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THE EVOLUTION OF CLUSTER MAGNETIC FIELDS PROBED BY THE SKA

M. Huarte-Espinosa,[1] P. Alexander,[1] R. Bolton,[1] J. Geisbuesch,[1] and M. Krause[2]

RESUMEN

El SKA será una herramienta sin paralelo para estudiar los campos magnéticos, y de hecho, uno de sus proyectos científicos prioritarios es el origen y la evolución del "Magnetismo Cósmico". Como parte de los Estudios Europeos de Diseño del SKA (SKADS) estamos desarrollando simulaciones del cielo y de varios experimentos asociados con su instrumentación para estudiar la evolución de estos campos magnéticos. En particular, consideramos detalladamente como pueden observarse los campos magnéticos en cúmulos de galaxias (cúmulos) en corrimientos al rojo altos, usando la rotación de Faraday con fuentes de radio ubicadas detrás de los cúmulos. En esta presentación describimos los modelos y observaciones de los campos magnéticos en los cúmulos en el contexto del SKA. Mostramos como será posible estudiar con este telescopio los campos magnéticos en cúmulos a altos corrimientos al rojo. Además discutimos nuestras simulaciones numéricas (3DMHD) de cúmulos magnetizados, en los que existe retroalimentación de Núcleos Activos de Galaxias (NAG) proveniente de fuentes de radio de tipo FR II. Implementamos la estructura magnética inicial de este cúmulo con un espectro espacial, con diferentes índices espectrales, y fases generadas al azar. Usamos las propiedades físicas observadas en varios cúmulos para simular el plasma del medio inter-galáctico de nuestro cúmulo. Finalmente, discutimos brevemente la capacidad del SKA de observar rasgos de actividad de NAG en los cúmulos.

ABSTRACT

The Square Kilometer Array (SKA) will provide an unparalleled tool to study magnetic fields, and indeed one of the "Key Science Cases" for the SKA is the origin and evolution of cosmic magnetism. As part of the European SKA Design Study (SKADS) we are developing sky simulations and associated instrumental simulations of various experiments to probe the evolution of magnetic fields. In particular we are considering in detail how cluster magnetic fields can be probed to high redshift using Faraday rotation against background sources as the probe. In this presentation, modelling and observations of the magnetic fields in galaxy clusters are described in the context of the SKA. We show how it will be possible with the SKA to study evolution of the field in clusters out to high redshift. We also discuss our work on 3D MHD simulations of a magnetised galaxy cluster, when we have AGN feedback from a powerful FR II radio source. The initial magnetic structure of this cluster has a spatial spectrum with a range of spectral index and randomly generated phases; the intra-cluster medium plasma is implemented with physical properties resembling those observed in many clusters. We discuss briefly the ability of the SKA to observe any signature of past AGN activity in clusters.

Key Words: galaxies: clusters — galaxies: jets — intergalactic medium — magnetic fields — MHD

1. INTRODUCTION

Magnetic fields of Mpc scale have been observed to permeate the the intra-cluster medium (ICM) inside galaxy clusters (clusters from now on). X-ray observations show that the ICM consist of hot plasma emitting Bremsstrahlung radiation with temperatures ranging from 10^7 to 10^8 K, and a β density profile extending to $\sim$ 2 Mpc distances (Sarazin 1988). This gas, with masses of the order of 10^{13} to 10^{14} $M_\odot$, is the dominant baryonic component in clusters. Observations in radio frequencies have been used to study the magnetic fields in clusters (see Feretti & Giovannini 2008, and references therein). These studies reveal non-thermal synchrotron structures embedded inside the clusters, which are divided in either halos or radio galaxies. The former are usually found in the cores of clusters, showing low surface brightnesses and are usually unpolarised. On the contrary, radio galaxies are extended and highly polarised sources, associated with active galactic nuclei (AGN) and quasars, which produce jets giving rise to sources which can extend beyond the core radius. The Coma cluster presents good examples of all these radio sources (Feretti & Giovannini 2008).

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[1] Astrophysics Group, Cavendish Laboratory, Cambridge CB3 0HE, UK (mh475, pa, rosie, joern@mrao.cam.ac.uk).

[2] Max-Planck-Institut fuer Extraterrestrische Physik, Garching, Germany (M.Krause@mpe.mpg.de).

The polarised radiation from radio galaxies, embedded in clusters or behind them (background sources), have been used to reveal yet another constituent of the cluster magnetic fields (CMFs). This is done by observing Faraday Rotation (e.g., see Clarke et al. 2001; Carilli & Taylor 2002; Govoni et al. 2006), where the plane of polarisation of the radio emission rotates as it goes through a magnetised medium. The degree of rotation is characterised by the Rotation Measure (RM). These investigations have found that, in general, the CMFs have coherence lengths of $\sim 5-10\,\mathrm{kpc}$ and intensities of the order of $1-10\,\mu\,\mathrm{G}$ decreasing with the distance from the core of the cluster. RM observations also show a correlation between the RM and the cooling flow rate in cool core clusters (Taylor et al. 2002). Moreover, RM data enables modelling and characterisation of the CMFs with spatial power spectra of the magnetic field fluctuations (Murgia et al. 2004; Vogt & Enßlin 2005). It is this component of the CMFs that we study in this letter.

Radio telescopes such as the VLA have been used to study the CMFs. However, a detailed analysis of the structure and origin of these, requires more powerful radio telescopes such as the Square Kilometre Array (SKA), which will provide an improvement of approximately two orders of magnitude in sensitivity over existing telescopes.

2. PROBING THE STRUCTURE OF CLUSTER MAGNETIC FIELDS

We have been implementing a Faraday screen to simulate the effects of a set of magnetised clusters at high redshift, on the radiation from background radio sources. The clusters are implemented with a β density profile, with a mean core radius of 100 kpc, and a radial RM distribution based on local universe data.

Figure 1 shows the different stages of one of these Faraday screens. The colour scale in each of the images shows the RM associated with it. The Faraday depth from cosmological clusters is simulated first, illustrated in Figure 1a. The clusters are resolved in this image. Figure 1b exhibits the simulated recovered SKA sampling of the screen above it, assuming a 100-hour observation. Figure 1c depicts the smoothened version of the SKA sampling above it (Figure 1b). Statistical analysis, on the number of clusters and their magnetic fields as a function of redshift, are done with these screens.

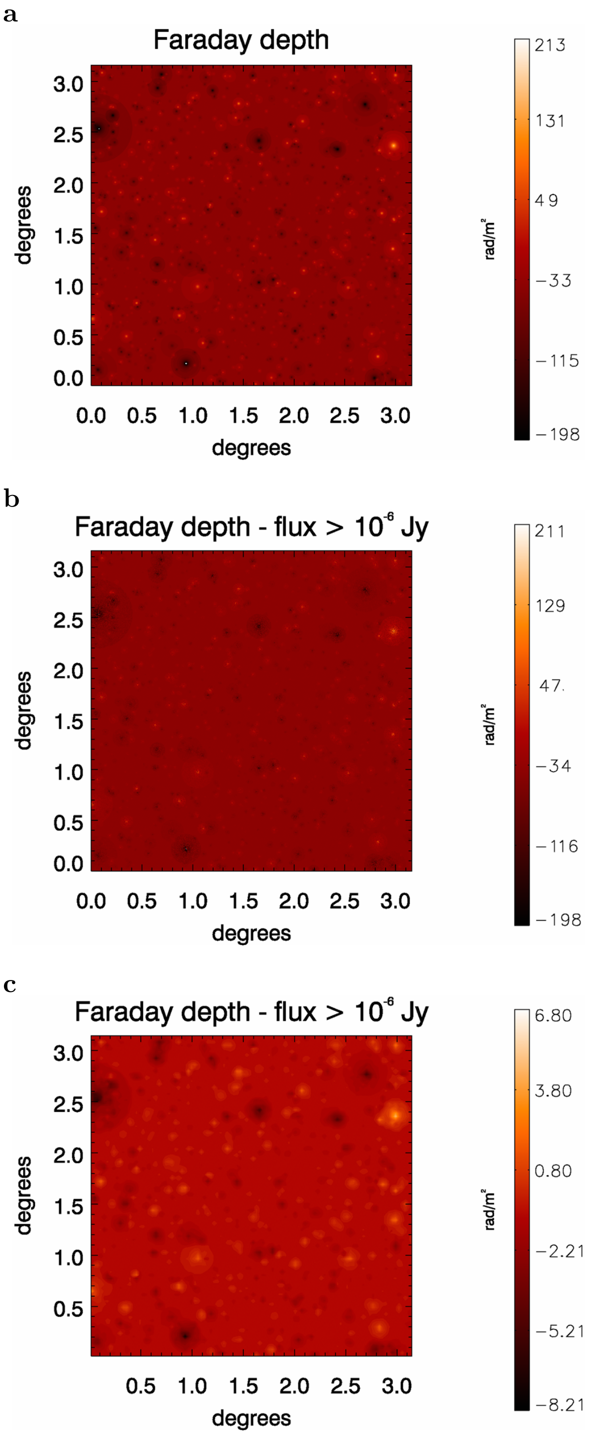

Fig. 1. Simulated Faraday screens. (a) Faraday Depth from Cosmological Clusters. (b) Recovered SKA sampling assuming a 100-hour of observation. (c) Smoothed SKA sampling.

We have also investigated random field structures using techniques similar to Murgia et al. (2004). 3D numerical cubes, simulating the ICM of a single cluster with a β density profile and a turbulent magnetic distribution, are produced. The latter is im-

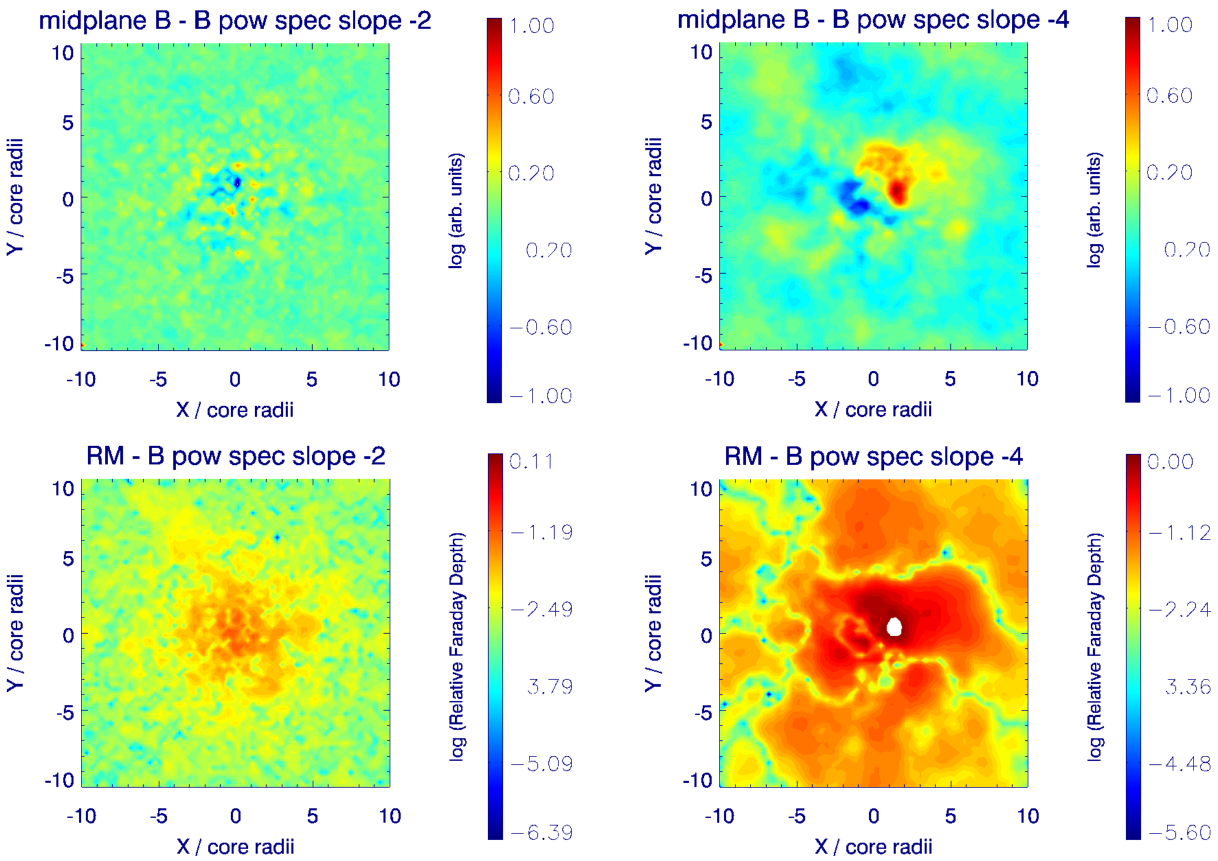

Fig. 2. (Top) Simulated magnetic cubes generated with random vector potentials with two different spatial power spectra. (Bottom) RM structure corresponding to the magnetic distributions of the top panel. The structure in the magnetic fields translates into structure in the RM screens.

plemented with a random vector potential following a given spatial power spectrum. Polarised radio emission is then simulated to pass through this environment with a range of lines of sight, to study the correlation between its RM and the structure of the ambient magnetic fields, i.e., the index of the magnetic power spectrum. The top panel in Figure 2 shows two of these cubes with power spectra indexes 2 and 4 (left and right, respectively). Below each of these cubes, the figure shows their associated RM screens. It is evident that the structure in the magnetic fields, i.e., the scales at which they are important, translates into structure in the RM screens. We have been using these magnetic cubes to investigate radio sources feedback on the CMFs, as we shall explain in the following section.

3. RADIO SOURCE FEEDBACK ON CLUSTER MAGNETIC FIELDS

The combination of high resolution X-ray and radio observations of clusters, reveal huge X-ray cavities filled with radio emitting structures (Fabian et al. 2000). This is evidence of the well known complex energy interchange taking place in the cores of clusters, between the ICM gas and the central radio galaxies (see Begelman 2004 and Ruszkowski 2007 for reviews). These galaxies obtain a great deal of energy from the neighbouring ICM gas via accretion. An substantial fraction of the energy is then injected back in kinetic form, as collimated ambipolar and relativistic outflows, or jets. A strong magnetohydrodynamical (MHD) shock is then produced ahead of an ellipsoidal cavity, the cocoon. The latter pushes away the ICM gas in its way and deposits hot plasma and magnetic fields into the ambient.

Once the injection ceases, the cocoon becomes hot under-dense magnetised bubbles that rise buoyantly into the ICM, interchanging energy with it. The stability and morphology of these bubbles, and the mixing of their plasma with that in the surrounding gas, strongly depend on the topology of the bubble and the ICM magnetic fields (see Ruszkowski et al. 2007, and references therein). The evolution of the bubbles is also influenced by the dynamical importance, or intensity, of the CMFs. This is characterised by the ratio of the ICM's thermal pressure over its magnetic pressure; the plasma β. The later is typically observed to be above unity (Blanton et al. 2003). CMFs seem to suppress hydrodynamical instabilities from the bubbles. On the other hand, the rising bubbles form kpc scale convective flows, like those simulated by Basson & Alexander (2003), give place to wakes behind the bubbles. Magnetic wakes of this nature seem to amplify and deform the topology of the neighbouring CMFs (Ruszkowski et al. 2007). Presumably the AGN jets, not only the bubbles, will have effects here as well.

To investigate this, we perform 3D MHD simulations of a magnetised jet injected into magnetised stratified atmospheres. We solve the equation of ideal MHD using the Flash code (Fryxell et al. 2000), which is a third order interpolation parallel code with an adaptive grid. We use a 3D cube with edge lengths of 0.5 Mpc and a mesh with $64 \times 64 \times 64$ zones. This grid is adjusted to refine adaptively up to scales of 0.98 kpc, necessary for the injection of the jet.

Our initial conditions are the following: an isothermal gas with $\gamma = 5/3$, a temperature of 10^8 K and a King density distribution (King 1972):

$$\rho(r) = \frac{1 \times 10^{-23}}{1 + (r/100\mathrm{kpc})^2}\,\mathrm{kg\,m^{-3}}\,. \qquad (1)$$

where r is the radial distance from the centre of the cluster (the centre of one of the faces of our cubic domain). Equation (1) simulates the ICM gas with an embedded dark matter halo, which we implement in hydrostatic equilibrium with the ICM's thermal pressure. The ICM initial magnetic distribution is taken form the cubes described in § 2; with a turbulent magnetic distributions. At every numerical zone we adjust the magnetic fields intensities so that $\beta = 10$, i.e.:

$$\mathbf{B}(r) = B_0 \sqrt{\frac{2\,\mu_0\,(0.1)\,P(r)}{\gamma - 1}}\,\hat{\mathbf{r}}\,, \qquad (2)$$

where μ_0 is the vacuum permeability, $P(r)$ is the ICM's thermal pressure (as a function of the radial distance from the cluster's centre), and B_0 is a factor characterised by a spatial spectrum and randomly generated phases. The index of the power spectrum of the magnetic distribution is a parameter we intend to vary in our simulations. Figure 3 shows the plane $z = 0$ of the initial magnetic distribution in our cluster. The colour scale exhibits B_z while the arrows depict the magnetic vectors corresponding to the xy plane. The random phases of the fields are evident.

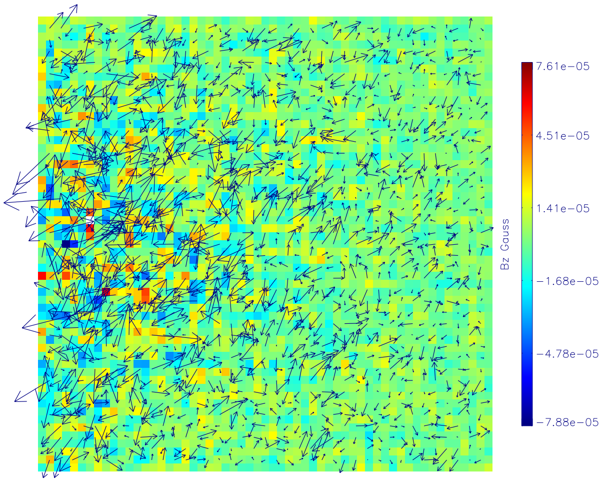

Fig. 3. The initial magnetic structure of our simulated ICM showing the xy plane in the middle of our numerical domain, with sides of length 500 kpc. The cluster's centre is located at the middle of the left boundary of the plane. The colour scale shows B_z and the arrows depict the magnetic vectors corresponding to the xy plane.

We then continue to the jet phase of the simulation. Using the (ghost) zones at the centre of one of the faces of the numerical domain (the one corresponding to the centre of the cluster), we inject a nearly-relativistic collimated jet. This outflow is under-dense with respect to the initial central density of the cluster by a factor of 10^3 and is in pressure equilibrium with the initial central ambient medium. Moreover, the jet has a radius of 3 kpc and a velocity of a third of the speed of light, hence simulating an FR II radio source, with a bulk kinetic power of $1.38 \times 10^{45}\,\mathrm{erg\,s^{-1}}$, over 10 Myrs. We discuss our preliminary results concerning this simulations in the following section.

Once the injection finishes, the simulation passes to the remnant phase. The jet's relic then evolves passively under the influence of gravitational, thermal and magnetic forces, in order to reach an equilibrium state. We expect to find magnetised buoyant bubbles and magnetic wakes behind them, having important effects on the neighbouring CMFs, as was found by Ruszkowski et al. (2007).

4. DISCUSSION AND CONCLUSIONS

The solenoidal nature of the magnetic fields introduces an important problem in numerical MHD simulations. This is because numerical analysis works with finite domains, with boundaries, and thus the

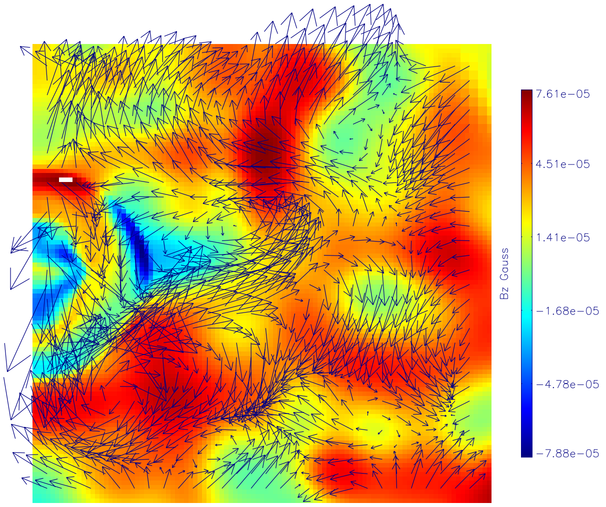

Fig. 4. The jet injected into the magnetised ICM showing the xy plane of a zoom to the centre of our simulated cluster. Each side is 100 kpc long. The colour scale shows B_z and the arrows, the magnetic vectors corresponding to the xy plane. The jet was injected at the middle of the left boundary of the plane, where ordering of the neighbouring magnetic fields is evident. The semicircular (radius $\lesssim$ 25 kpc) magnetic structures with smaller coherence length are the jet's cocoon and strong MHD shock, the former inside the latter.

magnetic lines cannot be continuous there. This is one of the problems we have been facing. Moreover, the state of the magnetic field lines present at the boundary between the cocoon and the ICM is not clear. These lines ought to be continuous there but the physical conditions are very different on each side of the boundary. This is a delicate numerical MHD problem (e.g., see Ruszkowski et al. 2007). As we inject the jet into the magnetised ICM, we do not have control over these "cocoon magnetic fields". We can implement the magnetic boundary conditions at the base of the jet though, which is an interesting parameter we have been experimenting with.

Our simulations are now giving us some information about the jet phase (see § 3). The cocoon and the MHD strong shock are shown in Figure 4 near the middle of the left side. These are semicircular (radius $\lesssim$ 25 kpc) magnetic structures with smaller coherence length than the magnetic fields away from them; the CMFs. Figure 4 also shows that after injecting the jet for 2.5 Myrs, the magnetic fields in the vicinity of the cocoon are ordered, and close to its contact discontinuity the fields get amplified by a factor of the order of 100.

Our preliminary results are interesting and we are now working in order to solve our numerical problems and get the full 3DMHD simulations of relativistic jets, and their remnants, propagating in magnetised galaxy cluster atmospheres.

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