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Cosmic magnetism evolution using cosmological simulations

Stela Adduci Faria[1], **Elisabete M. de Gouveia Dal Pino**[1] **and Paramita Barai**[2]

[1]Instituto de Astronomia, Geofísica e Ciências Atmosféricas, University of São Paulo (USP), São Paulo, Brazil
e-mail: stela.faria@usp.br

[2]Núcleo de Astrofísica - Universidade Cruzeiro do Sul (NAT - UNICSUL), São Paulo, Brazil

Abstract. The Intergalactic Medium (IGM) is the region comprising the environment between the galaxies. Gamma-ray observations have provided lower limits to IGM magnetic fields of the order of $\gtrsim 10^{-16}$ G. Magnetic fields are continuously ejected from galaxies by jets and galactic winds. However, the origin and evolution of cosmic magnetic fields in the more diffuse regions, like voids, is still debated. The difficulties in directly measuring magnetic fields and their coherent scales, make hydrodynamic and magnetohydrodynamic (MHD) cosmological simulations useful tools to shed light on this debate. As a first approach, we have performed hydrodynamic cosmological simulations assuming energy equipartition as an initial condition between the baryonic gas and the magnetic field, starting at $z = 8$, to track the evolution of magnetic fields, and compare with results of MHD simulations. We have found that for halos and cores, our results are comparable to the MHD description. For the less dense regions, the equipartition condition clearly overestimates the observed limits. In forthcoming work, we will investigate MHD simulations of cosmological evolution and amplification of seed magnetic fields, considering all relevant feedback processes and exploring turbulent dynamo amplification versus primordial mechanisms across cosmological timescales.

Keywords. Magneto-hydrodynamics, Cosmic Ray Propagation, Cosmological hydrodynamical simulations, Origin of magnetic fields

1. Numerical method and Results

The IGM is observed to contain diffuse magnetic fields that may have been seeded by starburst (SBs) galaxies, jets from radio galaxies, dynamo action, mergers and tidal interactions between galaxies, or they may have had a primordial origin (e.g. de Gouveia Dal Pino 2011; Barai & de Gouveia Dal Pino 2019). However, it is still not clear if such processes are able to reach the more diffuse regions of the IGM, i.e., the large scale voids where magnetic fields of $\gtrsim 10^{-16}$ G have been inferred from gamma-ray observations on scales of the order of Mpc (Fermi-LAT Collaboration 2018). Our aim is to investigate the origin of cosmic magnetic fields in the diffuse intergalactic medium and clusters of galaxies. In a first approach here we consider pure hydrodynamical simulations with passive magnetic fields in equipartition with the gas thermal pressure in order to compare with existing MHD cosmological simulations and check whether this hypothesis is valid.

We use the hydrodynamic version of the Lagrangian SPH code GADGET-3 (Dolag & Stasyszyn 2009) to simulate cosmological boxes with constant volume (2 Mpc)^3. The equipartition assumption is given by $u = \frac{u_E}{2} = \frac{B^2}{8\pi}$, where u is the magnetic energy density,

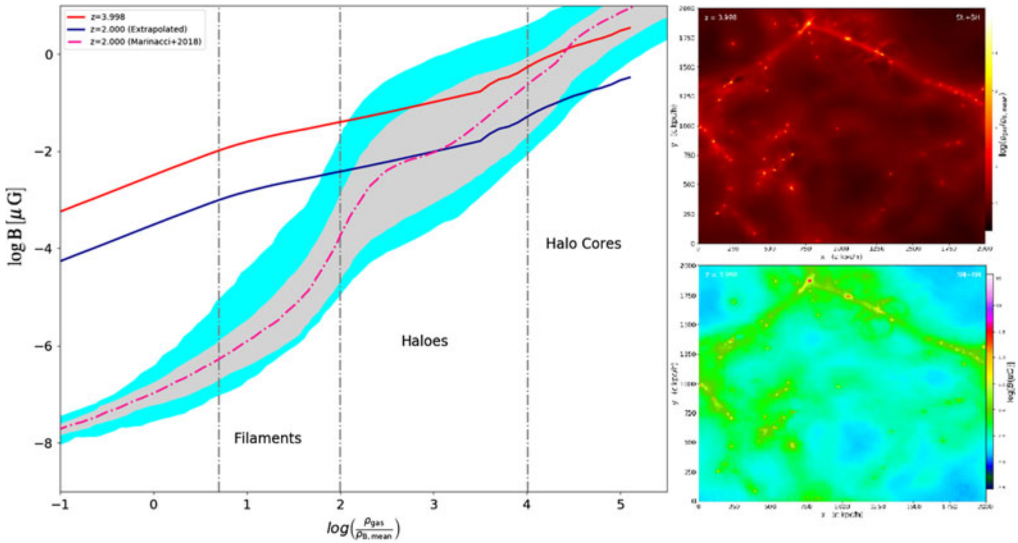

Figure 1. (Left) MHD simulations from Marinacci *et al.* (2018) at z = 2, shown as the pink dot-dashed curve (shaded areas are the 1σ (gray) and 2σ (cyan) scatter). We show our simulated mean magnetic field at z = 4 (red solid line) which we extrapolate to z = 2 (blue solid curve) for comparison to Marinacci *et al.* (2018). (Right) Projected 2D maps of the gas overdensity and the magnetic field, top and bottom respectively, are shown. We observe that the equipartition assumption is valid for the denser regions, i.e., the MFs follow a dependence with gas density that is compatible with cosmological MHD simulations, thus indicating that in such regions the gas and the MFs are in equipartition.

u_E the gas energy density, and B the magnetic field. To test our assumption, we compare our results with the MHD simulations of Marinacci *et al.* (2018).

In Fig. 1, we show our simulated results at $z = 4$ (red curve) for a range of densities from galaxy halos to voids. Marinacci *et al.* (2018) performed their simulations between $z = 2$ and 0. We take their results for $z = 2$ (represented in Fig. 1 by the dashed-pink curve) to compare with our results. Since our simulation stopped at $z = 4$ (Fig. 1, red solid curve), we extrapolated our results to $z = 2$ (Fig. 1, blue solid curve), assuming magnetic flux conservation and cosmological expansion of the IGM, using $\log B_1 = \log B_2 + \log \frac{(1+z_1)^2}{(1+z_2)^2}$, so that the magnetic field drops according to $\propto \frac{1}{a^2} = (1+z)^2$. The equipartition assumption yields magnetic field intensities which are highly overestimated for the less dense, large scale structures, while it gives consistent values for the denser regions, the halos and cores. Further studies performing MHD simulations are still needed in order to confirm these results. They also evidence that the dynamical effects of MFs *cannot* be neglected at halo cores scales. Therefore, at these scales HD simulations are not an optimal approach to describe the evolution of these systems. The astrophysical processes that enrich the IGM are local and could feed the voids, however, the potential MF in these regions are far from the equipartition condition with the thermal pressure of matter, as one should expect. Our calculations cannot eliminate the hypothesis that the field present in the voids is of primordial origin. We will continue to investigate these magnetic fields in the low density regions through cosmological MHD numerical studies of the formation and evolution of large scale structures. For this purpose, we will use the MHD version of the GADGET SPH code, along with its connection with turbulence at smaller scales (Santos-Lima *et al.* 2014), cosmic ray (CR) propagation, and all the important feedback ingredients (Alves Batista, Saveliev & de Gouveia Dal Pino 2019).

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