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Amplification of magnetic fields by a turbulent dynamo in the weakly collisional, viscous intra-cluster medium

S. Adduci Faria[1], R. Santos-Lima[1] & E. M. de Gouveia Dal Pino[1]

[1] Instituto de Astronomia, Geofísica e Ciências Atmosféricas
e-mail: `stela.faria@usp.br`

Abstract. Astrophysical plasmas are commonly described by standard collisional MHD theory, assuming that the gas is in local thermodynamic equilibrium. However, in the low-density plasma of the IntraCluster (ICM) and InterGalactic Medium (IGM), deviations from this equilibrium can occur due to the low rate of particle collisions. This generates pressure anisotropies that exert anisotropic stresses on the plasma movement, inhibiting its ability to stretch magnetic field lines. Paradoxically, these viscous environments are observed to be highly turbulent. Weakly collisional plasma with high β, i.e., with a large ratio between thermal and magnetic pressures, is susceptible to the appearance of kinetic instabilities, like Firehose and Mirror, which introduce effective collisionality, thus reducing the effective viscosity of the medium, regulating the anisotropy and allowing for the stretching and amplification of magnetic fields through turbulent dynamo action. We present here weakly collisional, viscous three-dimensional (3D) MHD simulations of the evolution of turbulence in the ICM starting with a tiny seed magnetic field. We assume isotropic and anisotropic viscosity, the latter given by field-parallel stress. We consider, for the first time, the self-consistent dynamic evolution of viscosity coefficients due to the increase in the effective collisionality of ions. Our results show that when considering this effect, the viscous coefficients decrease with time, the seed magnetic fields amplify exponentially, and the saturation value achieved is only slightly smaller than that of the collisional, non-viscous MHD model usually employed to describe the diffuse ICM. Furthermore, the field amplification is much larger than that of the viscous, collisional counterpart model, as expected. Therefore, our model can naturally explain the growth of magnetic fields in the turbulent ICM.

Resumo. Plasmas astrofísicos são comumente descritos pela teoria padrão de MHD colisional, assumindo que o gás está em equilíbrio termodinâmico local. No entanto, no plasma de baixa densidade do Meio Intracluster (ICM) e do Meio Intergaláctico (IGM), desvios desse equilíbrio devido à baixa taxa de colisões de partículas podem ocorrer. Isso gera anisotropias de pressão que exercem tensões anisotrópicas no movimento do plasma, inibindo sua capacidade de esticar as linhas do campo magnético. Paradoxalmente, observa-se que esses ambientes viscosos são altamente turbulentos. Plasmas fracamente colisionais com alto β, ou seja, com uma grande razão entre as pressões térmica e magnética, são suscetíveis à ocorrência de instabilidades cinéticas, como Firehose e Mirror, que introduzem uma colisionalidade efetiva, reduzindo assim a viscosidade efetiva do meio, regulando a anisotropia e permitindo o estiramento e amplificação dos campos magnéticos por meio da ação do dínamo turbulent. Apresentamos aqui simulações tridimensionais (3D) de MHD fracamente colisional e viscosa da evolução da turbulência no ICM a partir de um pequeno campo magnético inicial. Assumimos viscosidade isotrópica e anisotrópica, esta última dada pelo estresse paralelo ao campo magnético. Consideramos, pela primeira vez, a evolução dinâmica autoconsistente dos coeficientes de viscosidade, devido ao aumento da colisionalidade efetiva dos íons. Nossos resultados mostram que, ao considerar esse efeito, os coeficientes viscosos diminuem com o tempo, os campos magnéticos iniciais se amplificam exponencialmente, e o valor de saturação alcançado é apenas um pouco menor do que o do modelo MHD colisional não viscoso, geralmente usado para descrever o ICM difuso. Além disso, a amplificação do campo é muito maior do que a do modelo viscoso e colisional, como esperado. Portanto, nosso modelo pode explicar naturalmente o crescimento dos campos magnéticos no ICM turbulento.

Keywords. Magnetohydrodinamics

1. Introduction

Clusters of galaxies comprise hundreds to thousands of gravitationally bound galaxies, these clusters, with masses ranging from 10^{13} to 10^{15} solar masses, are predominantly composed of dark matter (Brunetti & Jones, 2014). Notably, energetic phenomena like mergers release substantial energy (around $10^{60} - 10^{64}$ erg) within a cluster's crossover time (approximately Gyr) (Voit, 2005; Brunetti & Jones, 2014; Bonafede, et al. 2021; Nishiwaki, Asano & Murase, 2021; Hussain, et al. 2021; Hussain, et al. 2023). This energy can potentially drive turbulent motions, amplifying seed magnetic fields (Dolag, Bartelmann & Lesch, 1999; Brüggen, et al. 2005; Ryu, et al 2008; Santos-Lima, et al. 2014; Santos-Lima, et al. 2016; Santos-Lima, et al. 2017; Vazza, et al. 2018; St-Onge, et al. 2020; Santos-Lima, et al. 2021; Adduci Faria, Santos-Lima & de Gouveia Dal Pino, 2023), and accelerating particles to very high energies (Hussain, et al. 2021; Hussain, S., et al. 2023). To address this, a more detailed understanding of magnetic field generation and maintenance inside clusters is essential.

The growth of magnetic fields in the intra-cluster environment, driven by a non-helical dynamo due to turbulence, challenges the conventional fluid (collisional MHD) approximation. The ion number density ($n_i \sim 10^{-2}$ cm^{-3}) and temperature ($T \sim 10^7$ K) in the intra-cluster medium do not align with collisional MHD assumptions (Santos-Lima, et al. 2014). Considering that the ion Coulomb collision rate, $\nu_{ii} \approx 10^{-15}$ s^{-1}, is much smaller than the Larmor gyrofrequency, describing the intra-cluster medium as weakly collisional or collisionless becomes more accurate. Anisotropies in pressure, triggered by low collisionality, and the presence of a magnetic field, induce electromagnetic instabilities (Kulsrud, 1983), allowing the amplification of magnetic fields through turbulence-induced random shear (Rosin, et al. 2011). Recent observations of turbulence in the Coma cluster by Chandra (Zhuravleva, et al. 2019) support

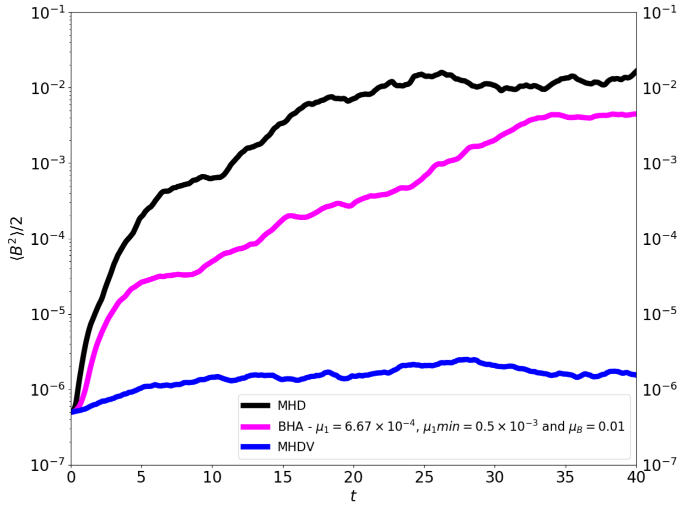

Figure 1. Evolution of the magnetic energy density for weakly collisional MHD model employing hard-wall pressure-anisotropy limiters, with isotropic and anisotropic Braginskii viscosity, compressive term, and self-consistent evolution of the viscosity coefficients (model BHA - magenta curve), the standard collisional MHD model with no viscosity (MHD - black curve), and collisional MHD with isotropic viscosity (MHDV - blue curve).

these theoretical results, showcasing density fluctuations consistent with a collisionless environment.

2. Numerical Method and Results

Our study aims to elucidate the origin and maintenance of magnetic fields through a turbulent dynamo in weakly collisional MHD clusters. High-resolution 3D-MHD numerical simulations, incorporating forced turbulence and an initial seed magnetic field, were conducted. Additionally, in all simulations, we introduced an initial magnetic field strength of 10^{-3}, and the resistivity in the BHA model was set to $\eta^{-1} = 1500$. All three models had a resolution of 256^3. The BHA model implemented hard-wall boundary conditions, where firehose and mirror instabilities limit the pressure gradient growth. For the first time, we self-consistently calculated the time evolution of transport coefficients as magnetic fields grew (Adduci Faria, Santos-Lima & de Gouveia Dal Pino, 2023).

Figure 1 illustrates the average magnetic energy density evolution for the MHD, BHA, and MHDV models. The BHA model reaches a saturated stage with a magnetic field strength comparable to standard collisional non-viscous MHD models. In contrast, the MHDV model exhibits negligible growth. Converted to physical units, these values align with observed magnetic fields in the intra-cluster medium at approximately 10^{-6} G over 15 Gyr for collisional MHD and 9.8 Gyr for BHA.

Figure 2 compares three models: collisional MHD without viscosity (MHD), highly viscous collisional MHD (MHDV), and weakly collisional with isotropic and anisotropic viscosities (BHA). The latter includes the effects of firehose and mirror kinetic instabilities, setting limits on pressure anisotropy.

In the weakly collisional BHA model, initial assumptions about the viscosity coefficient helped to eliminate small-scale numerical fluctuations. Over time, viscosity self-consistently decreased to approximately $0.015\nu_0$ (where ν_0 is the initial value) as magnetic fields amplified to saturated values (Adduci Faria, Santos-Lima & de Gouveia Dal Pino, 2023).

3. Conclusions

Our investigation into magnetic field amplification in the intracluster medium (ICM) through the small-scale turbulent dynamo, using a weakly collisional, viscous, and resistive magnetohydrodynamics (MHD) approach, yielded insightful results. The inclusion of kinetic instabilities to regulate pressure anisotropy added depth to our study.

A notable contribution was the introduction of a self-consistent calculation for the evolution of viscosity transport coefficients, providing a dynamic understanding of their changes during magnetic field amplification in the weakly collisional MHD model (BHA).

Our findings demonstrated that the weakly collisional MHD model, specifically the BHA variant, aligns with observations of the Coma cluster. Despite comparable magnetic field amplification to collisional MHD models, the weakly collisional MHD model exhibited more realistic magnetic field and density distributions.

Importantly, the viscosity in the weakly collisional MHD model converged to approximately $\sim 0.015\nu$, consistent with the reduced viscosity observed in the Coma cluster. This convergence supports the credibility of our model in capturing the physical conditions of the Coma cluster.

Future research will expand on these insights, involving global 3D collisional high-resolution MHD simulations of individual clusters. This will facilitate a detailed exploration of cosmic ray propagation, allowing for a comprehensive comparison between weakly collisional and collisional scenarios.

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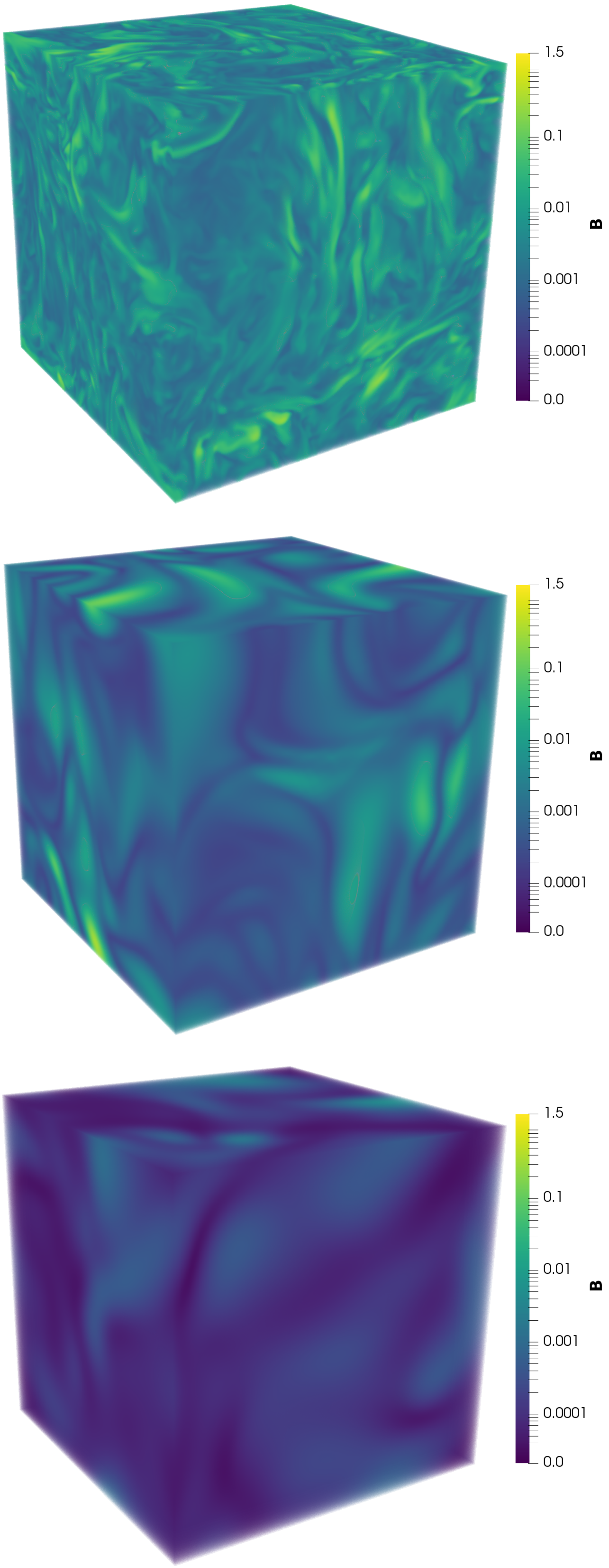

Figure 2. 3D maps of the magnetic field strength for the MHD (top row), BHA (middle row), and MHDV (bottom row) models.