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Evolution of Cosmic Magnetic Fields in Galaxy Clusters and the Connections with Cosmic Rays

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The origin of the turbulent magnetic fields is not yet fully understood in galaxy clusters, especially at the outskirts and surroundings. The existence of these background magnetic fields influences the propagation of cosmic rays (CRs), especially with energy $E < 10^{18}$ eV. Understanding the topology and intensity of these diffuse fields can also help to elucidate the origin of the diffuse high-energy emission of neutrinos and gamma rays. Therefore, it is possible to investigate the origin of these emissions if we reproduce as accurately as possible the magnetic fields present in clusters of galaxies. The reverse is also true. We have developed a model to describe more realistically the magnetic field amplification and evolution in the intracluster medium (ICM) based on weakly collisional 3D MHD simulations of turbulent dynamo evolution with forced turbulence. We have included effective Braginskii viscosity and resistivity as well as small scale kinetic instabilities which constrain the pressure anisotropy due to the low collisionality of this environment. The novelty of our model is the dynamic evolution of the viscosity coefficients, which is related to the back reaction of the increasing magnetic field on the plasma movements and the amplification and saturation of the dynamo process itself. We find that the magnetic fields amplify to values which are in agreement with those observed inside clusters. Also, the final viscosity decreases to values that align with the observations.

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1. Introduction

Leading open questions in high-energy astrophysics include the origin of ultra-high energy cosmic rays (UHECRs), which most likely originate in extragalactic sources [4, 12, 13, 22], and the diffuse emission of neutrinos and gamma rays. Observations of the energy fluxes of these three components suggest that they may have a common origin [37].

Cluster of galaxies are among the potential sources of CRs and very high energy diffuse emission. Their huge size ($\sim$ Mpc) and unique turbulent magnetic field distribution with strengths up to μG, favor long confinements of UHECRs. They consist of hundreds to thousands of gravitationally bound galaxies, having typical masses ranging from 10^{13} to 10^{15} solar masses, most of which are dark matter [10]. As mergers are the most energetic phenomena, releasing large amounts of energy ($\sim 10^{60} - 10^{64}$ erg) during a cluster crossover time ($\sim$ Gyr) [1, 10, 11, 19, 34, 35], a fraction of this energy can be channeled into turbulent motions that can amplify seed magnetic fields [6–8, 16, 20, 29–33] and into supra-thermal particles, accelerating them up to very high energies [34, 35]. The acceleration of the CRs is thus mainly due to shock waves and turbulence induced during the process of cluster formation or in mergers, but may also take place inside the cluster [3, 5, 9, 27]. Furthermore, relativistic particles can be also reaccelerated by similar processes in more diffuse regions of the intracluster medium (ICM), such as relics, halos, and filaments [1, 10, 19].

A particle with $E \lesssim 10^{17}$ eV can be confined for a time comparable to the age of the Universe, see, e.g., [17, 24, 25]. Hussain et al. [34, 35] found that clusters can contribute with 100% of the diffuse gamma-ray flux observed by Fermi-LAT above 100 GeV and with the diffuse background of neutrinos observed by the IceCube above 100 TeV, for cluster masses in the range $10^{13} \lesssim M/M_{\odot} \lesssim 10^{15}$, and CRs with spectral index around 2.3 and maximum energy in the range $E_{max} = 10^{16} - 10^{17}$ eV. The low resolution due to the large bunch of galaxies and redshifts analyzed in these previous works are a disadvantage of these models. In order to reproduce the observed fluxes more accurately in galaxy clusters we must provide a more accurate description of the origin and maintenance of magnetic fields inside clusters. These fields can have their growth explained by non-helical dynamo driven by the turbulence existing in the intra-cluster environment [e.g. 36]. However, this scenario is not described correctly in the fluid (i.e. collisional MHD) approximation [29], as the typical parameters of this environment are ion number density $n_i \sim 10^{-2}$ cm^{-3} and temperature $T \sim 10^7$ K [2], which yield an ion Coulomb collision rate $\nu_{ii} \approx 10^{-15}$ s^{-1} which is much smaller than the Larmor gyrofrequency of the order of 100 s^{-1}. In view of this, it is more correct to describe the ICM as a collisionless environment, or weakly collisional and the standard collisional MHD approximation for the description of turbulence and the amplification of the magnetic field of the dynamo must be revised, since we cannot neglect the kinetic aspects of the plasma.

As it has been shown for plasma under similar conditions, e.g. solar winds, the low collisionality together with the presence of a magnetic field generate anisotropies in the pressure. This, in turn, triggers electromagnetic instabilities [28] that introduce magnetic fluctuations, causing scattering of the ions and allowing the isotropization of their peculiar movements and the operation of the dynamo, through random shear [21]. Thus, it is possible to describe this collisionless environment with MHD-type models with some restrictions, which may lead to the stretching and growth of the field, [e.g., 7, 23, 29–31]. These theoretical results are supported by recent observations of the

Coma cluster turbulence made by the Chandra [14] telescope. The observed density fluctuations indicate the presence of much a smaller viscosity and viscous scale than that predicted by viscosity in the cluster that goes to scales smaller than what can be explained by the standard collisional fluid theory, assuming Spitzer viscosity. These results imply a larger effective collisional rate between particles in the plasma. These are probably due to the scattering of particles with microfluctuations caused by plasma instabilities, as we will investigate here.

2. Numerical Method and Results

We aim to explore magnetic field origin and maintenance via a turbulent dynamo in the weak collisional MHD cluster, in which way we may improve the models already developed by [7, 29].

We have developed 3D-MHD high-resolution numerical simulations of forced turbulence with an initial seed magnetic field, including Braginskii and isotropic viscosities, in order to follow the turbulent dynamo amplification in an environment with characteristics that suit a galaxy cluster. We have calculated self-consistently, for the first time, the time evolution of these transport coefficients as the magnetic fields grow in the system [33].

Fig. 1 compares a collisional MHD model without viscosity (MHD), with a highly viscous collisional MHD model (MHDV), and a weakly collisional model with isotropic and anisotropic viscosities (BHA). The latter includes the effects of the firehose and mirror kinetic instabilities that impose limits on the pressure anisotropy (see [33] for more details). Fig. 1 exhibits two-dimensional (2D) cuts of the central slice of the simulated box domain for the density, magnetic field, and velocity distributions of these three models.

Fig. 2 shows the average magnetic energy density evolution for the MHD, BHA, and MHDV models of Figure 1. The BHA model reaches the saturated stage with similar magnetic field strength as that of the standard collisional non-viscous MHD model, with intensities of the order of 10^{-2} code units, while the MHDV model shows negligible growth. This value, when converted to physical units, gives the strength of observed magnetic fields in the ICM of the order 10^{-6} G, in a time around 15 Gyr for the collisional MHD model, and 9.8 Gyr for the BHA model.

In our weakly collisional model BHA, we have assumed initial values for the viscosity coefficient large enough to overcome numerical fluctuations in the small scales which might kill the magnetic fields. As time evolves, this viscosity self-consistently decreases to a value which is $\sim 0.015\nu_0$ (where ν_0 is the initial value), at the same time that the magnetic fields amplify up to the saturated value depicted in Fig. 2 (see more details in [33].

3. Conclusions

We have explored the process of magnetic field amplification in the ICM through the small-scale turbulent dynamo, assuming a weakly collisional, viscous, and resistive MHD approach, where the pressure anisotropy is regulated by kinetic instabilities. We introduced a new approach by calculating self-consistently the evolution of the viscosity transport coefficients. We have found a magnetic field amplification similar to that of a collisional non-viscous MHD model, but with more realistic magnetic field and density distributions in intensity and coherent lengths. This weakly collisional MHD model is consistent with Coma cluster observations. Our final viscosity converges

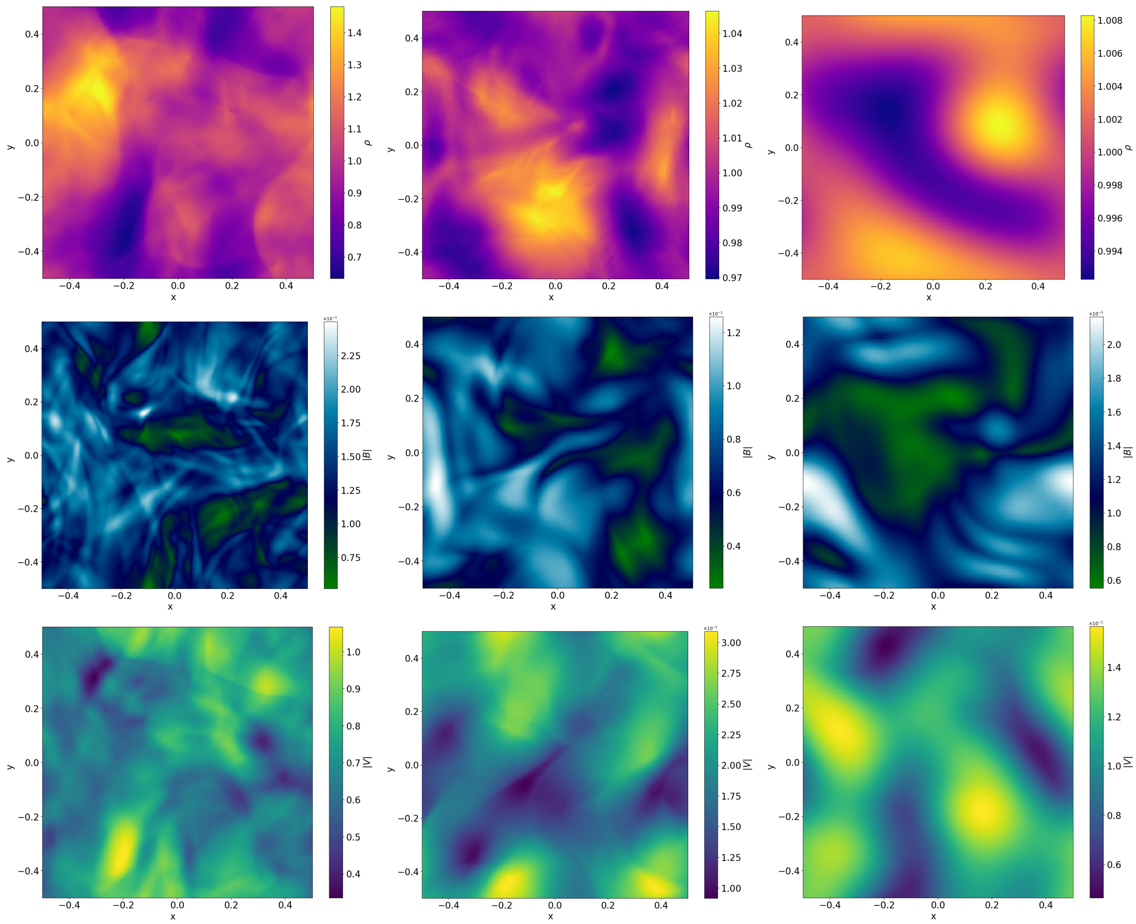

Figure 1: 2D maps of the central XY plane of the the 3D distributions of density (top row), magnetic field strength (middle row), and velocity (bottom row) for the collisional MHD (left column), the weakly collisional BHA (middle column), and collisional viscoues MHDV (right column) models.

to $\sim 0.015\nu_0$ which is compatible with the observed reduced viscosity of the Coma cluster measured by [14].

In forthcoming work, we will employ this weakly collisional MHD simulation as well as global 3D collisional high-resolution MHD simulations of individual clusters [e.g. 8] to perform the propagation and cascading of the CRs and then, compare the results in both scenarios. For the CR propagation we will employ the CRpropa 3 code [26], in order to derive, with a higher precision than ever, the fluxes of gamma-rays and neutrinos from individual clusters.

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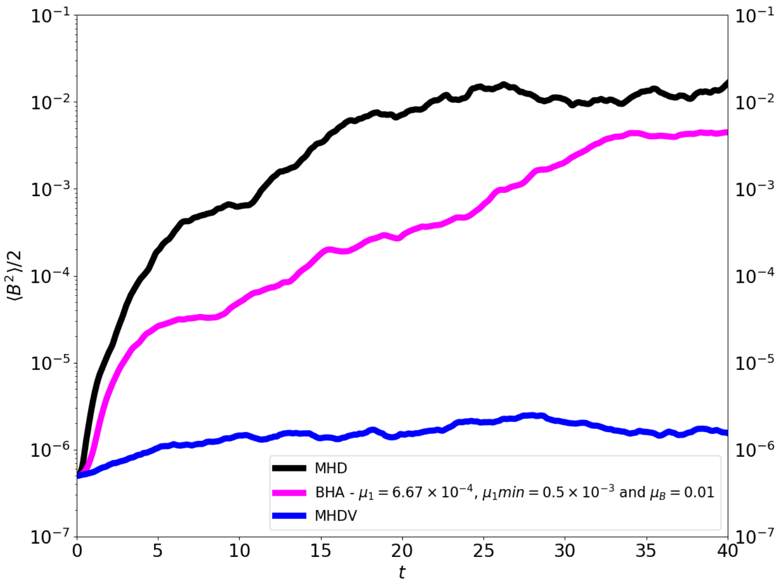

Figure 2: Evolution of the magnetic energy density for the collisional MHD (black), the weakly collisional BHA (magenta), and collisional viscoues MHDV (blue) models.The resolution employed in these models is 256^3.

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