Magnetic Fields on the Dynamics of the ICM

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Abstract. Could the discrepancies found in the determination of mass in clusters of galaxies, from gravitational lensing data and from X-rays observations, be consequence of the standard description of the ICM, in which it is assumed hydrostatic equilibrium maintained by thermal pressure? In analogy to the interstellar medium of the Galaxy, it is expected a non-thermal term of pressure, which contains contributions of magnetic fields. We follow the evolution of the ICM, considering a term of magnetic pressure, aiming at answering the question whether or not these discrepancies can be explained via non-thermal terms of pressure. Our results suggest that the magnetic pressure could only affect the dynamics of the ICM on scales as small as \(\sim 1\) kpc. These results are compared to the observations of large and small scale magnetic fields and we are successful at reproducing the available data.

1. Introduction

Since the work of Loeb & Mao (1994), the possibility of explaining the discrepancies on mass determinations, found by Miralda-Escudé & Babul (1994), via non-thermal pressure support has been widely discussed. The discrepancy arises from the two most promising techniques to obtain clusters of galaxies masses. On one hand, the determination of masses in clusters of galaxies, via X-ray data, is based on the hypothesis that the ICM is in hydrostatic equilibrium with the gravitational potential, using the radial profiles of density and temperature (Nulsen & Böhringer 1995). On the other hand, gravitational lensing measures the projected surface density of matter, a method which makes no assumptions on the dynamical state of the gravitating matter (Miralda-Escudé & Babul 1994; Smail et al. 1997).

In clusters with diffuse radio emission X-ray observations can give a lower limit to the strength of the magnetic field (the 3K background photons scattering off the relativistic electrons produces the diffuse X-ray emission). Typically, this limit is \(B \geq 0.1\) \(\mu\)G (Rephaeli et al. 1987) on scales of \(\sim 1\) Mpc. Such a kind of detection of clusters magnetic fields leads, using ROSAT PSPC data and also 327MHz radio map of Abell 85, to an estimate of \((0.95 \pm .10)\) \(\mu\)G (Bagchi et al.
2. Evolution of the ICM with Magnetic Pressure

Using a spherically symmetric finite-difference scheme Eulerian code, the evolution of the intracluster gas is obtained by solving the hydrodynamic equations of mass, momentum and energy conservation (see Friaça 1993), coupled to the state equation for a fully ionized gas with 10% helium by number. The mass distribution, \( M(r) \), is due to the contribution of the X-rays emitting gas plus the cluster collisionless matter (which is the sum of the contributions of galaxies and dark matter – the latter being dominant) following \( \rho_d(r) = \rho_c (1 + r^2 / a^2)^{-3/2} \), \( \rho_c \) and \( a \) (the cluster core radius) are related to the line-of-sight velocity dispersion, \( \sigma \), by \( 9\sigma^2 = 4\pi G a^2 \rho_c \). The total pressure \( p_t \) is the sum of thermal and magnetic pressure, e.g. \( p_t = p + p_B \). The constraints to the magnetic pressure come from observations, from which \( p_B = B^2 / 8\pi \approx 4 \times 10^{-14} \text{erg cm}^{-3} \text{s}^{-1} \) (cf. Bagchi et al. 1998) for a diffuse field located at \( \sim 700h_{50}^{-1} \text{kpc} \) from the cluster center.

The initial conditions for the gas are an isothermal atmosphere \( (T_0 = 10^7 \text{K}) \) with 30% solar abundance and density distribution following that of the cluster dark matter. The evolution is followed until the age of 14 Gyr. We assume: frozen-in field; spherical symmetry for the flow and the cluster itself; and that at \( r > r_c \) (the cooling radius), the magnetic field is isotropic, i.e., \( B_r^2 = B_0^2 / 2 = B^2 / 3 \) and \( l_r = l_t = l \) (where \( B_r \) and \( B_t \) are the radial and transversal components of the magnetic field \( B \) and \( l_r \) and \( l_t \) are the coherence length of the large-scale field in the radial and transverse directions). In order to calculate \( B_r \) and \( B_t \) for \( r < r_c \), we modified the calculation of the magnetic field of Soker & Sarazin (1990) by considering an inhomogeneous cooling flow (i.e. \( \dot{M}_i \neq \dot{M} \) varies with \( r \)). Therefore, the two components of the field are then given by \( D / Dt(B_r^2 r^4 \dot{M}^{-2}) = 0 \) and \( D / Dt(B_t^2 r^2 u^2 \dot{M}^{-1}) = 0 \). In our models it is admitted that the reference radius is the cooling radius \( r_c \). In fact, we modify the geometry of the field when and where the cooling time comes to be less than \( 10^{10} \text{yr} \). Therefore, our condition to assume a non-isotropic field is \( t_{\text{cool}} \equiv 3k_B T / 2\mu m_H n(T) \rho \gtrsim 10^{10} \text{yr} \).

3. Models and Results

There are four parameters to consider in each one of the models: \( \sigma = 1000 \text{ km/s} \), the cluster velocity dispersion; \( \rho_0 = 1.5 \times 10^{-28} \text{g cm}^{-3} \), the initial average mass
density of the gas; $a = 250$ kpc, the cluster core radius; and $\beta_0 = 10^{-2}$ (model A), $10^{-3}$ (model B), the initial magnetic to thermal pressure ratio.

First of all, the evolution we follow here is characteristic of cooling flow clusters and in this scenario we discuss the evolution of the basic thermodynamics parameters. Considering the overall characteristics of our models, we compare the present models with Peres et al. (1998) deprojection results (based on ROSAT observations), pointing out that the central cooling time here adopted as our cooling flow criterion, e.g. $t_{\text{cool}} \gtrsim 10^{10}$ yr, is typical for a fraction between 70% and 90% of their sample. This allows us to conclude that our models, which present cooling flows since the cluster has the age of $\sim 7 - 9$ Gyr, are typical for their sample.

Figures 1 shows the evolution of density, temperature and magnetic field strength, for model A, from which the presence of the cooling flow on later stages of the ICM evolution and at inner regions, is remarkable, if one notices the steep gradients of these quantities. We chose two values of magnetic field strength for the comparison of the results, on small and large scales (see figure). Our results for the magnetic field strength and also for the pressure, on large and small scales, are in agreement to the observed ones.

Obviously the magnetic pressure (Figure 2) is compatible with the magnetic field intensities and may be compared to the values determined by, for instance, Bagchi et al. (1998), $p_B = B^2/8\pi \simeq 4 \times 10^{-14}$ erg cm$^{-3}$ s$^{-1}$, at scales of 700 kpc, in the present time. From the analysis of the magnetic pressures expected from our models it is clear that they agree, as well as the magnetic field strength, with the observations.

The present models are in many aspects similar to the one of Soker & Sarazin (1990). However there are two important differences between our model and theirs: i) they take into account only small-scale magnetic field effects; and ii) they consider the magnetic field isotropic even in the inner regions of the cooling flow. As a matter of fact the magnetic pressure reaches equipartition
only at radius as small as $\gtrsim 1$ kpc (model A) or $\gtrsim 0.5$ kpc (model B), because the central increase of the $\beta$ ratio is moderate in our model. Our more realistic description of the field geometry is crucial. This implies that the effect of the magnetic pressure on the total pressure of the intracluster medium, even on regions as inner as few kpc, is small. Evolutive models for the intracluster medium, with a realistic calculation of the geometry and amplification of the magnetic fields, like the one presented here, indicate that magnetic pressure does not affect the hydrostatic equilibrium, except in the innermost regions, i.e. $r \lesssim 1$ kpc (see Gonçalves & Friaça 1998 for a more detailed discussion).

Acknowledgments. We would like to thank the Brazilian agencies FAPESP (97/05246-3 and 98/03639-0), CNPq and Pronex/FINEP (41.96.0908.00) for support.

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