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Magnetic Fields in Clusters of Galaxies Obtained Through the Study of Faraday Rotation Measures

Federica Govoni

Dip. Astronomia, Univ. Bologna, Via Ranzani 1, I-40127 Bologna, Italy

Luigina Feretti, Matteo Murgia

IRA-CNR, via Gobetti 101, I-40129 Bologna, Italy

Greg Taylor

NRAO, Socorro, NM 87801, USA

Gabriele Giovannini, Daniele Dallacasa

Dip. Astronomia, Univ. Bologna, Via Ranzani 1, I-40127 Bologna, Italy

Abstract. We are developing a new approach to investigate cluster magnetic field strengths and structures. It is based on the comparison of simulated Rotation Measure and radio halo images, obtained from 3-dimensional multi-scale cluster magnetic fields models, with observations. This approach is applied to A2255 in which wide diffuse radio emissions and Rotation Measure images show the evidence of cluster magnetic fields on both large and small scales.

1. Introduction

The existence of cluster magnetic fields has been demonstrated by different techniques.

Some clusters of galaxies show the presence of wide diffuse radio emissions (radio halos and/or relics) associated with the intra-cluster medium rather than a cluster galaxy. Under minimum energy assumptions, it is possible to calculate an equipartition magnetic field strength averaged over the entire halo volume. These estimates give $H_{eq}\simeq$0.1-1 μG (e.g. Feretti & Giovannini 1996; Govoni et al. 2001a).

In a few cases, clusters with radio halos show a hard X-ray excess. This emission is usually interpreted in terms of Inverse-Compton scattering of cosmic microwave background photons by the relativistic electrons responsible for the radio halo emission. In this case, the measurements of the magnetic field strength (e.g. Fusco-Femiano et al. 1999, Rephaeli et al. 1999) inferred from the ratio of the radio to X-ray luminosities are consistent with the equipartition estimates.

Indirect measurements of the cluster magnetic field strength can be determined in conjunction with the X-ray observations of the hot gas, through the

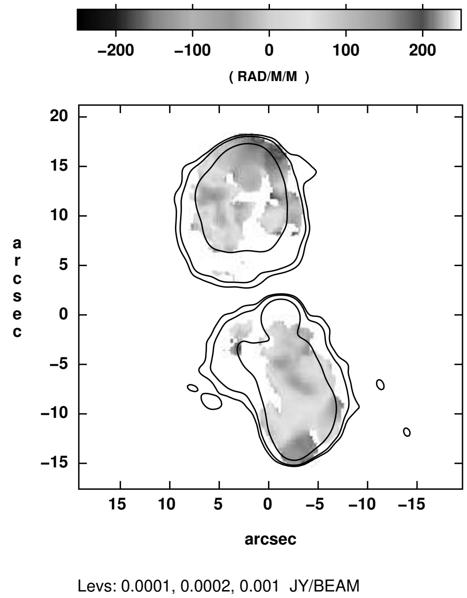

Figure 1. RM image of the radio source $B1713+641$ in A2255, computed using the polarization angle images at the frequencies 4535, 4885, 8085 and 8465 MHz with a resolution of $2''$. Contours refer to the total intensity image at 6 cm. The values of RM range between -100 rad/m^2 and 210 rad/m^2. The <RM> is 67 rad/m^2 and the σ_{RM} is 59 rad/m^2.

study of the Faraday Rotation Measure (RM) of radio sources located inside or behind the cluster. In clusters without cooling flows, RM studies of polarized radio sources lead to a magnetic field of 2-6 μG with a correlation length in the range 2-15 kpc (Feretti et al. 1995; Feretti et al. 1999; Clarke et al. 2001; Taylor et al. 2001; Govoni et al. 2001b).

The magnetic field strength obtained by RM studies is therefore higher than the value derived from the radio data and from Inverse-Compton X-ray emission in clusters with radio halos. However, both methods are based on many simplifying assumptions (see e.g. a recent review by Carilli & Taylor 2002). Moreover, as pointed out by Newman et al. (2002), and Murgia et al. (2002, in preparation) the observed RMs are usually interpreted in terms of the simplest possible magnetic field model, and previous estimates of the field by using RMs value are likely to be over-estimated.

2. The cluster A2255

Here we present a preliminary analysis of the magnetic field in the cluster A2255.

A2255 (z=0.0806; $1''\simeq 2$ kpc, with H_0=50 km/sMpc and q_0=0.5), is a suitable target for the investigation of magnetic fields because it is characterized by the presence of well polarized radio galaxies and contains both a radio halo and a relic source.

With high sensitivity and resolution ($\simeq 2''$) Very Large Array (VLA) polarization data, we obtained RM images of two extended radio galaxies belonging

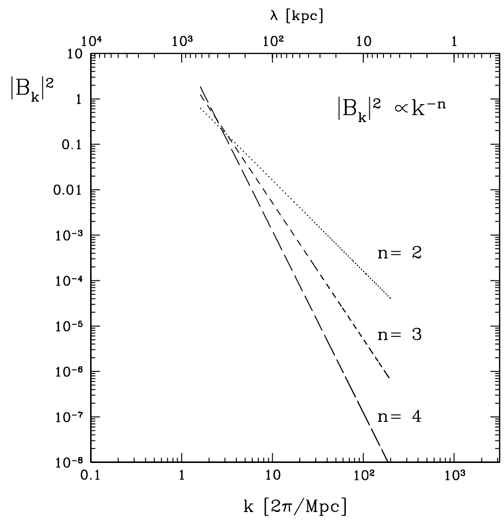

Figure 2. Power spectra of 3-dimensional multi-scale magnetic field models used in the simulations. All the models are normalized to have the same magnetic field energy. The magnetic field energy density decreases from the cluster center as the gas energy density, and the scale of the magnetic fields ranges from 5 kpc to 600 kpc.

to the cluster. The RM images of these radio sources indicates RM structures with coherence lengths of about 10 kpc. In Fig. 1 we report the RM image of one of these sources.

The radio halo in A2255 was studied by several authors (Jaffe & Rudnick 1997, Harris et al. 1980, Burns et al. 1995, Feretti et al. 1997) with angular resolutions of tens of arcsec. The extent of the radio emission implies the existence of magnetic field on a much larger scale than implied by the RM results. Therefore, the wide diffuse radio emissions and the Rotation Measure images in A2255 show the evidence of a cluster magnetic field both on large and small scales. For this reason, to study the cluster magnetic fields it is necessary to consider realistic magnetic field models where both small and large scale filamentary structures coexist.

3. Cluster Magnetic Field Models

We developed a new approach to investigate cluster magnetic fields by comparing simulated RM and radio halo images, with observations. We applied this method to A2255. The FARADAY tool (Murgia et al. 2002, in preparation) permits us to simulate RM and radio halo images from 3-dimensional multi-scale cluster magnetic fields. The magnetic field power spectrum of our models follow the equation: $|B_k|^2 \propto k^{-n}$. Different models will generate different magnetic field configurations and therefore will give rise to very different simulated RM and radio halo images.

Fig. 2 shows power spectra of magnetic field models used in the simulations. All the models are normalized to have the same total magnetic field energy. The

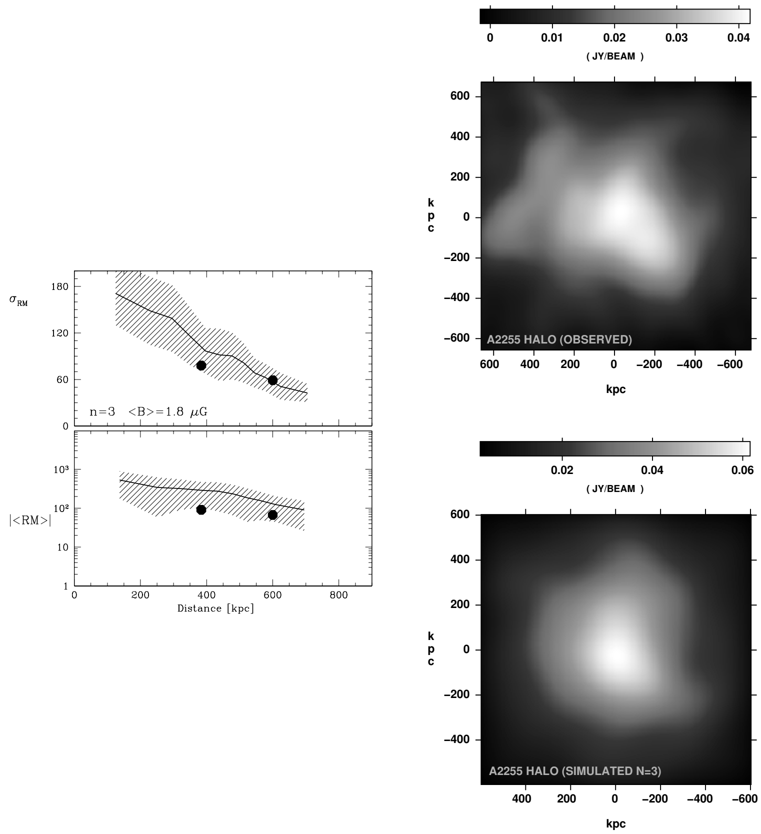

Figure 3. Simulation results obtained with a power spectrum index $n = 3$. Left: RM data points (σ_{RM} and $\mid$ <RM> $\mid$) obtained in A2255 (black points) are compared with the simulation (shaded region). Right Top: WSRT radio image at 90 cm with resolution of $\simeq$ 170 kpc of the halo source in A2255 obtained by Feretti et al. (1997). Right Bottom: Simulated large scale radio features as expected at the same frequency and resolution of the WSRT image.

magnetic field energy density decreases from the cluster center as the gas energy density, and the scale of the magnetic fields ranges from 5 kpc to 600 kpc. The aim of this new approach is to find the optimal magnetic field strength and structure capable of describing both the small scale structures (of about 10 kpc) seen in the RM images, and the large scale features visible in the radio halo of A2255 (Feretti et al. 1997, see Fig. 3, right on the top).

The best power spectrum index which can explain both the RM data and the radio halo structure seems $n = 3$. Fig. 3 compares the results from a simulation with a power spectrum index $n = 3$ with the observations. On the left the RM data points (σ_{RM} and $\mid$ <RM> $\mid$) obtained in A2255 are compared with the expectation of the simulations (shaded region). On the right the Westerbork Synthesis Radio Telescope (WSRT) radio image at 90 cm with a linear resolution of about 170 kpc (Feretti et al. 1997) is compared with the simulated large scale radio halo as expected at the same frequency and resolution. This steep magnetic field power spectral index is consistent with that (i.e. n=2.7) found by Dolag et al. (2002) in cosmological magnetic hydrodinamical simulations.

Simulations with power spectrum index $n = 2$ explain the RM data, but predict a much smoother than observed structure of the radio halo, while $n = 4$ seems to be ruled out since the $| <\mathrm{RM}> |$ is overestimated by a large factor. Moreover, since most of the magnetic field energy is in the large scales, the model with $n = 4$ fails to reproduce the small features seen in the RM images.

4. Conclusions

Observable radio data, compared with simulated RM and radio halo images obtained from 3-dimensional multi-scale cluster magnetic field models, can significantly improve the knowledge of the cluster magnetic field structure and strength. This approach is applied to A2255 in which wide diffuse radio emissions and Rotation Measure images show the evidence of cluster magnetic fields on both large and small scales. We find a magnetic field power spectral index of 3 from scales of 5 to 600 kpc can reproduce both the RM structures and the large scale radio halo.

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