MAGNETICALLY CONSTRICTED PLASMAS IN CLUSTERS OF GALAXIES

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ABSTRACT We have studied the role of magnetic fields on the evolution and dynamics of Intracuster Medium (ICM) through magnetohydrodynamics simulations. We expect that the magnetic fields that are anchored in the gravitational potential of galaxies can be considerably twisted, braided and stretched due to the motion of galaxies, and reconnect and heat the plasma trapped in the tangled fields. To this end, we have performed a simple calculation of two counter-rotating galactic disks in an ambient magnetic field parallel to the rotation axes of the disks. Through the rotation of the galactic disks, toroidal magnetic fields are produced leading to the amplification of the initial fields. The evolution creates an intermittent plasma in the intergalactic medium with hot plasma surrounded by cooler gas regions, thus causing a two-phase medium and nonuniform temperature in the ICM.

INTRODUCTION

There have been many recent studies on the nature of the Intracuster Medium in both the optical and X-ray regime (e.g. Davis et al. 1995). In most clusters, the ICM smoothly fills the cluster potential with some evidence of multiphase nature especially near the central galaxies. Some clusters also show evidence of a recent merger of smaller substructures. Although the level of substructure in clusters of galaxies can be a direct result of the underlying cosmological model, the ICM is also significantly influenced by local galaxy evolution and interaction, such as gravitational clustering, shocks, and jet ejection of gas from galaxies into the ICM. There is also accumulated evidence that magnetic fields of at least $\sim 1\mu G$ exist in most clusters of galaxies (Kronberg 1994). Stronger fields up to $100\mu G$ with a coherence length of $l \sim 10 - 100\text{kpc}$ have been measured in cluster cores (Taylor & Perley 1993, Ge & Owen 1993). We believe that due to local galaxy motions, the intergalactic magnetic field can be vio-
lently stretched, tangled and amplified (Tajima 1995, Makishima 1994, Tajima & Mineshige 1991). The fields can also be further amplified by compression and inflow as is suggested in cooling flow clusters. In addition, due to large magnetic Reynolds number in ICM, the plasma is expected to be strongly turbulent which can cause the magnetic pressure to build up. Therefore, we contend that magnetic fields can play a significant role in shaping the structure and heating of the ICM. In this paper we explore this effect by performing a set of magneto-hydrodynamic simulations. The numerical method and initial conditions are described below.

NUMERICAL METHOD AND INITIAL CONDITIONS

We carry out a simple calculation of two counter-rotating galactic disks penetrated by magnetic field lines parallel to the axis of rotation of the disks. The disks rotate differentially in the outer portion, and as a rigid body near the center (bulge). We impose axial symmetry and thus perfect alignment of the two disk axes with precisely the same angular speeds. We have neglected self-gravity of the disks and instead assumed that the gravitational potential is produced by a point mass located at the center of the disk. However, we believe that these assumptions are not essential and will not disallow generalization. We have numerically solved the basic equations of conservation of mass, momentum and energy and the Faraday’s Law in MHD approximation by using a modified Lax-Wendroff scheme (Rubin & Burstein 1967) with artificial viscosity (Richtmyer & Morton 1967) in a 2.5D cylindrical geometry. Extensive tests of the code are summarized in Shibata (1983). Boundary conditions are chosen to be periodic in the top and bottom surfaces. On the axis \((r = 0)\), we have adopted symmetric boundary conditions for \( \rho, p, v_z, B_z \) and antisymmetric for \( v_r, v_\phi, B_r, B_\phi \). At \( r = R_{\text{max}} \), we have chosen free boundary condition where the mass and waves can go through freely. The effects of this are minimal. The total number of mesh points are \((N_r \times N_z) = (128 \times 162)\).

RESULTS

The main observed features from our simulations are as follows: (1) By rotation of the galactic disks, an axial current is induced between the two disks, which amounts to strong toroidal magnetic fields in the intracluster plasma. As a result, the axial interconnecting magnetic fields are enhanced from their initial values. (2) The plasma trapped in the magnetic field lines is squeezed and its density at certain spots is enhanced. Its temperature is also raised. Since our model currently does not allow 3D reconnection of magnetic field lines, the actual temperature as a result of tangled magnetic field lines and their reconnection would be much higher as demonstrated in Zaidman & Tajima (1989). (Therefore in this respect the present model is incomplete (or even inadequate) due to the neglect of 3D magnetic reconnection.) (3) As the disks rotate and magnetic
fields get twisted, polar flows are emanated from each disk. These flows cause pockets of dense plasma regions and when these flows collide, they create shocks and other structures. (4) The evolution created an intermittent plasma between the two galactic disks (Figure 1). The hot gas constricted by magnetic fields will essentially remain hot, surrounded by cooler gas producing a multiphase medium. As a result, an X-ray luminosity much higher than the initial value is obtained in the intracluster plasma (Figure 2).

We conclude from our study that the presence of magnetic fields in the intracluster medium can influence the evolution and structure of ICM. Even with rather high values of the initial plasma $\beta$ (the plasma pressure divided by the magnetic pressure) such as 200, a plasma with a lot lower $\beta$ value (such as near unity) can be created in the intracluster space through the present process. The evolution yields a nonuniform temperature along with a two-phase medium in the ICM.

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Figure 1: Intermittent structure in the Intergalactic Medium: Shaded contour plot of gas density illustrates hot gas filaments, trapped in tangled magnetic field lines, occupy the space between the two galactic disks. The gray scale bar indicates contour levels for log $\rho$. The two bright spots signify the location of the disks.

Figure 2: Luminosity of the intergalactic gas as a function of elapsed time. An increase by more than a factor of 2 is observed for a case with initial plasma $\beta$ of $\sim 20$. Time is in units of free fall time ($v_\phi/r$).