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Cosmological MHD simulation of a cooling flow cluster

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ABSTRACT

Context. Various observations of magnetic fields in the Intra-Cluster Medium (ICM), most of the time restricted to cluster cores, point towards field strength of the order of a few μG (synchrotron radiation from radio relics and radio halos, inverse Compton radiation in X-rays and Faraday rotation measure of polarised background sources). Both the origin and the spatial structure of galaxy clusters magnetic fields are still under debate. In particular, the radial profile of the magnetic field, from the core of clusters to their outskirts, is of great importance for cosmic rays propagation within the Cosmic Web.
Aims. In this letter, we highlight the importance of cooling processes in amplifying the magnetic field in the core of galaxy clusters up to one order of magnitude above the typical amplification obtained for a pure adiabatic evolution.
Methods. We have performed a "zoom" cosmological simulation of a 3 keV cluster, including dark matter and gas dynamics, atomic cooling, UV heating and star formation using the newly developed MHD solver in the AMR code RAMSES.
Results. Magnetic field amplification proceeds mainly through gravitational contraction. Shearing motions due to turbulence provide additional amplification in the outskirts of the cluster, while magnetic reconnection during mergers causes magnetic field dissipation in the core.
Conclusions. Cooling processes have a strong impact on the magnetic field structure in the cluster. First, due to the sharp rise of the gas density in the center, gravitational amplification is significantly amplified, when compared to the non–radiative run. Second, due to cooling processes, shearing motions are much stronger in the core than in the adiabatic case, leading to additional field amplification and no significant magnetic reconnection. Cooling processes are therefore of great importance in determing the magnetic field profile in galaxy clusters.

Key words. – methods: numerical

1. Introduction

Clusters of galaxies are known to be magnetized (see review by Govoni & Feretti 2004). The existence of magnetic fields has been determined either by direct methods like diffuse synchrotron radio or inverse Compton hard X-ray emission or by indirect method like Faraday Rotation Measures (RM). They all suggest that μG fields lie in central regions of galaxy clusters up to several 10 μG magnetic fields in large cooling flows clusters. Magnetic field strength can differ from a method to another: direct methods usually capture large scale fields averaged over large volumes, while RM are derived from the analysis of background point sources, and are thus sensitive to small scale variations (cold filaments, shear flows, shocks, galaxy stripping, galaxy winds...) In order to shed light on the magnetic topology found in cosmic structures, it is of great interest to perform direct, self-consistent numerical simulations of galaxy clusters. Magnetic fields in clusters are also of great importance to determine the deflection angle of ultra-high energy cosmic rays, since they probably host the source of these cosmic rays (see Lemoine 2005; Kotera & Lemoine 2007; Globus et al. 2007).

Simulations of galaxy clusters with magnetic fields have been performed using Smooth Particle Hydrodynamics (SPH) codes (Dolag et al. 1999, 2005), grid-based codes (Roettiger et al. 1999; Miniati et al. 2001; Sigl et al. 2004; Asai et al. 2007) and Adaptive Mesh Refinement (AMR) codes (Brüggen et al. 2005), using both cosmological simulations (Dolag et al. 1999; Miniati et al. 2001; Sigl et al. 2004; Dolag et al. 2005), or idealized simulations (Roettiger et al. 1999; Asai et al. 2007). In this letter, we report the first cosmological simulation with AMR that includes atomic cooling, UV heating and star formation physics, with a full treatment of the ideal MHD equations. We have also performed a reference adiabatic run in order to compare our results with previous works and to point out the differences with the radiative case.

2. Simulations

We have performed a "zoom" cosmological simulation of a galaxy cluster using the AMR code RAMSES (Teyssier 2002). Gas dynamics is computed using a second–order unsplit Godunov scheme for the ideal MHD equations (Teyssier et al.

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2006; Fromang et al. 2006), while collisionless dark matter particles are evolved using a Particle–Mesh solver. Gas cooling and heating are taken into account as source terms in the energy equation. The cooling and heating functions are computed for a primordial H and He plasma, using the Haardt & Madau (1996) background model. Radiative losses leads to the formation of high density, (low temperature) regions, where stars are allowed to form according to a Schmidt law: $\dot{\rho}_* = \epsilon\rho/t_{\rm ff}$ if $\rho > \rho_0$. The density threshold for star formation was set to $\rho_0 = 10^5\Omega_b\rho_c(z)$. The star formation efficiency was set to $\epsilon = 5\%$. The simulation comoving box length was chosen equal to 80 h^{-1} Mpc with a ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_b = 0.045$ and $H_0 = 70$ km.s^{-1}.Mpc^{-1}. A spherical region of radius 12.5 h^{-1} Mpc around our simulated cluster was defined as our high-resolution region, with an effective resolution of 512^3. A coarser grid with an effective resolution of 256^3 was used to cover the inner 40 h^{-1} Mpc, and finally an even coarser 128^3 grid was used to cover the whole box. The mass of dark matter particles on each coarse grid are respectively 2.9×10^{10} M$_\odot$, 3.6×10^9 M$_\odot$ and 4.5×10^8 M$_\odot$. Only the finest grid was allowed to trigger new refinements during the course of the simulation, up to 7 additional levels of AMR cells. We used a quasi-Lagrangian criterion: each cell is individually refined if the number of dark matter particles exceeds 8, or if the baryonic mass exceeds 8 times the initial high-resolution mass resolution. We solved the full set of ideal MHD equations using a new scheme based on a Godunov implemenation of Constrained Transport and presented in Teyssier et al. (2006) and Fromang et al. (2006) and we used the HLLD Riemann solver from Miyoshi & Kusano (2005). The *comoving* magnetic field was set initially to a constant value, $B_z \simeq 10^{-11}$ G, as suggested in Dolag et al. (2005) to reproduce the μG fields in cluster cores. With these parameters, in the course of the simulation, the plasma $\beta = P_{gas}/P_{mag}$ never decreased below 1000: the dynamical effect of the magnetic field can therefore be considered as negligible, even in the core of our simulated cluster.

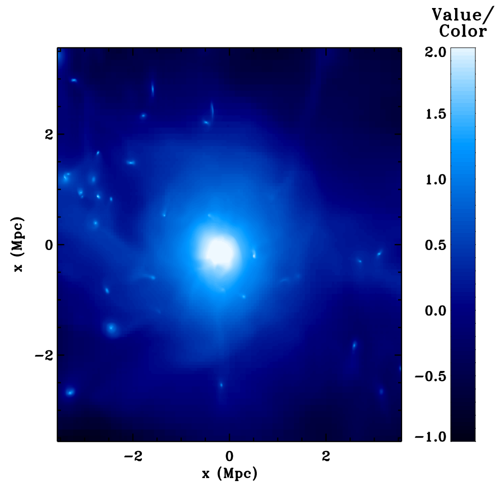

Fig. 1. Logarithm of the column density map of the gas at $z = 0$ (in units of the mean baryons density).

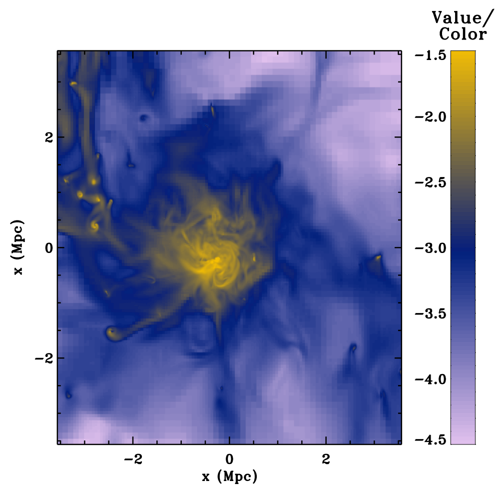

Fig. 2. Logarithm of the mass–averaged magnetic field amplitude at $z = 0$ in units of μG.

3. Results

Figure 1 shows the column density distribution of the gas for the cooling run at $z = 0$. We see in figure 2 that the magnetic field amplitude are well-correlated with the density distribution with mass-averaged values of $B \sim 10^{-1}\,\mu$G in the cluster core, galaxies with $B \sim 10^{-2}\,\mu$G in satellite clumps and $B \sim 10^{-3}\,\mu$G in filaments. We define the virial mass as $M_{200} = 200\times4\pi/3\rho_c R_{200}^3$, where ρ_c is the critical density. For the adiabatic simulation, we found for our cluster at $z = 0$ the following properties: $R_{200}^{ad} \simeq 1\,h^{-1}$Mpc, $M_{200}^{ad} \simeq 2.7\times10^{14}\,h^{-1}M_\odot$ and $T_X^{ad} \simeq 3.4$ keV. In the radiative case, we obtained $R_{200} \simeq 1.1\,h^{-1}$Mpc, $M_{200} \simeq 3.5\times10^{14}\,h^{-1}M_\odot$ and $T_X \simeq 5.1$ keV. The magnetic field amplification of a collapsing three dimensional gas sphere with infinite conductivity is given by $B \propto \rho^{2/3}$, for the magnetic flux to be conserved. Thus a subsequent increase (or decrease) of the magnetic field with respect to this purely gravitaional amplification should reveal other amplification or dissipation mechanisms. Figure 3 shows the mass–weighted historgram if the radiative simulation in the ρ-$|B|$ plane, within 2 Virial radii around the cluster. The dashed line shows the mean amplitude as a function of density for the radiative case, while the dotted line is for the adiabatic case ($\rho^{2/3}$ is also shown for comparison). For densities lower than $10^4\bar{\rho}$, the magnetic field amplification is one order of magnitude higher than for pure gravitational compression. As discussed in Dolag et al. (2005), this is likely due to shearing motions in the cluster atmosphere, due to turbulence and frequent mergers. At higher densities, the radiative run diverges strongly from the adiabatic case. The gravitational compression due to the cooling flow provides additional field amplification in the high–density tail. As we will see below, cooling also provides a sustained turbulent regime in the core and the corresponding additional field amplification. Based on the Zel'dovich approximation of gravitational dynamics, King & Coles (2006) predicted that a cosmological magnetic field should evolve as a $B \propto \rho^{0.87}$, due to anisotropic collapse in a Gaussian random field. This compares favorabily with the low density part of our simulation (see Fig. 3).

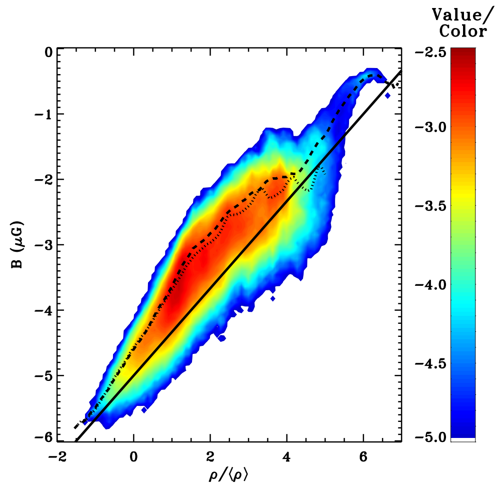

Fig. 3. Histogram of the mass fraction for the cooling run as a function of the normalised density and the magnetic amplitude at $z = 0$. The black solid line is the $\rho^{2/3}$ collapse amplification, the averaged magnetic field as a function of the normalised density for the cooling case (dashed line) and the adiabatic case (dotted line) are also plotted.

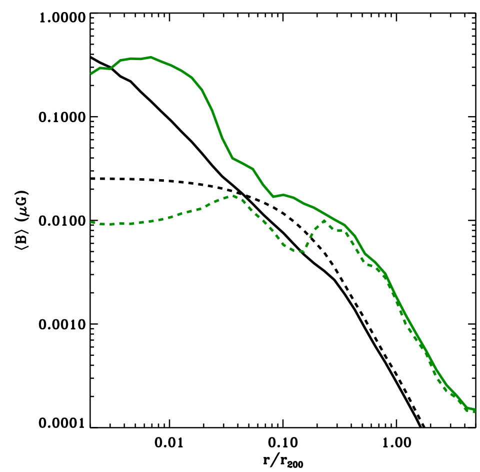

Fig. 4. Mean magnetic field as a function of the normalised radius. The black lines are the $\rho^{2/3}$ collapse amplification, the green lines are respectively the run values for the adiabatic (dotted) and cooling (solid) runs at $z = 0$.

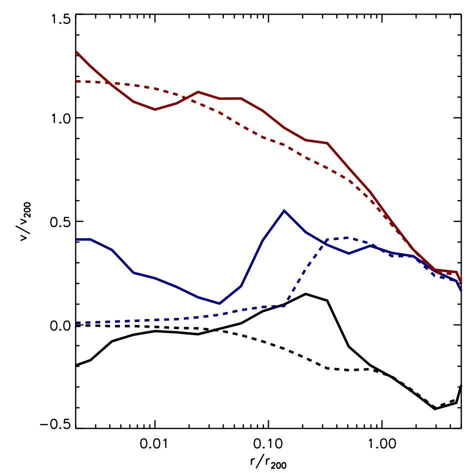

Fig. 5. Mean radial velocity (black), radial velocity dispersion (blue) and sound speed (red) for the adiabatic (solid) and the cooling (dashed) runs at $z = 0$ in units of V_{200} for the adiabatic case.

At higher density, in the core of our simulated cluster, the situation is more complex. In the adiabatic case, the magnetic field amplitude decrease *below* the expected value for pure compression. The mean magnetic field is of the order of $10^{-2}\,\mu$G, far below the typical observed values of magnetic field amplitude in observed cluster cores. It is also apparent in the magnetic field profile plotted in figure 4, for which a dip in the field strength is visible in the cluster core. If shear flows are able to sustain additional magnetic amplification in outer parts of the cluster $r > 150\,\mathrm{h^{-1}kpc}$, we find magnetic *dissipation* in the cluster core. Identified first by Roettiger et al. (1999)), this effect is due to magnetic reconnection occuring during merger events. Since we are not considering any microscopic process here, this reconnection is due to our numerical scheme that captures the weak solution of the ideal MHD equations. Although magnetic reconnection probabily occurs in nature within converging flows, the exact amplitude of the dissipation is likely to depend on the microphysics. In the present numerical approach, results should depend strongly on the spatial resolution and on the numerical scheme used. It is however interesting to analyze in this respect the effect of cooling. As can be seen in Figure 4, magnetic reconnection in the cluster core is suppressed. The magnetic field strength, $0.3\,\mu$G, is now more compatible with observations (Clarke et al. 2001). Magnetic amplification in the core now proceeds in the same way than in the outer parts, with gravitational compression and shearing motions. Only in the very center (below $3\,\mathrm{h^{-1}kpc}$, close to the resolution limit), do we see magnetic reconnection again.

To illustrate this point further, we show in Figure 5 velocity profiles in the adiabatic and in the cooling case. The radial velocity dispersion is a signature of turbulent motions and it is not a surprise to see that a strong velocity dispersion at a given radius corresponds to an excess of field amplification at the same radius (see figure 4). In the adiabatic case, turbulence is dissipated in the core, and magnetic reconnection occurs. In the cooling case, gravitational contraction resumes, as well as shearing motions, so that magnetic amplification is now more active in the core. RM maps at $z = 0$ of the adiabatic simulation and the cooling simulation shown in figure 6 strongly differ. In the adiabatic case, we obtain RM values of $30\,\mathrm{rad.m^{-2}}$ in the cluster centre, whereas in the radiative case, we reach $1000\,\mathrm{rad.m^{-2}}$ in the very center ($r < 10\,\mathrm{h^{-1}kpc}$) and we obtain RM values of $100\,\mathrm{rad.m^{-2}}$ in the core. RM results of the cooling simulation are consistent with the Clarke et al. (2001) sample ($200\,\mathrm{rad.m^{-2}}$) and also with the maximum values found in the cluster sample of Taylor et al. (2002) (up to $1800\,\mathrm{rad.m^{-2}}$ for the hot gas cluster).

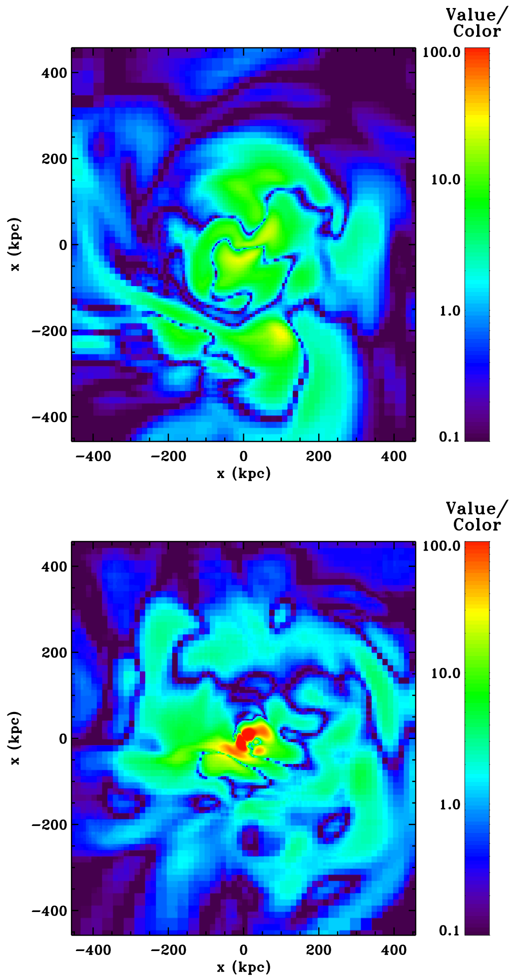

Fig. 6. RM maps colour scale of the cluster core for the adiabatic run (left pannel) and the cooling run (right pannel) at $z = 0$.

4. Conclusion and discussion

There are noticeable differences in the magnetic field characteristics between a galaxy cluster with an adiabatic evolution and a galaxy cluster with radiative cooling: the average magnetic field in the cluster core is significantly higher when a cooling flow is present, due to additional gravitational compression but also due to an increased level of turbulence in the core driving shearing motions. The main consequence is that Faraday Rotation Measure simulated maps are in better agreement with observations in the cooling case, if the initial comoving magnetic field value is taken equal its standard value of 10^{-11} G. In low density regions, however, the magnetic field evolution in the radiative run is very close to the adiabatic case.

We have also shown that magnetic reconnection is responsible for field dissipation in the cluster core. This was already discussed in Roettiger et al. (1999) in the context of adiabatic simulations of idealized mergers. Since we are dealing with ideal MHD, magnetic reconnection occurs at the numerical level, so that we should be affected to some extent by the effect of numerical resolution. Moreover, this underlines the importance on the choice of the numerical code used, especially when one considers the fundamental differences existing between grid–based and particle–based codes. Using a MHD version of GADGET, Dolag et al. (2005) found in their adiabatic run much larger magnetic field strength for a subset of their simulated particles. They report mean field values one order of magnitude larger than median field values, in apparent contradiction with our present result. Magnetic reconnection appears therefore much less efficient in the SPH case. On the other hand, using the grid-based code ZEUS, Roettiger et al. (1999) report results very similar to ours, with strong field dissipation occuring in converging part of the flow. One interesting outcome of the present work is that radiative cooling drastically changes the effect of magnetic reconnection, since turbulence and gravitational compression easily counterbalance the associated dissipation.

Nevertheless, this large additional amount of magnetic energy in the core of cooling clusters is a crucial step in determining the structure of the cosmological magnetic field. It has a direct consequence on the propagation of high energy cosmic rays in the universe. Since we have no direct observations of magnetic fields outside of cluster cores, only cosmological numerical simulations can address this problem. Their weakness is that the initial magnetic field value must be normalized a posteriori in order to fit the observed values. We have shown that for the same seed field, the final magnetic field strength in a cooling cluster core is one order of magnitude higher than in the adiabatic case. Cooling processes are therefore of great importance if one wants to describe the proper evolution of magnetic fields in the Universe.

References

Asai, N., Fukuda, N., & Matsumoto, R. 2007, ApJ, 663, 816
Brüggen, M., Ruszkowski, M., Simionescu, A., Hoeft, M., & Dalla Vecchia, C. 2005, ApJ, 631, L21
Clarke, T. E., Kronberg, P. P., & Böhringer, H. 2001, ApJ, 547, L111
Dolag, K., Bartelmann, M., & Lesch, H. 1999, A&A, 348, 351
Dolag, K., Grasso, D., Springel, V., & Tkachev, I. 2005, Journal of Cosmology and Astro-Particle Physics, 1, 9
Fromang, S., Hennebelle, P., & Teyssier, R. 2006, A&A, 457, 371
Globus, N., Allard, D., & Parizot, E. 2007, ArXiv e-prints, 709
Govoni, F. & Feretti, L. 2004, International Journal of Modern Physics D, 13, 1549
Haardt, F. & Madau, P. 1996, ApJ, 461, 20
King, E. J. & Coles, P. 2006, MNRAS, 365, 1288
Kotera, K. & Lemoine, M. 2007, ArXiv e-prints, 706
Lemoine, M. 2005, Phys. Rev. D, 71, 083007
Miniati, F., Jones, T. W., Kang, H., & Ryu, D. 2001, ApJ, 562, 233
Miyoshi, T. & Kusano, K. 2005, Journal of Computational Physics, 208, 315
Roettiger, K., Stone, J. M., & Burns, J. O. 1999, ApJ, 518, 594
Sigl, G., Miniati, F., & Enßlin, T. A. 2004, Phys. Rev. D, 70, 043007
Taylor, G. B., Fabian, A. C., & Allen, S. W. 2002, MNRAS, 334, 769

Teyssier, R. 2002, A&A, 385, 337
Teyssier, R., Fromang, S., & Dormy, E. 2006, Journal of Computational Physics, 218, 44