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Simulations of the Magnetic Field Structure in the Local Minivoid

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1. Introduction

The lack of sufficient observational hints about the structure, topology and distribution of the large scale magnetic field within the Local Group of galaxies (hereafter LG) prompted us with the need to perform a series of simulations, varying the range of parameters defining the physical state of the Intracluster Medium (hereafter ICM) in the LG. More specifically, we have performed a set of 22 simulations, spanning a range of parameters which we believe to be representative of a wide range of scenarios for the formation and evolution of the LG and of its ICM content. This is a work still in progress, and we will present elsewhere the simulations (Antonuccio-Delogu et al., in preparation). Here we will comment on some features of the evolution and final configuration of the MF which seem to be rather well established and probably are not plagued by resolution and/or numerical effects.

The LG is conventionally defined as a region of radius $1.5h^{-1}$ Mpc centered around the center of mass of the system composed by our Galaxy and M31. This system is dominated in mass by two spiral galaxies: our Galaxy and M31 (Andromeda), and otherwise encompasses 34 dwarf galaxies, whose total mass amounts to less than 20 % of the total mass. The Galaxy and M31 approach each other at a speed of about 120 km/sec [18]. These dwarf galaxies are mostly distributed in an almost planar configuration aligned with the Local Superclusters [11]. Notably, there seem to be no galaxies in a region extending more than $6h^{-1}$ Mpc above the LG plane: this is the so-called *Local Minivoid* (hereafter LMV).

The main purpose of our work is that of attempting to understand the structure of the intergalactic MF within the LMV. In principle, the average value of the MF could be very low within this region, thus opening the possibility that Ultra-High-Energy-Cosmic-Rays (hereafter UHECRs) could propagate almost undisturbed over this "channel", whose outer extent has not yet been measured. To appreciate this point, we recall that the rms deflection angle in presence of a MF is given by [15]:

$$\theta(E,r) \simeq 0.8^\circ\, Z \left(\frac{E}{10^{20}\,\mathrm{eV}}\right)^{-1} \left(\frac{r}{10\,\mathrm{Mpc}}\right)^{1/2} \times \left(\frac{l_c}{1\,\mathrm{Mpc}}\right)^{1/2} \left(\frac{B}{10^{-9}\,\mathrm{G}}\right) \qquad (1)$$

For a given deflection angle, the coherence length scales as B^2, thus showing that UHECRs could in principle travel very large distances when they meet Voids with a very low magnetic field. As is well known, the Large Scale Structure of the Universe is "filled" with Voids. More quantitative studies of their distribution have now been made possible by survey projects like the Sloan

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Digital Sky Survey (SDSS) and the 2dF survey [8], and show that regions with average overdensity $\delta = (\rho - \bar{\rho})/\rho > -0.85$ span the range $2.5 \leq r \leq 15h^{-1}$ Mpc in radius. Thus, regions like the LMV could be quite common in our Universe, and they could also percolate within each other creating privileged diffusion channels through which UHECRs move almost undisturbed.

These considerations then prompt a series of questions: How is the magnetic field structured within Voids? Can the IGM/ICM plasma keep ionized? How does it evolve while the Void expands? This work aims only at providing a first attempt at answering some of these questions: a full picture would be very difficult to attain, lacking a complete understanding of the origin and evolution of Voids. The latter is a remarkable issue: not surprisingly, most of the theoretical effort from cosmologist has been directed at an understanding of overdense regions of the Universe, like galaxies and clusters thereof, while little attention has been dedicated to underdense regions [12].

In the following we will adopt the standard cosmological units for distance, i.e. the Megaparsec (1 Mpc $\approx 3.085 \times 10^{24}$ cm). The quantity h will denote the Hubble constant at present epoch in units of 100Km/sec/Mpc.

2. Mass distribution within the Local Group

Magnetic fields decay rapidly if they are not "supported" by a fully ionized plasma. However, it is very difficult to deduce observationally the properties of the ICM, particularly in the LG. Only upper limits on the density and temperature of the ICM in the direction of M31 have been obtained from recent measurements with the ASCA satellite [14]. In external galaxies, very recent measurements show that the density of the Intergalactic plasma decreases rapidly far from the visible component. One should then expect that the density of the IGM/ICM should be quite low. In the standard cosmological paradigm, baryons follow the distribution of the dark matter. In the LG, the distribution of galaxies within $3h^{-1}$ Mpc is quite irregular (by definition, the LG is the region within $1.5h^{-1}$ Mpc around the LG). The dynamics of galaxies externally and around the LG is poorly known, because of the sparseness of the data [20].

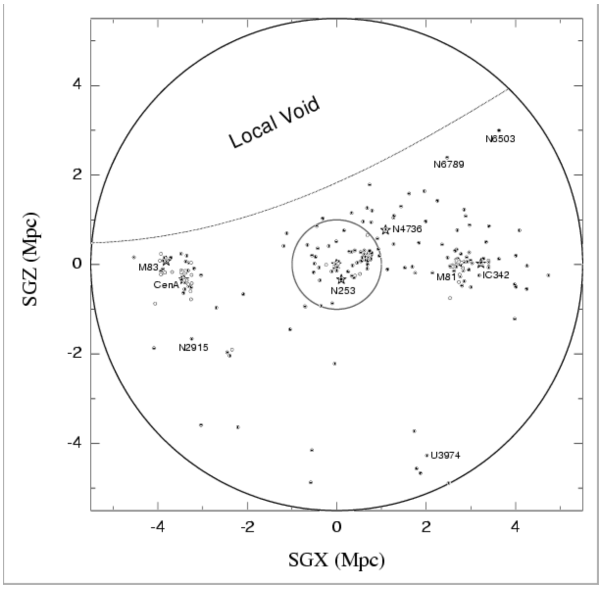

Figure 1. Galaxy distribution within $6h^{-1}$ Mpc around the Local Group's center, from [10]. The red circles denotes the Local Group, according to the standard definition of van den Bergh's [18]. The Local Minivoid is traced by a circular section spanning the $z > 0$ region. Coordinates are supergalactic coordinates, here the $y = 0$ section is shown.

2.1. The local Minivoid

The existence of what has been called the "Local Minivoid" [11] has been confirmed by the most recent work on the distribution and velocity field of dwarf galaxies [9,10]. This feature occupies a significant extent in galactic coordinates (see e.g. Fig. 3 of [11]), and has a radial extent of about $5h^{-1}$ Mpc. In Figs. 1, 2 we show the distribution of galaxies within $6h^{-1}$ Mpc around the LG's center of mass [11], showing clearly the concentration of galaxies in the supergalactic plane. Most of the galaxies represented in these figures are dwarf galaxies, whose distance has been obtained from recent Hubble Space Telescope data. The mass of these objects can be estimated with a large uncertainty, but are certainly $1-2$ orders of magnitude smaller than the mass of system Galaxy/M31. For this reason, we will include only the gravitatiional potential of these two galaxies in our simulations.

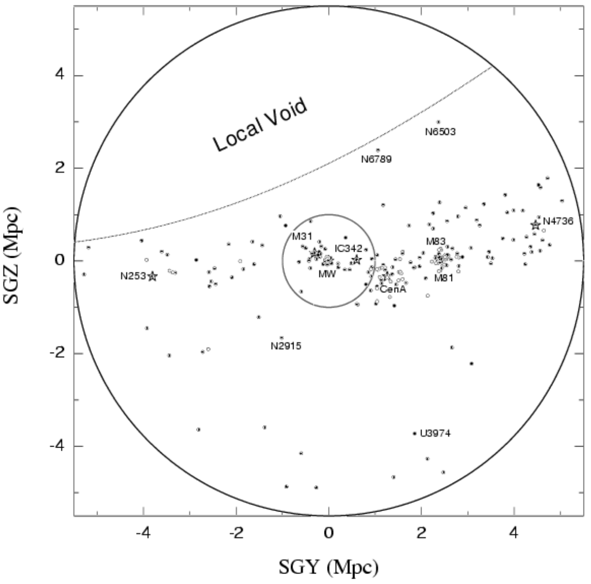

Figure 2. Same as Fig. 1 for the $x = 0$ section.

3. Model configuration and Numerical method

As we said before, we include only the gravitational force from our Galaxy and M31, fixed respectively at $M = 10^{12}\mathrm{M}_{sol}$ and $M = 1.5 \times 10^{12}\mathrm{M}_{sol}$. The simulation box has a fixed size of $12h^{-1}$ Mpc in physical coordinates, and the Galaxy amd M31 move along an (almost) straight trajectory at $y = -4h^{-1}$ Mpc, approaching each other and reaching a final velocity of -120 Km/sec at the present epoch. All the simulations are started at an epoch corresponding to 10^9 years ago. The parameters of the ICM in the LMV and, generally speaking, in the LG, lie in ranges where one could expect that the ICM easily develops supersonic turbulence. As is well know, simulations of MHD turbulence are still in their infancy today (see e.g. [13] for a recent review), and it would be highly hazardous to attempt to draw quantitative conclusions even from very high resolution simulations like those presented in this work. For these reasons, we prefer rather to perform a series of *numerical experiments*, where the model configuration we simulate contains the essential ingredients of the system we want to simulate (i.e. a region of radius $6h^{-1}$ Mpc centered on the LG center of mass.

The simulations have been performed with FLASH [5], an Adaptive Mesh Refinement (AMR) code developed at the FLASH ASCI Center. FLASH has a modular structure which allows an easy control on the physical framework. In our simulations, in addition to the ordinary set of Magnetohydrodynamic equations, we have included also thermal conduction and radiative cooling. The first is modelled via a Spitzer coefficient [19] multiplied by a correction factor taking into account transport effects due to the presence of strong turbulence [3]. Radiative cooling depends on the square of the electron density, and for the very low densities typical of the LMV it contributes very little to the energy budget. Out of 22 runs, 18 were performed in 2D, and the remaining were full 3D runs. In the latter the maximum resolution is smaller. The main difference between the 2D and 3D results is in the *topology* of the final MF configuration.

3.1. Results

Some general features, common to the all final configurations, can also be seen in Figs. 3,4. In this simulation we started with a very low value of the MF, supposedly frozen within the ICM. The perturbed gravitational potential produced by the motion of the Galaxy and M31 within the LMV induces a shock wave. The ICM from outside the LMV tends to diffuse within this region, but this difffusion is never quantitatively relevant. The shock itself propagates in a very rarifed medium, and it does not heat very much. The MF however is not significantly modified by the shock. This circumstance is not common to all the simulations, however (Antonuccio-Delogu et al., in preparation). The behaviour of the MF can be simply understood if one considers in detail the propagation of the shock within the LMV. The shock wave evolves rapidly within the LMV, but it leaves almost unchanged the density and velocity structure. Thus, the MF keeps almost unchanged, and the lines keep their coherence.

4. Final considerations

There are many differences between this work and similar simulations of the structure of the MF in the nearby Universe performed until now. Dolag et al. [7] have recently simulated the evolution of the MF in a constrained model of the Local Supercluster. Their volume is much larger than ours, and this guarantees that tidal fields in the relevant region are appropriately taken into account. However, their resolution in the region corresponding to the LMV is worse than in our simulation, which is done on a smaller

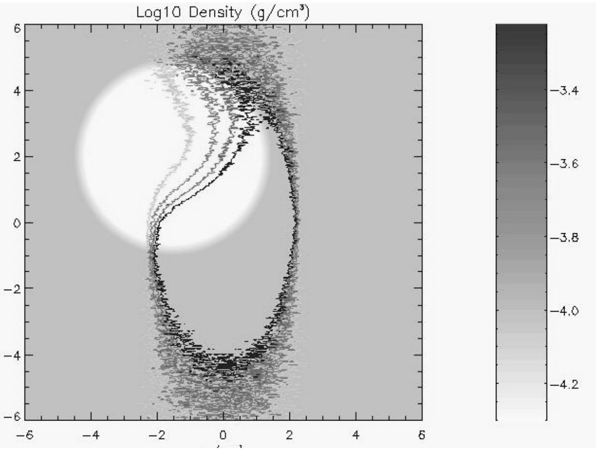

Figure 3. Initial configuration of the LMV simulation. Density is in units of particles/cm^3. The LMV is modelled as an initially underdense region ($n_e = 10^{-6}\,\mathrm{cm}^{-3}, T_e = 10^9\mathrm{K}$). The IGM is supposed to be fully ionized and the density is exponentially increasing from the center of the LMV out. The magnetic field is supposed to be frozen ($B \propto \sqrt{\rho}$). The Galaxy and M31 are located on the $y = 0$ plane and approach each other as in the least action model. We show 4 magnetic field lines, corresponding to $B = 10^{-10}, 2 \times 10^{-10}, 4 \times 10^{-10}, 8 \times 10^{-10}$ G.

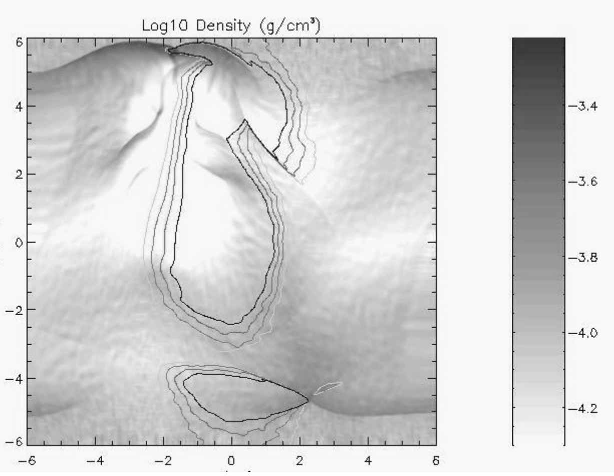

Figure 4. Final configuration of the LMV simulation at the present epoch. Units and labels are as in 3.

volume. Similar simulations on smaller volumes have been recently done by Sigl et al. (these proceedings) and Grasso et al. (these proceedings). These simulations were performed with codes implementing different algorithms. The code used by Sigl et al. is a modified version of GADGET, a Smoothed Particle Hydrodynamics (SPH) code, while Grasso et al. use a mesh-based code with fixed mesh resolution. It is interesting to observe that these simulations differ greatly in their predictions concerning the strength and structure of the MF in underdense regions. The code we have adopted (FLASH) is an adaptive mesh hydrodynamic code, and we find results similar to those by Grasso et al. for the strength of the MF in Voids. Clearly, it would be highly desirable to try to understand better these differences, possibly by comparing the outputs of these different codes on a similar suite of benchmarks.

Lacking direct measurements of the intergalactic MF, the predictive rôle of numerical simulations can esily be overemphasized. We believe that numerical experiments, like those performed in the present study, could help us in distinguishing robust features from numerical artifacts.

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