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The role of the dynamo on the large scales of the Universe

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Abstract. The nature and origin of turbulence and magnetic fields on cosmological scales are open problems in astrophysics. Turbulent flows amplify weak seed magnetic fields by the process known as turbulent dynamo. As the amplification of cosmic magnetic fields depends on the properties of the plasma, knowing the characteristics of these environments is essential. A dynamo effect converting kinetic flow energy into magnetic energy is often accepted in the context of large scale structures of the universe; however, the intracluster plasma is weakly collisional, and opposes the standard collisional MHD theory. The magnetic field growth and maintenance through an efficient turbulent dynamo in such weakly collisional plasma is not understood yet. Previous studies point out that turbulence is subsonic inside clusters/groups, while it is transonic or slightly supersonic in filaments. We aim at studying the weakly collisional plasma dynamo in these environments, as well as the role of viscosity in this process. Viscosity is related to the ion-ion collision rate, but it can also be affected by ion scattering by magnetic fluctuations originating from instabilities in weakly collisional plasma. Viscosity tends to cancel some movement patterns that can allow the stretching of the magnetic field lines, however when it is too high it ends up inhibiting the action of turbulence. For this purpose, we use 3D MHD numerical simulations of forced turbulence in a periodic box domain, which emulates the IGM and ICM endowed with a viscosity model adequate for a weakly collisional plasma, by implementing the viscous stress tensor, as well as a Braginskii viscosity. Such a scenario allows the growth of the field to stages that resemble the saturated stage of the MHD dynamo. In this work, we will present results of magnetic field amplification for forced turbulence with different viscosity models.

Resumo. A natureza e origem da turbulência e dos campos magnéticos em escalas cosmológicas são problemas em aberto na astrofísica. Fluxos turbulentos amplificam campos magnéticos de sementes fracas pelo processo conhecido como dínamo turbulento. Como a amplificação dos campos magnéticos cósmicos depende das propriedades do plasma, conhecer as características desses ambientes é essencial. Um efeito dínamo que converte energia de fluxo cinético em energia magnética é frequentemente aceito no contexto de estruturas em grande escala do universo; no entanto, o plasma intracluster é fracamente colisional e se opõe à teoria MHD colisional padrão. O crescimento e manutenção do campo magnético através de um dínamo turbulento eficiente em tal plasma fracamente colisional ainda não é compreendido. Estudos anteriores apontam que a turbulência é subsônica dentro de aglomerados/grupos, enquanto é transônica ou ligeiramente supersônica em filamentos. Nosso objetivo é estudar o dínamo de plasma fracamente colisional nesses ambientes, bem como o papel da viscosidade nesse processo. A viscosidade está relacionada com a taxa de colisão íon-íon, mas também pode ser afetada pelo espalhamento de íons por flutuações magnéticas originadas de instabilidades no plasma fracamente colisional. A viscosidade tende a anular alguns padrões de movimento que podem permitir o estiramento (e amplificação) das linhas do campo magnético, porém quando é muito alta acaba inibindo a ação da turbulência. Para tanto, utilizamos simulações numéricas 3D MHD de turbulência forçada em um domínio de caixa periódica, que emula o IGM e ICM dotadas de um modelo de viscosidade adequado para um plasma fracamente colisional, implementando o tensor de tensão viscosa, bem como uma viscosidade de Braginskii. Tal cenário permite o crescimento do campo para estágios que se assemelham ao estágio saturado do dínamo MHD. Neste trabalho, apresentaremos resultados da amplificação de campo magnético para turbulência forçada com diferentes modelos de viscosidade.

Keywords. Magneto-hydrodynamics – Magnetic Fields – Turbulent Dynamo

1. Introduction

Magnetic fields permeate the entire universe and accompany and even affect the formation and evolution of astrophysical systems from galaxies to planetary scales. However, despite the importance of dynamic magnetic fields on the large scales of the universe, obtained from Faraday rotation of polarized emission from quasars (Peterson, 1997), and from the propagation of particles and radiation, their origin and maintenance are still not well understood, particularly in the rarefied regions of the Intergalactic Medium (IGM), Intracluster Medium (ICM) and the voids. As the amplification of cosmic magnetic fields depends on the material properties of the plasma, knowing the characteristics of these environments is essential.

One of the important features is turbulence, whose nature and origin, as well as that of magnetic fields on cosmological scales are not well understood yet. Studies have shown that the feedback processes from galactic sources are not enough to increase the magnetic seeds in diffuse medium (ICM and IGM) up to the observed values (de Gouveia Dal Pino, 2006 and references therein). Turbulence in these environments may be injected by galaxy mergers, active galaxies and starburst galaxies, and may justify the amplification of magnetic fields via turbulent dynamo (Schekochihin et al. 2004; Santos - Lima et al., 2014).

Our goal is to describe the low-density ICM with a more rigorous method, employing a collisionless MHD approach, which allows to account for the effects of anisotropic pressure with regard to the magnetic field orientation including dissipation terms, such as effective and Braginskii viscosity, and resistivity. With this model, we can evaluate the increase of the magnetic field by turbulent dynamo more precisely for individual clusters. The study will provide valuable information on the amplification of primordial seed magnetic fields and their maintenance, which can later be used in cosmological MHD simulations of large scale structures.

2. Collisionless MHD Model

Collisionless plasmas do not meet the requirements of standard MHD theory, causing temperature anisotropy, which is known from kinetic theory to trigger electromagnetic instabilities, like Firehose and Mirror (Kulsrud 1983). These electromagnetic fluctuations, in turn, redistribute the particle's tilt angles, introducing effective collisions and decreasing temperature anisotropy (Gary 1993).

Previous works have accounted for the isotropization of the plasma and temperature due to these instabilities in the study of the turbulent dynamo growth (Santos-Lima et al. 2014). Here we incorporate these effects explicitly in the MHD (Eq. 1) through the isotropic viscous tensor (Eq. 2) and the Braginskii tensor that accounts for the anisotropy in the pressure Δp (Eq. 3)

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho\mathbf{u}\\ \mathbf{B}\\ A\left(\rho^3/B^3\right)\end{pmatrix}+\nabla\cdot\begin{pmatrix}\rho\mathbf{u}\\ \rho\mathbf{uu}+\Pi_p+\Pi_B\\ \mathbf{uB}-\mathbf{Bu}\\ A\left(\rho^3/B^3\right)\mathbf{u}\end{pmatrix}=\begin{pmatrix}0\\ \mathbf{f}\\ 0\\ \dot{A}_S\left(\rho^3/B^3\right)\end{pmatrix}, \quad (1)$$

where $A = p_\perp/p_\parallel$, the effective viscosity and Braginskii tensor are, respectively,

$$\Pi_p = \mu\left(\left[\nabla\mathbf{v}+(\nabla\mathbf{v})^T\right]-\frac{2}{3}(\nabla\cdot\mathbf{v})\,I\right) \quad (2)$$

$$\Pi_B = -\left(\hat{\mathbf{b}}\hat{\mathbf{b}}-\frac{1}{3}\mathbf{I}\right)\Delta p \quad (3)$$

where $\Delta p = 3\mu_B\hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla\mathbf{u}$ is the anisotropy in the pressure. The instabilities arise naturally in this case. We can also constrain the growth of Δp, by imposing what we call a hard-wall limiter $-\frac{B^2}{4\pi} \leqslant \Delta p \leqslant \frac{B^2}{8\pi}$, which is established either by Mirror ($\Delta p > 0$)

$$\Delta p = \min\left(\frac{B^2}{8\pi}, 3\mu_B\hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla\mathbf{u}\right) \quad (4)$$

or Firehose ($\Delta p < 0$)

$$\Delta p = \min\left(-\frac{B^2}{4\pi}, 3\mu_B\hat{\mathbf{b}}\hat{\mathbf{b}} : \nabla\mathbf{u}\right) \quad (5)$$

3. Numerical Method

The simulations were performed using the PLUTO code (Mignone et al., 2007), 3D MHD simulations endowed with a viscosity, where we model the ICM with forced turbulence varying the viscosity models. We simulate the following models, with periodic boundary conditions.

Table 1. Parameters of the Simulated Models.

Run	Limiter	ν_{S0}	μ_B^{-1}	μ^{-1}	η^{-1}	B_0
UL	Unlim	1	10^2	1500	1500	10^{-3}
LM	HW	1	20	1500	1500	10^{-3}

where μ is the effective coefficient viscosity, μ_B is the Braginskii coefficient viscosity, η is the coefficient resistivity and B_0 is the magnetic seed.

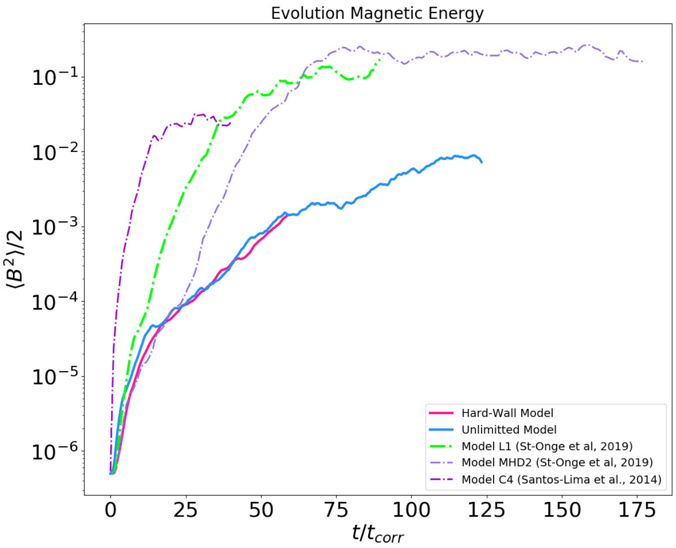

Figure 1. Comparison of our UL (continuous blue curve) and LM (continuous pink curve) models of evolution of the magnetic field for the resolution 128^3. Also shown are the models L1 (dashed green curve), MHD2 (dashed lilac curve), by St-Onge et. al (2019), and the C4 model (dashed purple curve) by Santos-Lima et. al. (2014).

4. Simulation Results

Fig. 1 shows the magnetic field amplification in the presence of isotropic and Braginskii viscosity models in the situations with and without limiters to control the increase of Δp.

In Fig. 1, MHD2 (St-Onge et al. 2019) gives the growth of B by turbulence in standard collisional MHD model with no pressure anisotropy; L1 model (St-Onge et al. 2019) includes both viscosities and the HW limiter, keeping the values of the coefficients constants, as in our model LM and we see that they are not comparable. On the other hand, C4 model (Santos-Lima et al. 2014) employs the collisionless CGL-MHD approach with a finite rate of isotropization given by $\nu_s = 100$, which should mimic the effects of isotropization when accounting for the explicit dissipative terms, as in the present work. However, we note that our results do not reproduce neither of the results of these previous studies.

5. Conclusion

As we can see in Fig. 1, the initial exponential growth of the magnetic seed is observed due to the turbulent stretching of the lines, where the kinetic energy of the turbulence is transformed into magnetic energy, and the dynamo moves to the saturated stage, when the dynamo actually accommodates itself in the environment. This proves that it is possible that a turbulent dynamo acts on the seeds of the magnetic field in the non-colliding medium of the ICM, but we have not yet reached the observed field strengths. In the first model, without the limiter for increasing the pressure gradient, it reaches values close to the collisional MHD model, but we expect the result with the HW limiter to approach due to isotropization by instabilities.

So far we have considered fixed values for the viscous coefficients in eqs. 2 and 3 . In progress, we have studies of them evolving self-consistently with time.

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