The role of pressure anisotropy in the turbulent intracluster medium

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Abstract. In low-density plasma environments, such as the intracluster medium (ICM), the Larmour frequency is much larger than the ion-ion collision frequency. In such a case, the thermal pressure becomes anisotropic with respect to the magnetic field orientation and the evolution of the turbulent gas is more correctly described by a kinetic approach. A possible description of these collisionless scenarios is given by the so-called kinetic magnetohydrodynamic (KMHD) formalism, in which particles freely stream along the field lines, while moving with the field lines in the perpendicular direction. In this way a fluid-like behavior in the perpendicular plane is restored. In this work, we study fast growing magnetic fluctuations in the smallest scales which operate in the collisionless plasma that fills the ICM. In particular, we focus on the impact of a particular evolution of the pressure anisotropy and its implications for the turbulent dynamics of observables under the conditions prevailing in the ICM. We present results from numerical simulations and compare the results which those obtained using an MHD formalism.

1. Introduction

Magnetic fields play an important role in the development of large-scale structure in the Universe, and in recent years their presence in galaxy clusters has been unambiguously proved. According to the standard scenario of structure formation, galaxy clusters are built-up by gravitational merger of smaller units, such as groups and sub-clusters. They are composed of hundreds of galaxies in a Mpc-size region, and the Intra Cluster Medium (ICM) is filled with hot and rarefied gas, emitting in the soft-X ray domain through optically thin bremsstrahlung, magnetic fields and relativistic particles. Magnetic fields in the ICM are investigated through synchrotron emission of cluster-wide radio sources and from the study of the Rotation Measure of radio galaxies revealing the turbulent nature of these fields [1].

Moreover, the ICM is weakly magnetized and nearly collisionless, i.e., the gyro-frequency of both the electrons and the ions is much greater than the collision frequency (under these conditions the mean free path of ions is \( \approx 30 \) kpc in the hot ICM, [2]). Plasmas with such characteristics are known to present anisotropic pressures with respect to the magnetic field orientation (see e.g. [3–5]), whose imprints can survive for considerably long periods compared with the dynamical timescales of the system. The presence of mergers, accretion, active galactic nuclei (AGN), galactic winds and instabilities cause complex flows that generate
shocks, discontinuities and shear. All these processes lead to the generation of turbulence, which transports and amplifies the magnetic fields present [6].

Understanding the role and evolution of magnetic fields in clusters of galaxies is of significant importance for many questions including the origin of cluster magnetic fields, the interaction of AGN with the ICM, and physical processes operating within the ICM plasma. Which (if any) physical mechanism dominates in the ICM depends sensitively upon the magnitude and distribution of turbulence, which is currently only poorly understood [7].

The fact that the ICM is a low density environment makes the typical MHD description not reliable. As a consequence, these astrophysical plasmas are known to present anisotropic pressures with respect to the magnetic field orientation, which can be generated by several different processes, such as kinetic pressure of cosmic rays, supernovae explosions, stellar winds or anisotropic turbulent motions (see [5, 8]). On small scales, this turbulence is often expected to consist of highly anisotropic fluctuations with frequencies small compared to the ion cyclotron frequency. For a number of applications, the small scales are also collisionless, so a kinetic treatment of the turbulence is necessary, thus making a Kinetic MHD (KMHD) description more appropriate.

The purpose of this contribution is to show and discuss some recent advances in the KMHD description of the ICM plasma. After a brief discussion of the properties and applicability of the Chew-Golberger-Low (CGL) closure, we will describe the KMHD framework, which does include a pressure anisotropy in the description of plasma systems. We will then discuss the impact of this pressure anisotropy on the turbulent evolution of MHD observables, using as an illustrative case a particular variation in time for the pressure anisotropy ratio that reaches the isotropic, thus MHD, state. We will show numerical results corresponding to both developments and briefly discuss implications for this scenario.

2. The KMHD model

In order to determine the influence of pressure anisotropy on the turbulent evolution of the plasma in the ICM, in this work we use an MHD formalism with a Chew-Golberger-Low double-isothermal closure, the so called CGL closure [9], as implemented in the numerical code [8, 10–12]. As already mentioned, AGNs and the random motion of galaxies are the main sources of kinetic energy of the ICM plasma, and may be considered the main reason for the eventual pressure anisotropy observed in this medium. Because the kinetic energy injection is continuous the timescale of anisotropic radiative loses is much larger than the timescale associated with plasma instabilities, thus rendering the CGL closure applicable. Here, we will only consider this regime since we are interested in the large scale properties of the ICM for which this condition is satisfied.

In order to study the magnetic field dynamics in the ICM we simulate turbulence in a periodic box of 1 Mpc of size with $128^3$ grid points solving the set of double-isothermal KMHD equations in a conservative form given by the equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0$$  \hspace{1cm} (1)

$$\frac{\partial (\rho \vec{V})}{\partial t} + \nabla \cdot (\rho \vec{V} \vec{V} + (P + \frac{B^2}{8\pi})\hat{I} - \frac{1}{4\pi} \vec{B} \vec{B}) = f$$  \hspace{1cm} (2)

$$\frac{\partial \vec{B}}{\partial t} - \nabla \times (\vec{V} \times \vec{B}) = 0$$  \hspace{1cm} (3)

where the term $f$ is a random solenoidal large-scale driving force representing the turbulence driving, which is driven at wave scale $k = 2.5$, the scale injection in the model (2.5 times smaller than the size of the box), and $P = p_\perp \hat{I} + (p_\parallel - p_\perp)\hat{b}\hat{b}$ is the pressure tensor with components
$p_\parallel$ and $p_\perp$ parallel and perpendicular to the magnetic field direction ($b = \vec{B}/|\vec{B}|$) (see [8]). To close the system a CGL closure [9] is used, which yields:

$$\frac{\partial (\rho \vec{V})}{\partial t} + \nabla \cdot \left[ (a_\perp^2 \rho + \frac{B^2}{8\pi})I - (1 - \alpha)\vec{B}\vec{B} \right] = f$$

with $p_{\perp,\parallel} = a_{\perp,\parallel}^2 \rho$, where $a_{\perp,\parallel}$ are constants and represent speeds of sound along the perpendicular and parallel directions to the magnetic field, and $\alpha = (p_\parallel - p_\perp)/(2P_{mag})$, where $P_{mag} = \frac{B^2}{8\pi}$ is the magnetic pressure.

### 3. Numerical simulations

In this work, we do not take into account viscosity and diffusion in the equations. The scale at which the dissipation starts to act is defined by the numerical diffusivity of the scheme. The numerical integration of the system evolution governed by the KMHD equations were performed by using the second-order shock-capturing Godunov-scheme code and the time integration was done with the second-order Runge-Kutta method [8, 11–13].

The spatial coordinates are given in units of a typical length $L_0$. The density $\rho$ is normalized by a reference density $\rho_0$, and the velocity field $\vec{V}$ by a reference velocity $V_0$. The constant sound speed $c_s$ is also given in units of $V_0$, and the magnetic field $\vec{B}$ is measured in units of $V_0\sqrt{4\pi\rho_0}$. Time $t$ is measured in units of $L_0/V_0$.

To go one step further in the comparison between KMHD and MHD, the simulation includes a variation in time for the pressure anisotropy. The values for the parallel and perpendicular sound speeds are set equal to 1.0 and 3.0, respectively, keeping them constant until $t = 2.0$, when the turbulence may be considered as fully developed. From $t = 2.0$, there is a change of pressure anisotropy (reducing the perpendicular sound speed and increasing the parallel one) according to the following law $a_{\perp}(t) = a_{\perp 0} + (a_{\perp 0} - a_{\perp \infty})/(1 - t_{half})/t$, where $a_{\perp 0} = 1.0$ and $a_{\perp 0} = 3.0$ are the initial values of the sound speed, $a_{\perp \infty} = 1.5$ is the perpendicular sound speed in the limit $t_{\infty}$, and $t_{half} = 6.3$ is the time after which the perpendicular speed decays to the value of $(a_{\perp 0} + a_{\perp \infty})/2$. As the parallel sound speed also changes, the total square sound speed, $a_{\parallel}^2(t) + 2a_{\perp}^2(t)$, is kept constant and equal to the initial value, i.e. the total pressure is kept constant and there is an interplay between the parallel and perpendicular pressures. In this way, we change the pressure anisotropy in time starting from a low value ($\sim 0.3$) and ending up close to the isotropic value, thus reaching the MHD regime. The chosen final value of the anisotropy parameter reaches the value $\sim 0.98$ corresponding to the value in the ICM that is expected from theoretical considerations [14–16]. Figure 1 shows the evolution of the anisotropy parameter.

We also consider the conditions prevailing in the ICM: superalfvenic and subsonic regime with $B_0x = 0.1$ as the initial magnetic field.

#### 3.1. Results

The results obtained for the evolution of the physical observables, namely velocity, magnetic field and density show strong differences between the KMHD and standard MHD models. It is interesting to note that kinetic instabilities play a role in the evolution of turbulence under the particular conditions taken into account. In figures 2-7, we present the density, velocity intensity and magnetic field intensity in the central slices of the computational domain obtained for the KMHD model (first line), as well as for the MHD model (second line) for comparison at $t=2$ when the turbulence can be considered as fully developed and the pressure anisotropy rate starts changing. It is seen that for the three quantities that we consider the structures obtained in KMHD are significantly smaller than the ones obtained in MHD. Moreover, density, magnetic field intensity and velocity fluctuations are slightly smaller in the isotropic case.
It is interesting to quantify the impact of the pressure anisotropy change on the evolution of the three observables mentioned above. To this end, we show in figures 8-13 density, velocity intensity and magnetic field intensity in the central slices of the computational domain obtained for the KMHD model (first line), as well as for the MHD model (second line) at $t=5$. Comparing the results obtained at both times it is seen that the size of the structures in KMHD evolved
towards their MHD counterpart. This is reasonable because at \( t=5 \) the pressure becomes almost isotropic in the KMHD model. However some differences are still observable due to the action of mirror instabilities during the evolution of the plasma. The mirror instability is responsible for changes in the velocity distribution by slowing the gas and reducing the effective sonic Mach number (see also [8]). Another feature that can be observed from figures 8-13 is that the number of structures that develop in KMHD is considerably larger than that obtained in MHD. Our results show that even at late times important imprints of the pressure anisotropy are clearly observed, thus indicating that for a more accurate description of the evolution of this plasma the effects of pressure anisotropy should be included in the simulations.

![Figure 8](image1.png)  ![Figure 9](image2.png)  ![Figure 10](image3.png)

**Figure 8.** Idem figure 2 at \( t=5 \).

**Figure 9.** Idem figure 3 at \( t=5 \).

**Figure 10.** Idem figure 4 at \( t=5 \).

![Figure 11](image4.png)  ![Figure 12](image5.png)  ![Figure 13](image6.png)

**Figure 11.** Idem figure 5 at \( t=5 \).

**Figure 12.** Idem figure 6 at \( t=5 \).

**Figure 13.** Idem figure 7 at \( t=5 \).

The correlation between different scales can be characterized by the energy spectrum, whose evolution is shown in figure 14 for both formalisms. It is seen that the spectrum in KMHD evolves toward its MHD counterpart. At late times, the slope of the spectra of both formalisms is similar. Besides providing crucial information on scale correlations of the plasma, the analysis of the simulated energy spectra is also important because the slope of the spectra is one of the quantities that can be indirectly determined by observations using synthetic rotation maps with the observed polarization coming from radio sources in the ICM [17]. The results of previous numerical works based on MHD [18] seems to favor a power law spectrum with a \( k \sim -5/3 \) slope, providing support for the use of this value in the construction of synthetic rotation maps (see e.g. [1]). In figure 14 we have added the Kolmogorov slope of \(-5/3\) (black line). We note that our results are preliminary and, therefore, further studies are still required to determine the spectrum slope more precisely.
4. Conclusions
As an example of the application of the KMHD with a variable $a_{\parallel}/a_{\perp}$, we compare this formalism with the MHD one performing turbulence simulations for astrophysical conditions, namely those prevailing in the ICM, under a Godunov scheme. We find that pressure anisotropy changes have significant impact on the turbulent properties of nearly collisionless magnetized plasmas, such as the ICM. Particularly, the three observables presented here (plasma density, magnetic field and velocity field) show a much more granular structure in the KMHD formalism. The differences can be understood from the action of the mirror instabilities which are fully developed for values of the pressure anisotropies studied here ($a_{\parallel}/a_{\perp} \leq 2$) (see figures 2-13).

The development of kinetic instabilities, such as these, which arise in the KMHD regime from pressure anisotropy, causes the accumulation of energy at the smaller scales. This may have important consequences on the formation of large scale structures in the intergalactic medium (IGM) and the ICM, and also in the dynamo amplification of cosmic magnetic fields, e.g. [6, 8, 19]. A more detailed study of the relation between pressure anisotropy and structure formation in the ICM and IGM is currently in progress [6, 20].

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