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SIMULATIONS OF MAGNETIC FIELDS IN CLUSTERS AND FILAMENTS

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RESUMEN

El origen de los campos magnéticos afuera de las galaxias es aún controversial. Para el medio intra-cúmulo se han reportado magnitudes de los campos del orden de μG. Es posible que los flujos de núcleos de galaxias activas hayan magnetizado el medio intra-cúmulo. El campo magnético intergaláctico dentro de filamentos debería ser menos contaminado por flujos magnetizados de galaxias activas. Más aún, se piensa que los filamentos contienen el medio intergaláctico tibio-caliente, el cual representa una gran fracción de la materia bariónica del universo. La emisión difusa de sincrotrón de los rayos cósmicos en éstos filamentos revelará la presencia de tal medio. Presentamos simulaciones de alta resolución con malla adaptativa de campos magnéticos cósmicos y hacemos prediciones de la evolución y estructura de dichos campos en filamentos. Los campos magnéticos en cúmulos de galaxias pueden también tener su origen en núcleos de galaxias activas, cuya evolución es a su vez fuertemente afectada por los campos magnéticos. Mostramos como la dinámica de burbujas producidas por núcleos de galaxias activas, mecanismo vital de retroalimentacoón en cúmulos de galaxias, es gobernado por los campos magnéticos del ambiente, los cuales suprimen de manera efectiva inestabilidades hidrodinámicas.

ABSTRACT

The origin of cosmic magnetic fields outside of galaxies remains controversial. In the intracluster medium field strengths of the order of μG have been reported. Possibly the outflows of AGN have magnetised the ICM. The intergalactic magnetic field within filaments should be less polluted by magnetised outflows from active galaxies than magnetic fields in clusters. Therefore, filaments may be a better laboratory to study magnetic field amplification by structure formation than galaxy clusters, since they host less active galaxies. Moreover, filaments are thought to contain the Warm-Hot Intergalactic Medium which represents a large fraction of the baryonic matter in the universe. Diffuse synchrotron emission by cosmic rays in these filaments will reveal the presence of this medium. We present highly resolved cosmological adaptive mesh refinement simulations of magnetic fields in the cosmos and make predictions about the evolution and structure of magnetic fields in filaments. Magnetic fields in clusters may also have their origin in AGN, whose evolution, in turn, is strongly affected by magnetic fields. We show how the dynamics of AGN-blown bubbles, that are vital for feedback mechanisms in clusters and galaxies, is governed by ambient magnetic fields that are effective at suppressing hydrodynamic instabilities.

Key Words: H II regions — ISM: jets and outflows — stars: mass loss — stars: pre-main sequence

1. INTRODUCTION

Clusters of galaxies are known to host magnetic fields with strengths that are of the order of 1 μG and with coherence scales that are of the order of 10 kpc (Carilli & Taylor 2002; Govoni et al. 2004a). In cool cores of clusters remarkably high fields have been found: For example, Blanton et al. (2003) have found magnetic fields as high as 11 μG in the cool core of A2052. Knowledge about cluster magnetic fields comes from synchrotron and inverse Compton radiation, radio halos, as well as Faraday rotation measurements. The field estimates do not all agree. In particular, the inverse Compton estimates tend to be lower by almost an order of magnitude than the estimates derived from Faraday rotation (for a review see Govoni & Feretti 2004b). The latter method has also been used to make inferences about the structure of magnetic fields in clusters. Based on analyses of rotation measure maps in three clusters, Vogt & Enßlin (2003) have derived spectral indices (slopes of the 1D power spectrum of the magnetic field) of 1.6 to 2.0 (Vogt & Enßlin 2005; Enßlin & Vogt 2003).

Meanwhile, the origin of cluster magnetic fields in the intergalactic medium (IGM) remains unclear. It has been suggested that they are of primordial origin (see e.g. Widrow 2002 for a review of the

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origin of cosmic magnetic fields), i.e. a seed field that has formed prior to recombination is subsequently amplified by compression and turbulence. In Dolag et al. (2002), the average fields in the core of clusters at redshift 0 were found to range between 0.4 and 2.5 μG if the initial seed fields at redshift 15 were of the order of a nanogauss. The question, of course, remains, where the seed fields come from. It is quite possible that the first stars and the first AGN have produced magnetic fields. The magnitude of these seed fields, though, is as uncertain as most processes at this epoch.

Other mechanisms have been proposed (see references in Brüggen et al. 2005). Also, it has been suggested that the IGM has been magnetised by bubbles of radio plasma that are ejected by active galactic nuclei (AGN) (Furlanetto & Loeb 2001). A growing number of large, magnetised bubbles are being discovered in clusters of galaxies (Bîrzan et al. 2004), and simulations show that they may not be very long-lived (Brüggen et al. 2005; Brüggen & Kaiser 2002). Presumably, the magnetised bubble plasma gets mixed with the IGM and is thus likely to contribute to present cluster fields. Here one may note that the life time of the bubbles is itself dependent on the magnetic field in the IGM as magnetic fields tend to stabilise the bubble against instabilities (Jones & De Young 2005). AGN activity favours the centres of massive clusters, so that the IGM in filaments ought to be much less affected by magnetised plasma ejected from AGN.

An interesting question that follows from studies of cluster magnetic fields is whether significant magnetic fields also exist on other scales in the cosmic large-scale structure, as for example in filaments of galaxies. This is particularly interesting against the background of the elusive Warm-Hot Intergalactic Medium (WHIM). As pointed out by Cen & Ostriker (1999), hydrodynamic simulations suggest that up to half of the baryons at present should have temperatures between 10^5 and 10^7 K. Accretion shocks associated with filamentary structures in the cosmic web are believed to have heated gas up to these temperatures. These shocks may also have amplified magnetic fields and helped to accelerate particles to relativistic energies. Such relativistic particles will emit faint and diffuse radio emission that will be detected with the upcoming generation of radio telescopes. The detection of this diffuse radio emission by the WHIM will be an important milestone because the study of the structure and distribution of the WHIM is notoriously difficult as its main tracers are highly excited Oxygen lines that are difficult to observe.

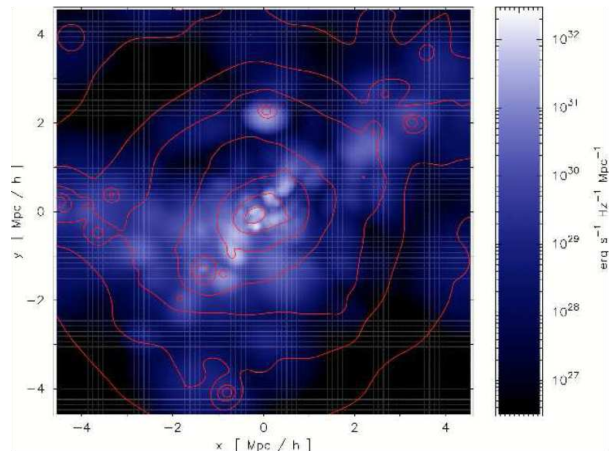

Fig. 1. The contours show the X-ray emission from a galaxy cluster. The blue denotes the diffuse radio emission. For details see Hoeft et al. (2008).

Moreover, it has been noted (Kronberg et al. 2008) that diffuse radio emission offers an alternative way of probing large-scale structure that is quite different from that defined by the distribution of galaxies. A prediction of the radio emission around filaments and in the outskirts of clusters has also been performed by Hoeft et al. (2008) (see Figure 1).

Bagchi et al. (2002) have discovered diffuse radio emission from a large network of filaments of galaxies that span several Mpc containing at least 80 galaxies. Minimising the total non-thermal energy, Bagchi et al. (2002) estimated a minimum field strength of $B \sim 0.3\,\mu$G. This estimate hinges on several assumptions, e.g. that the emission is synchrotron emission, that the energy ratio of protons to electrons is 1, that the spectral index of the radio-frequency spectrum is -0.5 and that the volume filling factor is of order unity. However, meanwhile it is being debated whether the filament described in Bagchi et al. (2002) is really a filament or rather a group of galaxies.

Kronberg et al. (2008) have discovered faint diffuse radio emission in the vicinity of the Coma cluster. It indicates intergalactic magnetic fields in the range $0.2-0.4\,\mu$G on scales of up to 4 Mpc. While a possible relationship to the WHIM awaits confirmation, the observations suggest that some cosmic ray acceleration mechanism must exist in this medium.

Brüggen et al. (2005) have simulated the magnetic field in filaments with sufficient resolution in order to make predictions about their magnitude and structure. There have been few cosmological simulations that include magnetic fields, and most of them focus solely on galaxy clusters.

2. SIMULATIONS OF MAGNETIC FIELDS IN FILAMENTS

In order to bridge the large range of scales in a cosmological simulation to get down to the scales in a galaxy filament, we used the adaptive-mesh piecewise parabolic method (PPM) code FLASH that provides full support for particles and cosmology.

The initial conditions for our simulations are the publicly available conditions of the Santa Barbara cluster (Frenk et al. 1999) at redshift $z = 50$. Consequently, our cosmological parameters are those of the Santa Barbara cluster, i.e. $H_0 = 50$ km s^{-1} Mpc^{-1}, $\Omega_m = 1$ and $\Omega_\Lambda = 0$. The cluster perturbation corresponds to a 3σ peak in density smoothed over 10 Mpc. We assumed standard cosmic composition, i.e. the hydrogen and helium fractions were 0.7589 and 0.2360, respectively. Star formation has been neglected.

Our computational domain was a cubic box of side $L = 64\ h^{-1}$ Mpc. FLASH is a modular block-structured adaptive mesh refinement (AMR) code, parallelised using the Message Passing Interface (MPI) library. FLASH solves the Riemann problem on a Cartesian grid using the Piecewise-Parabolic Method (PPM) and, in addition, includes particles that represent the dark matter. Our simulation included 2,097,152 dark matter particles with a mass of $7.8 \cdot 10^9\ M_\odot$ each. Thus, in clusters and filaments, the mean separation between dark matter particles is less than the grid spacing. We chose a block size of 16^3 zones and used periodic boundary conditions. The minimal level of refinement was set to 4, which means that the minimal grid contains $16 \cdot 2^{(4-1)} = 128$ zones in each direction. The maximum level of refinement was 10, which corresponds to an effective grid size of $16 \cdot 2^{(10-1)} = 8192$ zones or an effective resolution of $7.8\ h^{-1}$ kpc. This was the maximum that we could afford computationally.

Depending on the dark matter density, the mesh is refined and derefined automatically. It was set up such that no more than 8 dark matter particles occupied one computational cell. We first ran a simulation with only 8 levels of refinement, then identified three regions that contained filaments, and reran the simulation with 10 levels of refinement. In addition to refining on the dark matter we enforced full refinements in the regions that contain the filaments. However, the dark matter distribution, represented by the particles, is not refined.

In order to achieve satisfactory accuracy even on small scales we decided to implement a passive magnetic field solver in FLASH that keeps the divergence of the magnetic field very small. The price for this is that, currently, we are unable to compute the full MHD equations. However, we find that the magnetic fields in the intracluster medium (ICM) will rarely be dynamically important, and, at this level, they are described with sufficient accuracy by a passive field solver. We do not include thermal conduction which may have important effects in the intracluster medium. For a treatment of heat transfer by turbulent motions see Lazarian (2006).

We chose to implement the passive field solver described by Pen (2003), which solves the magnetic field on a staggered mesh. It is straightforward to show that if the magnetic field is evolved on a staggered instead of a centred grid, the magnetic field will remain divergence-free provided that it was divergence-free to start with (Evans & Hawley 1988). At every time step, the magnetic field is evolved using a total-variation diminishing (TVD) scheme that solves

$$\partial \mathbf{B} = \nabla \times (\mathbf{v} \times B) - \frac{3}{2}\frac{\dot{a}}{a}\mathbf{B}\,, \qquad (1)$$

where $\mathbf{B} = \mathbf{B}_{\rm physical}/a$ and a is the scale-factor. The thus evolved field is then interpolated with a third-order scheme to the cell centres.

Initially we set up a divergence-free field using the vector potential. The magnetic vector potential $\tilde{\mathbf{A}}(k)$ was composed of 512 Fourier modes with random phases and amplitudes that were drawn from a Gaussian distribution. $\tilde{\mathbf{A}}$ was then scaled as $k^{-\alpha}$, where k is the wavenumber of the mode. This leads to a magnetic power spectrum of $P_B(k)\,dk \sim k^{2(2-\alpha)}\,dk$. Here, α was chosen to be 2. The vector potential was then Fourier-transformed into physical space with a Fast Fourier Transform. The field was normalised such that the physical mean field at redshift 50 was $3 \cdot 10^{-11}$ G.

In agreement with what Dolag et al. (2002) have found using smoothed particle hydrodynamic (SPH) simulations, we verified that the resulting magnetic fields are very insensitive to the topology of the initial field at $z = 50$. Even if one starts with an initially uniform magnetic field, the results are not significantly different. The field at any time obviously depends on the strength of the initial field. However, since the field is only evolved passively, the normalisation is arbitrary.

3. RESULTS IN FILAMENTS

Roughly speaking, we found that the magnetic field correlates with density as one would expect from the conservation of magnetic flux, which implies $B \propto \rho^{2/3}$. However, we find that in some regions the magnetic field is amplified significantly beyond $B \propto \rho^{2/3}$, which is what one would expect from compression alone. This is caused by shear flows and occurs mainly in the outskirts of the cluster and near accretion shocks. An analytic calculation of magnetic field amplification by shear has been presented by King & Coles (2005).

If indeed filaments host magnetic fields of the order of $B \geq 0.3\ \mu$G, as suggested by Bagchi et al. (2002), this would require seed fields of the order of 10^{-9} G at $z \sim 50$. Seed fields of this order of magnitude may be hard to produce (see also Dolag et al. 2005). Consequently, this would call for alternative origins for IGM magnetic fields (Kronberg 2004). Future observing campaigns with instruments such as the Low Frequency Array (LOFAR) and the Square Kilometer Array (SKA) are expected to shed some light on magnetic fields in the early universe.

As is evident from Figure 2, we find that magnetic fields are predominantly oriented in a direction parallel to the filaments. This is true for all filaments in our simulation volume. As material accretes onto the filaments, the magnetic fields are compressed parallel to the filaments, and, as clusters and groups form, the filaments are stretched. This field topology could have several interesting implications: For one, the diffusion length of cosmic rays along filaments may be much greater than the diffusion length out of the filaments. This makes filaments efficient traps for cosmic rays and could help to explain the diffuse radio emission seen along the entire length of the filament in Bagchi et al. (2002). Secondly, heat conduction is likely to be more efficient along filaments than elsewhere. This could lead to heat being conducted from the outskirts of the clusters into the filaments. Further details on these simulations can be found in Brüggen et al. (2005).

4. SIMULATIONS OF MAGNETISED AGN-BLOWN BUBBLES

In the previous section we reported on simulations of magnetogenesis in filaments of galaxies. Meanwhile, magnetic fields in clusters of galaxies have received wider attention in recent years with some numerical work, both using SPH and AMR simulations. Here, we do not have sufficient space to review this work. Instead, we would like to present some work on the effects of magnetic fields on the interaction between active galactic nuclei and the ICM. This is a very important issue, as the absence of cooling flows in galaxy clusters as well as the cut-off of the galaxy luminosity function is ascribed to feedback by AGN. Radio-loud active galactic nuclei drive strong outflows in the form of jets that inflate bubbles or lobes. The lobes are filled with hot plasma,

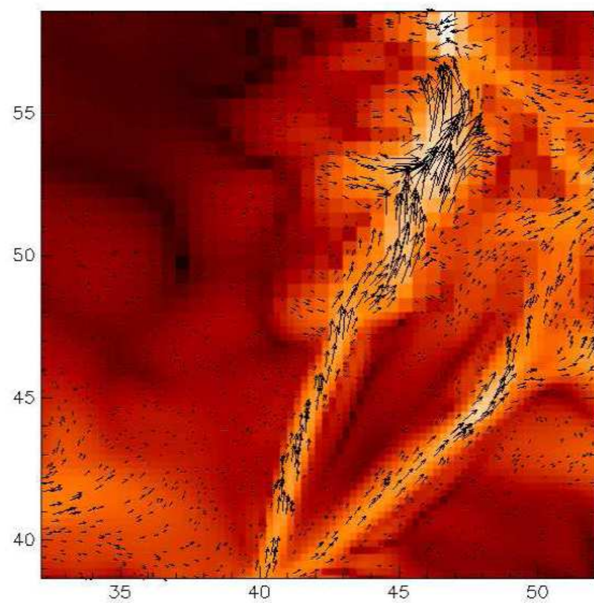

Fig. 2. Magnitude of the magnetic field in a slice through two filaments in our computational box. The colors represent the logarithm of the magnitude of the magnetic field, and the tick marks denote Mpc. The lines show the orientation of the magnetic field in the plane of the plot.

and can heat the cluster gas. However, the physics of heating by AGN is still poorly understood. One of the main questions is how the energy in the AGN-inflated bubbles that appear as cavities in the X-ray surface brightness is transferred to the ICM.

One problem is that these cavities all appear to be intact, even after inferred ages of several 10^8 yrs, as for example the outer cavities in Perseus. However, hydrodynamic simulations fail to reproduce the observed morphology as hydrodynamic instabilities shred the bubbles in relatively short time.

Although magnetic fields in clusters are known to have plasma $\beta > 1$; (e.g. Blanton, Sarazin, & McNamara 2003), they may in principle have a strong effect on suppressing Kelvin-Helmholtz and Rayleigh-Taylor instabilities. Jones & De Young (2005) considered the evolution of bubbles in a magnetized ICM by performing two-dimensional numerical magnetohydrodynamical (MHD) simulations and found that bubbles could be prevented from shredding even when β is as high as ~ 120. However, two-dimensional simulations cannot easily be generalised to 3D problems. Here we focus on a later stage in the evolution of the AGN-blown cavities and consider more realistic (stochastically tangled) field configurations in fossil bubbles (i.e. after the transi-

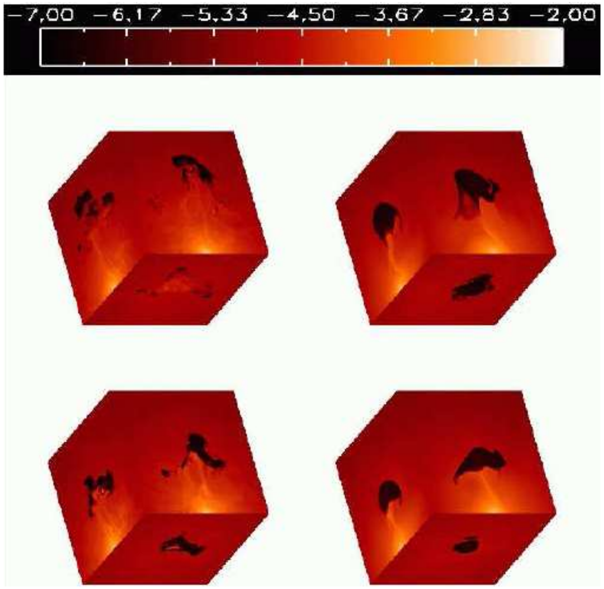

Fig. 3. Natural logarithm of density distribution. The left-hand column shows density for the random (i) case (lower panel t = 15, upper t = 25 code time units) but twice as high mean magnetic pressure. The right-hand column corresponds to the draping case for twice the mean magnetic pressure compared to the original draping case.

tion from the momentum-driven to buoyancy-driven stage) than in previous buoyant stage MHD simulations. We show that only when the power spectrum cut-off of magnetic field fluctuations is larger than the bubble size can the bubble shredding be suppressed.

The simulations were performed with the PENCIL code (e.g. Haugen, Brandenburg, & Dobler 2003). Although PENCIL is non-conservative, it is a highly accurate grid code that is sixth order in space and third order in time. It is particularly suited for weakly compressible turbulent MHD flows. Magnetic fields are implemented in terms of a vector potential so the field remains solenoidal throughout simulation.

We consider magnetic fields inside the bubbles and in the ICM that are dynamically unimportant in the sense that their plasma β parameter is greater than unity, that is, magnetic pressure may become important when compared to the bubble ram pressure associated with the gas motions in the ICM but it is generally small compared to the pressure of the ICM in our simulations. Regarding the geometry of magnetic fields, we consider random isotropic fields with coherence length smaller than the bubble sizes (hereafter termed random), and the "draping" case of isotropic fields characterized by coherence length exceeding bubble size as well as a non-magnetic case. Magnetic draping has been considered previously in the context of merging cluster cores and radio bubbles using analytical approach by Lyutikov (2006). He found that even when magnetic fields are dynamically unimportant throughout the ICM, a thin layer of dynamically important fields can form around merging dense substructure clumps (bullets) and prevent their disruption. We suggest that, depending on the unknown value of magnetic diffusivity, there may be some relic magnetic power spectrum with a smaller amplitude than the freshly injected one (either by AGN-driven bubbles or dynamo-driven) that extends to scales larger than the bubble size and that provides draping fields to stabilize the bubbles.

We considered three-dimensional MHD simulations of buoyant bubbles in cluster atmospheres for varying magnetic field strengths characterized by plasma $\beta > 1$ and for varying field topologies. We find that field topology plays a key role in controlling the mixing of bubbles with the surrounding ICM. We show that large-scale external fields are more likely to stabilize bubbles than internal ones but a moderate stabilizing effect due to magnetic helicity can make internal fields play a role too. The simulations show that a bubble morphology that resembles the fossil bubbles in the Perseus cluster can be reproduced if the coherence of magnetic field is greater than the typical bubble size. While it is not clear if such a "draping" case is representative of typical cluster fields, Vogt & Ensslin (2005) find that length-scale of magnetic fields in Hydra A is smaller than typical bubble size. If this also holds true in other clusters then other mechanisms, such as viscosity, would be required to keep the bubbles stable. Unfortunately, the Faraday rotation method used by Vogt & Ensslin (2005) is not very sensitive to large-scale magnetic fields if aligned with the bubble surface. Moreover, their maximum-likelihood method assumes a power-law relation between magnetic field and density, statistical isotropy for the purpose of de-projection and a particular jet angle with respect to the line of sight. Smaller angles and different magnetic field configurations might yield a weaker decline of the power spectrum at larger scales. Taking into account the above limitations, it is entirely possible that magnetic draping provides a solution to the problem of bubble stability. We also suggest that a hybrid model that combines helical fields inside the bubble with external draping fields could be successful in explaining morphologies of X-ray bubbles in clusters. Another possibility is that dynamically significant fields are present inside the bubbles and the consequences of the high-β case for bubble dynamics and stability should be investigated further. We note that the bubbles will most likely eventually get disrupted (partially helped by cosmological sloshing gas motions in clusters). A generic feature found in our simulations is the formation of a magnetic wake where fields are ordered and amplified. We suggest that this effect could prevent evaporation by thermal conduction of cold Hα filaments observed in the Perseus cluster. The physical process of bubble mixing in the presence of magnetic fields has important consequences also for modelling of mass deposition and star formation rates in cool core clusters as well as the particle content of bubbles and cosmic-ray diffusion from them. These issues will be further complicated by the effects of anisotropy of transport processes due to magnetic fields. This may give rise to the onset of magnetothermal instability on the bubble-ICM interface (Parrish & Stone 2005). Further details on these simulations can be found in Ruszkowski et al. (2007).

5. CONCLUSIONS

With the upcoming instruments LOFAR and SKA, the study of cosmic magnetism and cosmic rays will take centre stage for years to come. Magnetism holds the clue for understanding the physics of the intergalactic medium and the dynamics of cosmic rays. Diffuse synchrotron emission by cosmic rays in magnetic fields will reveal the Warm-Hot Intergalactic Medium which represents a large fraction of the baryonic matter in the universe. Here we have presented cosmological adaptive-mesh simulations that predict the evolution of magnetic fields in filaments. In the second part of this review, we have shown how even weak magnetic fields can have a strong impact on the dynamics of the intracluster medium. In particular, we have shown how the dynamics of AGN-blown bubbles, that are vital for feedback mechanisms in clusters and galaxies, is governed by ambient magnetic fields that are effective at suppressing hydrodynamic instabilities.

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