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Cosmic magnetism in the large scale universe

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Abstract. Primordial magnetic fields are amplified by turbulent dynamo effects, as well as by the processes of formation and evolution of stars in the Interstellar Medium (ISM). At the same time, galactic outflows are generated by the energetic feedback from stars and supernovae (SN) explosion, along with large-scale dynamic events (e.g. galaxy mergers and tidal interactions between galaxies). In massive galaxies, energetic winds are also produced by accretion of gas in central supermassive black holes, and resulting in the feedback from Active Nuclei of Galaxies (AGN). The magnetic fields in the ISM are pushed out by strong galactic outflows over time, magnetically enriching the InterGalactic Medium (IGM) at larger cosmological distances. These magnetic fields permeate the turbulent IGM and can influence the formation of structures on large scales. However, upper limits of magnetic fields of the order of 10^{-15} - 10^{-16}G are also observed in the very diffuse regions of the intergalalactic and intracluster media, in the voids. The origin of this large-scale diffuse InterGalactic Magnetic Fields (IGMFs) is not known. IGMFs could be either generated primordially in the early Universe, or produced locally in galaxies and efficiently transported by galactic outflows to fill a significant volume fraction of the IGM . For the later, the contribution of SN-driven *versus* AGN-driven outflows in the transport of magnetic fields is also unknown. The properties of the magnetic fields are very difficult to measure directly, especially in the low density diffuse regions of the IGM. We used cosmological hydrodynamical simulations and assumed equipartition between the gas and the magnetic field pressures in order to investigate how the magnetic fields can be distributed in the different scales, through cosmic time, and test whether the equipartition hypothesis is reliable. From the simulated data analysis, we obtained information about the contribution of the Black Hole and star formation feedback in the IGM, the correlation between the density and the magnetic field. We found that the correlation hypothesis is quite appropriate in the densest regions, but it predicts magnetic field intensities a the voids much larger than the expected values from the observations.

Resumo. Os campos magnéticos primordiais são amplificados por efeitos de dínamo turbulentos, bem como pelos processos de formação e evolução de estrelas no meio interestelar (ISM). Ao mesmo tempo, fluxos de ventos galácticos são gerados pelo *feedback* energético de estrelas e de explosão de supernovas (SN), juntamente com eventos dinâmicos em larga escala (por exemplo, fusões de galáxias e interações de maré entre galáxias). Nas galáxias massivas, os ventos energéticos também são produzidos pelo acumulo de gás em buracos negros supermassivos centrais resultando, dessa forma, no *feedback* dos Núcleos Ativos das Galáxias (AGN). Os campos magnéticos no ISM são expulsos por esses fortes fluxos galácticos ao longo do tempo, enriquecendo magneticamente o Meio Intergaláctico (IGM) a distâncias cosmológicas cada vez maiores. Esses campos magnéticos irão permear o turbulento IGM, podendo, assim, influenciar a formação de estruturas em grandes escalas. No entanto, limites superiores de campos magnéticos da ordem de 10^{-15} - 10^{-16} G também são observados nas regiões muito difusas dos meios intergalaláctico e intracluster, nos *voids*. À vista disso, a origem dos Campos Magnéticos Intergalácticos Difusos em grande escala (IGMFs), até o momento atual, não é conhecida. Conjectura-se que os IGMFs podem ser ter sido gerados primordialmente no Universo primitivo ou mesmo produzidos localmente em galáxias e transportados eficientemente por fluxos galácticos para preencher uma fração de volume significativa do IGM. Logo após, computar as contribuições dos fluxos acionados por SN *versus* AGN no transporte de campos magnéticos até então desconhecidas. As propriedades dos campos magnéticos são muito difíceis de serem medidas diretamente, especialmente nas regiões difusas de baixa densidade do IGM. Usamos simulações hidrodinâmicas cosmológicas e assumimos equipartição entre as pressões do gás e do campo magnético, a fim de investigar como os campos magnéticos podem ser distribuídos nas diferentes escalas, através do tempo cósmico, e testar se a hipótese da equipartição é confiável. A partir da análise dos dados, obtivemos informações sobre a contribuição do Buraco Negro e do *feedback* da formação estelar no IGM, a correlação entre a densidade e o campo magnético e também a evolução do campo magnético ao longo do tempo. Descobrimos que a hipótese de correlação é bastante apropriada nas regiões mais densas, mas prediz intensidades do campo magnético nos vazios muito maiores que os valores esperados das observações.

Keywords. AGN Feedback – SN Feedback – IGM – Magnetic Field – Cosmological Simulation

1. Introduction

The universe, according to Draine (2010), is divided into two main regions, one is the Interstellar Medium (ISM) - comprising the interior of galaxies - and the Intergalactic Medium (IGM) - space among galaxies. Most of the baryonic matter in the universe is in the plasma state, that is, totally or partially ionized gas, permeated by magnetic fields de Gouveia Dal Pino (2009). These magnetic fields have an important role in many astrophysical processes, such as star formation and the propagation of cosmic rays (RCs) in the IGM. However, its importance in processes, such as the formation of structures in the early universe, is not well understood yet.

Measurements of synchrotron radiation and Faraday rotation prove the existence of regular and turbulent magnetic fields with intensity of 100μ G in starburst (SB) galaxies. For Intergalactic Medium there are only the limits imposed by the observations, such as lower 10^{-16} G in voids. These magnetic fields may be fed by galactic winds from SBs galaxies, radio galaxy jets, galaxy fusion, or turbulent dynamo effect (10; 8). However, it is not clear where and how these magnetic fields and their seeds originated, and it is still investigated whether they have a primordial origin.

As a first step to investigate the origin of the Intergalactic Magnetic Fields (IGMFs), we here have computed the contributions of SN *versus* AGN driven galactic outflows in the advection of magnetic fields from the galaxies to the IGM, and explored the evolution of the IGMFs through cosmic times. We have assumed equipartition between the thermal and the magnetic pressures. For this aim, we made use of hydrodynamic simulations of cosmological volumes with periodic boundary conditions using the GADGET-3 code e.g. Barai et al. (2013).

2. Numerical Method and Results

According to Monaghan (2012), SPH is a method used to obtain approximate numerical solutions of fluid dynamics equations by replacing the fluid with a set of particles with a smoothed density distribution, where each is described by a nucleus. This is the method used by GADGET-3 code made by Springel (2005).

We performed simulations e.g.Barai et al. (2013) within the cosmological volume is a $(2Mpc)^3$ box, undergoing Hubble expansion (12; 6). As remarked, we assume that there is equipartition of energy between the thermal energy density of the gas and the magnetic energy density:

$$u = \frac{u_E}{2} = \frac{B^2}{8\pi} \tag{1}$$

where u is the energy density of the magnetic field, u_E is the energy density of the gas particles and B is the magnetic field.

3. Simulation Results and Discussions

Using the analysis methods, the figures 1 and 2 were obtained for the magnetic field in the $(2Mpc)^3$ cosmological volume at the cosmic epoch $z = 4.494$.

The left side of Figure 1 shows the projected 2D map of the gas overdensity – which is ratio of density of the gas particle and the average density of the Universe – in the whole box. It is possible to note the IGM (dark and red regions), and the galaxies and clusters of galaxies (yellow and white filaments) as the high density regions, as well as the magnetic field is distributed in the cosmological volume according to the concentration of matter (Figure 1, right side).

From the maps, in Figure 2, we observe that the Magnetic field has a positive correlation with the overdensity, as one should expect for an ideal MHD flow. The limiting overdensity of 10^3 divides the cosmic gas into two regions. In the right side, it is possible to see a high-density region, where the highest probability of star formation occurs (inside the galaxies), while on the left side there is the low density region, which represents mainly the diffuse IGM.

However, we find that the magnetic field in regions of voids is very small, but still much larger than the lower limit values inferred from gamma-ray observations 10^{-15} - 10^{-16} G e.g. Acharya et al (2019). On the other, the equipartition hypothesis results magnetic fields in the densest regions which are compatible with observations. Finally, our calculations do not eliminate the hypothesis that the field present in the voids is of primordial origin.

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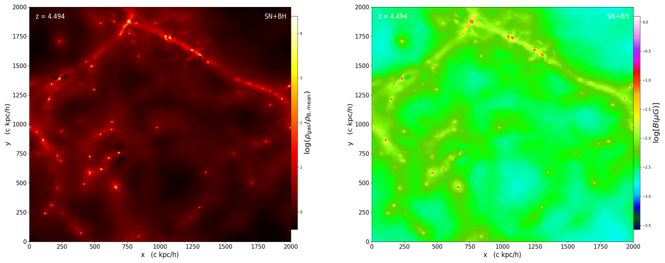

Figure 1. Projected 2D maps of the gas overdensity and the magnetic field, respectively.

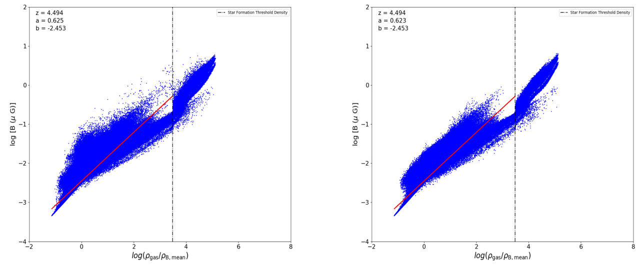

Figure 2. Diagrams of correlation of magnetic field with overdensity distribution, left: SN+BH feedback run, right: SN feedback only run. The red lines correspond to the best fit and have a power law dependence with power law index = 0.62.

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