, while a flat power spectrum (n<2) implies that the magnetic energy density is larger on the small spatial scales. Thus a large value of n combined with a small $\Lambda_{\max}$ may be equivalent to a small value of n combined with a large value of $\Lambda_{\max}$.

For more details on the application of this model, we refer to Govoni et al. (2005) for Abell 2255 and to Guidetti et al. (2008) for Abell 2382.

4. RESULTS

Both | <RM¿| and $\sigma_{\rm RM}$ decrease going from the centre to the periphery of the cluster. Non zero values of <RM> implicate that the ICM magnetic field fluctuates on scales larger than the source's extension. RM images also show a patchy structure, that can be explained by magnetic field fluctuations

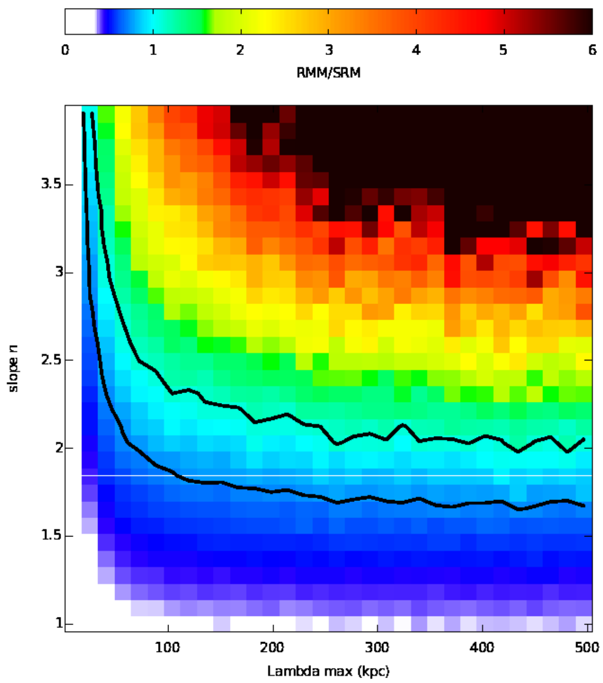

Fig. 2. Plot of the ratio $| < RM > |/\sigma_{\rm RM}$, calculated in simulated RM images over boxes of 13×13 kpc^2 (colors) as a function of n and $\Lambda_{\rm max}$. Black curves refer to the $| < RM > |/\sigma_{\rm RM}$ observed ratio of the Coma cluster sources.

smaller than the source's size. This is the reason why in order to interpret properly the RM data we have to take into account magnetic field fluctuations in a wide range of spatial scales, that is, we have to model the magnetic field power spectrum. The main results are as follows:

– The power spectrum degeneracy: Since both <RM> and $\sigma_{\rm RM}$ scale with B_0 but have different trends with n and $\Lambda_{\rm max}$, the ratio of these quantities may be used to investigate the magnetic field power spectrum.

Figure 2 shows the ratio calculated in simulated 2-D RM images (colors) as a function of both n and $\Lambda_{\rm max}$. The black lines refer to the same ratio as observed in the sources of Coma cluster.

Because of the $n-\Lambda_{\rm max}$ degeneracy, several combination of these two parameters are consistent with our data. In a huge interval of $\Lambda_{\rm max}$ values, n is constrained to be ~ 2. An asymptotic trend is achieved for $\Lambda_{\rm max} = 512$ kpc and n=1.8. In fact, if n$\sim$2, the bulk of the magnetic energy density is on the small spatial scales, so that the effect of increasing $\Lambda_{\rm max}$ is negligible after a certain threshold. Another asymptotic trend is achieved for n=11/3 and $\Lambda_{\rm max} = 25$ kpc. In fact, if n>3 the magnetic energy density is higher on the larger scale, so that as the power spectrum steepens, the value of $\Lambda_{\rm max}$ must be reduced.

– The $B_0 - \eta$ degeneracy: Because of the $B_0 - \eta$ degeneracy, different magnetic field models give similar good fits to our data. In Figure 3, we show three fits performed with different values of B_0 and η. In order to compare these preliminary results with the equipartition estimate, we have to average the field strength over the same volume assumed in the equipartition analysis, that is ~ 1 Mpc^3. The magnetic field model resulting from our RM analysis gives an average magnetic field strength of $\sim 1.2\ \mu$G, that is consistent with the equipartition estimate.

The Inverse Compton Hard X ray emission has been observed with the *Beppo Sax* satellite. Its field of view is $\sim 1.3^\circ \times 1.3^\circ$. Averaging the field obtained here over the corresponding volume and assuming spherical symmetry we obtain <B>$\sim 0.4\ \mu$G, that is consistent, in a factor 2 with the Inverse Compton estimate.

5. FUTURE PROSPECTS

The work is still in progress and these preliminary results need to be refined. In fact the magnetic field model derived here is not strongly constrained yet because of the above mentioned degeneracies. In spite of this, the work is really promising to achieve a detailed study of the magnetic field in the Coma cluster. In order to break the degeneracies and achieve a robust estimate of the magnetic field intensity, radial profile and power spectrum, RM images of more sources are needed. Another source will be soon observed in the next few months, and besides, we are asking for further observing time in order to observe the whole initially selected sample.

The Coma cluster is the ideal candidate for this study since it is nearby and there is a great number of polarized sources inside and behind the cluster.

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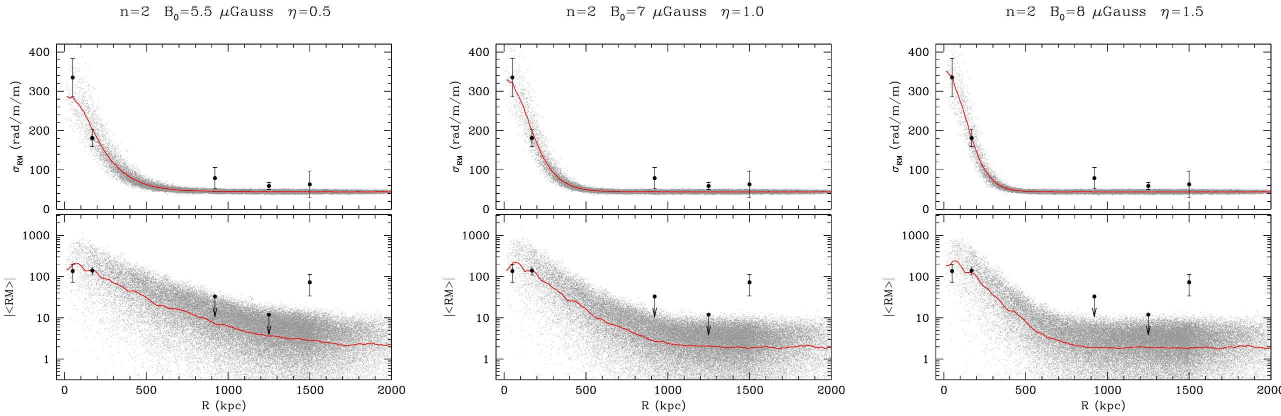

Fig. 3. Fits to RM data performed on $\sigma_{\rm RM}$ with different magnetic field models, specified at the top of each fit (red lines); black points refer to RM observations; grey points represent the scatter in simulated RM images.

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