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THE INTRA-CLUSTER MAGNETIC FIELD POWER SPECTRUM IN ABELL 2382

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RESUMEN

Investigamos la relación entre el campo magnético y los efectos de polarización de Faraday en el cúmulo de galaxias Abell 2382. Para este propósito presentamos observaciones del Very Large Array en 20 cm y 6 cm de dos fuentes de radio polarizadas embebidas en el cúmulo, y obenemos imágenes detalladas de las medidas de rotación para ambas. Hacemos modelos de campos magnéticos aleatorios con diferentes espectros de potencia y con ellos producimos imágenes de observaciones sintéticas. Comparando nuestras simulaciones con las propiedades observadas de las fuentes de radio podemos determinar la magnitud y el índice espectral de las fluctuaciones del campo magnético intracumular que se ajustan mejor a las observaciones. Los datos son consistentes con una ley de potencias con un índice espectral de Kolmogorov ($n = 11/3$), y una escala superior para las fluctuaciones magnéticas del orden de 35 kpc. La magnitud promedio del campo magnético en el centro del cúmulo es de 3 μG, y disminuye hacia las zonas externas como la raíz cuadrada de la densidad electrónica. La magnitud promedio del campo magnético el Mpc^3 central es de alrededor de 1 μG.

ABSTRACT

We investigated the relationship between magnetic field and Faraday rotation effects in the cluster of galaxies Abell 2382. For this purpose we present Very Large Array observations at 20 cm and 6 cm of two polarized radio sources embedded in the cluster, and we obtained detailed rotation measure images for both of them. We produced random three-dimensional magnetic field models with different power spectra and thus produced synthetic rotation measure images. By comparing our simulations with the observed polarization properties of the radio sources, we can determine the strength and the power spectrum of intra-cluster magnetic field luctuations that best reproduce the observations. The data are consistent with a power law magnetic field power spectrum with the Kolmogorov index ($n = 11/3$), while the outer scale of the magnetic field fluctuations is of the order of 35 kpc. The average magnetic field strength at the cluster center is about 3 μG and decreases in the external region as the square root of the electron density. The average magnetic field strength in the central 1 Mpc^3 is about 1 μG.

Key Words: galaxies: cluster: general — integalactic medium — radio continuum: galaxies — X-rays: galaxies: cluster

1. INTRODUCTION

The intra-cluster medium in clusters of galaxies is known to possess a magnetic field, but its origin and properties are not well known (see e.g. the review by Govoni & Feretti 2004; Carilli & Taylor 2002, and references therein). The strongest evidence for the presence of cluster magnetic fields comes from radio observations. Magnetic fields are studied through the synchrotron emission of cluster-wide diffuse sources, and from studies of the Faraday rotation of polarized radio galaxies. The magnetized plasma that is present between an observer and a radio source changes the properties of the polarized emission from the radio source. Therefore, the magnetic field strength can be determined with the help of X-ray observations of the hot gas, through the investigation of the Faraday Rotation Measure (RM) of radio sources located inside or behind the cluster. On the basis of the available RM images, increasing attention is given in the literature to the power spectrum of the intra-cluster magnetic field fluctuations. Several studies (Vogt & Ensslin 2003; Murgia et al. 2004) have shown that detailed RM images of radio galaxies can be used to infer not only the cluster magnetic field strength, but also the cluster magnetic field power spectrum.

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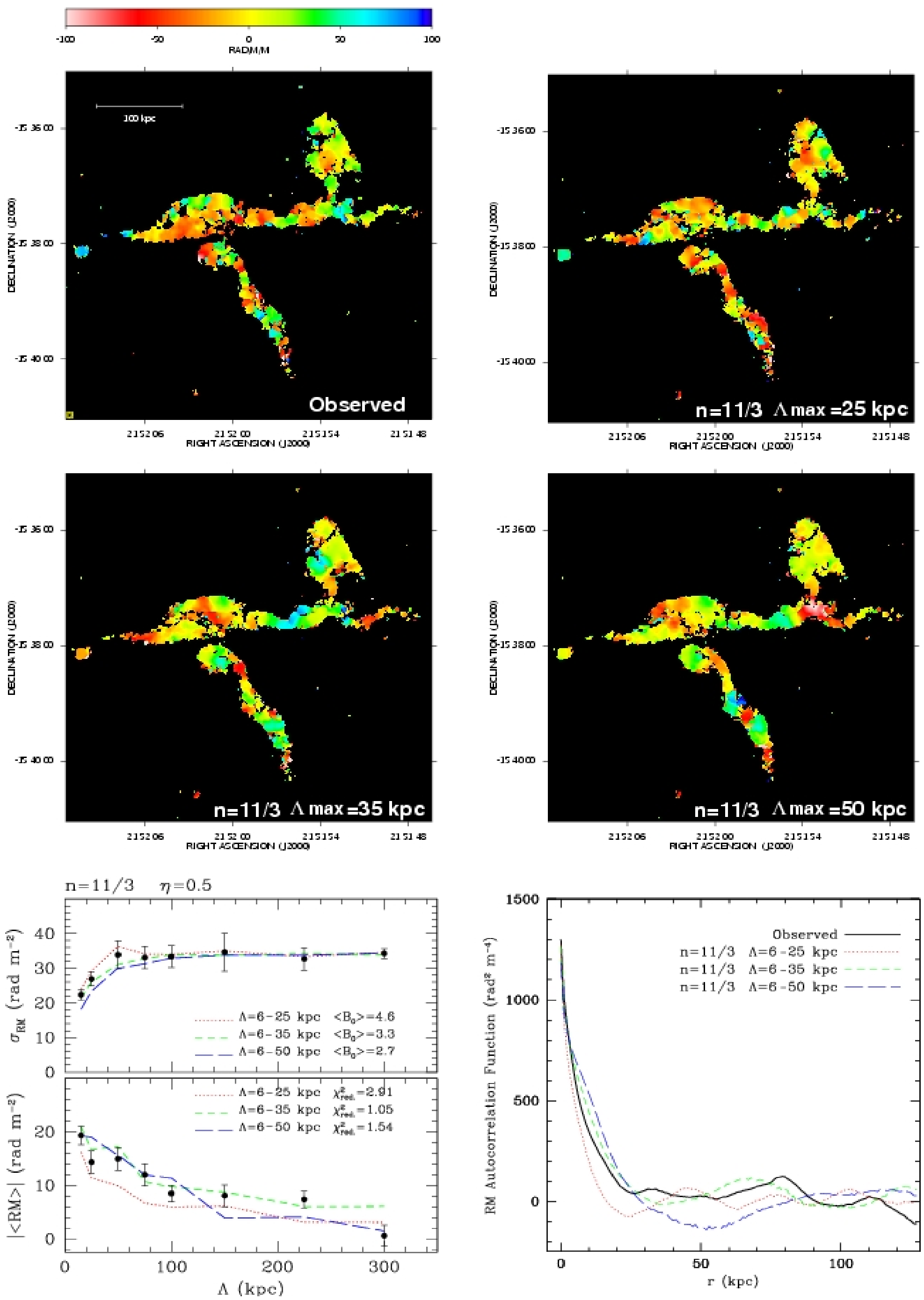

Fig. 1. Comparison of observed and simulated RM images in Abell 2382.

2. RADIO OBSERVATIONS

Our work is based on a polarimetric study conducted with the Very Large Array (VLA) at 20 cm and 6 cm of the radio galaxies PKS 2149-158 and PKS 2149-158C in the cluster Abell 2382. A2382 is an ideal case to study RM along different lines-of-sight because PKS 2149-158 and PKS 2149-158C are quite extended, both in angular and linear size, and thus they are ideal targets for an analysis of the rotation measure distribution: detailed RM images can be constructed which can serve as the basis of an accurate study of magnetic field power spectrum.

3. ROTATION MEASURE IMAGES

Polarized radiation from cluster and background radio galaxies may be rotated by the Faraday effect if magnetic fields are present in the intra-cluster medium. Linearly polarized radio waves passing through a magnetized ionized medium suffer a rotation of the plane of polarization:

$$\Psi_{\rm obs} = \Psi_0 + \lambda^2 \ {\rm RM}\,, \tag{1}$$

where $\Psi_{\rm obs}$ is the position angle observed at a wavelength λ, Ψ_0 is the intrinsic position angle and RM is the Rotation Measure. By performing a fit of the polarization angle images at different frequencies we obtain the RM at each location in the source. The RM image of the two radio galaxies in Abell 2382 is shown in the top-left panel of Figure 1.

4. NUMERICAL SIMULATIONS

The RM is related to the electron density (n_e), and the magnetic field along the line-of-sight ($B_{||}$), through the path integral across the intra-cluster medium:

$${\rm RM} \propto \int n_e B_{||}\, dl\,. \tag{2}$$

Thus, given a model for the electron density distribution we can reconstruct the magnetic field B by inverting equation (2).

The software package FARADAY (Murgia et al. 2004) permits the study of cluster magnetic fields by comparing the observed RM with simulated RM images obtained by considering three-dimensional multi-scale cluster magnetic field models. In fact, given a three-dimensional magnetic field model and the density distribution of the intra-cluster gas, FARADAY calculates the expected RM image by integrating equation (2) numerically. In the specific case of A2382, the integration is performed from the cluster center up to three core radii (1.1 Mpc) along the line-of-sight, i.e. both sources are supposed to lie in a plane which is perpendicular to line-of-sight and intercepts the cluster centre. For the gas density we assume a double beta-model derived from the fit to the X-ray surface brightness profile of the cluster. For the intra-cluster magnetic field we adopt a power law power spectrum characterized by the following five free parameters:

(i) the average magnetic field at the cluster centre, B_0;

(ii) the power spectrum index n ($|B_k|^2 \propto k^{-n}$);

(iii) the minimum scale of the magnetic field fluctuations, $\Lambda_{\rm min}$;

(iv) the maximum scale of the magnetic field fluctuations, $\Lambda_{\rm max}$;

(v) the slope of the radial profile magnetic field strength, $B(r) = B_0[n(r)/n_0]^{\eta}$.

By using a source model of the intrinsic polarization, FARADAY produces, at each frequency and with the same noise as the data, the expected polarization images corresponding to the simulated RM. Furthermore, we can take into account both the beam and bandwidth depolarization effects. The synthetic polarization images can be then processed as they were real data, resulting in final simulated RM images which are filtered with the same algorithm as the observations.

5. CONCLUSIONS

By comparing the observed and the simulated RM images, we conclude that the data are consistent with a power law magnetic field power spectrum with the Kolmogorov index $n = 11/3$ while the largest scales of the magnetic field fluctuations are of the order of $\Lambda_{\rm max} = 35$ kpc (see Figure 1). However, because of the degeneracy existing between n and $\Lambda_{\rm max}$, the observed RM can be quite well explained also by a shallower power spectrum with $n = 2$ and $\Lambda_{\rm max} = 128$ kpc. From the observed depolarization levels we also found a constraint to the minimum scale of the magnetic field fluctuations: $\Lambda_{\rm min} \sim 6$ kpc.

The analysis of the radially average RM profiles shows that the best fit of the data is obtained with $\eta = 0.5$ and $B_0 = 3.6\ \mu$G. The value of η corresponds to a magnetic field whose energy density decreases from the cluster center as the square root of the gas electron density. The average magnetic field strength over the central 1 Mpc^3 is about 1 μG.

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