Does magnetic pressure affect the ICM dynamics?

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**ABSTRACT**

A possible discrepancy found in the determination of mass from gravitational lensing data, and from X-rays observations, has been largely discussed in the latest years. For instance, Miralda-Escudé & Babul (1995) have found that the mass estimate derived from gravitational lensing can be as much as a factor of 2$^{-2.5}$ larger than the mass estimate derived from analysis of the X-rays observations. Another important discrepancy related to these data is that X-ray imaging, with some spectral resolution, suggest that the mass distribution of the gravitating matter, mostly dark matter, has a central cusp, or at least that the dark matter is more centrally condensed than the X-ray-emitting gas, and also with respect to the galaxy distribution (Eyles et al. 1991), at variance to what is expected from the most accepted models of formation of large scale structure. Could these discrepancies 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, turbulence and cosmic rays. 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. Our models are constrained by the observations of large and small scale fields and we are successful at reproducing available data, for both Faraday rotation limits and inverse Compton limits for the magnetic fields. In our calculations the radius (from the cluster center) in which magnetic pressure reaches equipartition is smaller than radii derived in previous works. The crucial difference in our models comes from our more realistic treatment of the magnetic field geometry, and from the consideration of a sink term in the cooling flow which reduces the amplification of the field strength during the inflow. In addition the magnetic field calculations are changed after the cooling flow has been formed.

**Key words:** Galaxies: clusters – Intracluster medium – Cooling flows – X-rays: galaxies – Gravitational lensing – Magnetic fields

1 INTRODUCTION

Since the work of Loeb & Mao (1994), the possibility of explaining the discrepancies on mass determinations, found by Miralda-Escudé & Babul (1995), via non-thermal pressure support has been widely discussed (see also Wu & Fang 1996, 1997; Wu et al. 1998). 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. There are uncertainties in the determination of temperature profiles, particularly for radii $> 1$ Mpc, and for most systems only a mean emission-weighted X-ray temperature is available (radial temperature profiles are available only for a few clusters e.g., Allen & Fabian 1994; 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 (Fort & Mellier 1994; Miralda-Escudé & Babul 1995; Smail et al. 1997).

One can find in the literature some attempts to resolve the discrepancy between X-ray and gravitational lensing mass measurements of clusters of galaxies. For instance, Allen (1998) studied in detail a sample of 13 galaxy clusters (including cooling flows, intermediate and non-cooling flows systems) with the goal of comparing X-ray and lensing mass
measurements. His conclusions pointed out that, at least for cooling flows systems, being more relaxed systems, this discrepancy is completed resolved, and therefore, non-thermal pressures can be discarded in these systems.

The magnetic field of the ICM can be obtained via Faraday rotation, due to the effect of magnetic field on the polarized radio emission from the cluster or the background radio sources. The polarization plane of linearly polarized radiation is rotated during the passage through a magnetized plasma. The angle of rotation is \( \phi = (RM) \lambda^2 \), where \( RM \) is the rotation measure and \( \lambda \) the radiation wavelength (Sarazin 1992, for a review). In clusters with diffuse radio emission, X-ray observations can give a lower limit to the strength of the magnetic field. Typically, this limit is \( B \geq 0.1 \mu G \) (Rephaeli et al. 1987) on scales of \( \sim 1 \) Mpc. In the case of Faraday rotation the information obtained is the upper limit on the intensity of the field, and the measured values are \( RM \leq 100 \text{ rad/m}^2 \), that is more or less consistent with a intracluster field of \( B \sim 1 \mu G \), with a coherence length of \( l_B \leq 10 \) kpc. This strength of the magnetic field corresponds to a ratio of magnetic to gas pressure of \( p_B/p_{gas} \lesssim 10^{-3} \), implying that \( B \) does not influence the cluster dynamics (at least on large scales).

At inner regions, of the cooling flow clusters, the magnetic fields are expected to be amplified due to the gas compression (Soker & Sarazin 1990). If they are frozen in the mass flow flux, and if this flux is homogeneous and spherically symmetric, \( B \propto r^{-1} \) and \( RM \propto r^{-3} \), \( (p_B \propto r^{-2} \text{ and the gas pressure increases slowly}) \). Even in this case \( p_B \) reaches equipartition at a radius \( r_B \) of \( r_B \sim 1 \) kpc \((B \propto \lambda^{1/2} (M/100 \text{ M}_\odot \text{ yr}^{-1})^{1/4}) \). In these inner regions many sources with very strong Faraday rotations were observed, in which the rotation measure can reach values of \( RM \sim 4000 \text{ rad/m}^2 \) (radio sources associated with the central galaxies of the clusters with very strong cooling flows (M87/Virgo, Cyg A, Hydra A, 3C 295, A1795)), implying, \( B \gtrsim 10 \mu G \) at \( l_B \sim 1 \) kpc (Taylor & Perley 1993; Ge & Owen 1993, 1994). These observations strongly suggest that the Faraday rotation is created by magnetic fields within the cooling flow clusters.

Another promising method to estimate the cluster scale magnetic field, as cited above, is the detection of co-spatial inverse Compton X-ray emission with the synchrotron plasma emission (the 3 K background photons scattering off the relativistic electrons can produce a diffuse X-ray emission) (Rephaeli & Gruber 1988). Therefore, this method provides limits on the cluster scale magnetic fields, in addition of limits on the non-thermal amount of X-ray emission (or even on the relativistic electrons energy) in galaxy clusters. Such a kind of detection of clusters magnetic fields leads, using ROSAT PSPC data and also 327 MHz radio map of Abell 85 (a cooling flow cluster, with a central dominant cD galaxy and about 100 M\(_\odot\)/yr), to an estimate of \( 0.95 \pm 0.10 \) \( \mu G \) (Bagchi et al. 1998). However, even non-cooling flows clusters present this diffuse, relic radio source which can be used to estimate magnetic field strength. For instance Ensslin & Biermann (1998) studied limits on the Coma cluster magnetic field strength, using this multifrequency observations. They showed that the central magnetic field limit is \( B > 0.3 \mu G \). Others have determined the strength of the magnetic field for Coma cluster, using different techniques and obtaining similar values: \( B \lesssim 1.2 \mu G \) (Lieu et al. 1996); \( B > 0.4 \mu G \) (Sreekumar et al. 1996). For the same cluster (Coma), but using Faraday rotation measure, Feretti et al. (1995) estimated magnetic fields of \( 6.0 \mu G \) (at scales of 1 kpc), and of \( 1.7 \mu G \) (at scales of 10 kpc) was estimated by Kim et al. (1990).

The above scenario allow us conclude that for both methods the observational resolution of the telescope limits the detection of smaller scales magnetic fields, implying that at scales smaller than 1 kpc the magnetic field strength can be higher (Ensslin et al. 1997). Another point to be noted is that Faraday rotation measures always gives values higher than inverse Compton/CBM measures. Anyway, these fields are present in the ICM and therefore justify the such a kind of study we present here. Other theoretical works concerning the magnetic pressure on the ICM are available (for instance Soker & Sarazin 1990; Tribble 1993; Zoabi et al. 1996) and we briefly compare our results with those obtained by these authors.

Our goal in this paper is trying to answer the question whether or not magnetic support can be relevant in cooling flow clusters, using a more realistic treatment of the magnetic field geometric evolution. The scope of the paper is the following: in Section 2 we present the hydrodynamical equations and the method applied for their solution; Section 3 describes our models and results compared to the available observations; and in Section 4 we discuss our results in the light of others obtained in previous works, as well our main conclusions.

## 2 EVOLUTION OF THE ICM WITH MAGNETIC PRESSURE

The evolution of the intracluster gas is obtained by solving the hydrodynamic equations of mass, momentum and energy conservation:

\[
\frac{\partial \rho}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} (r^2 \rho u) = -\omega \rho \\
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} = -\frac{1}{\rho} \frac{\partial p_t}{\partial r} - \frac{GM(r)}{r^2} \\
\frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial r} = \frac{\rho_0}{\rho^2} \left( \frac{\partial \rho}{\partial t} + u \frac{\partial \rho}{\partial r} \right) - \Lambda \rho
\]

where \( u, \rho, p_t, U \) are the gas velocity, density, total pressure and the specific internal energy. The equation of state relates \( U \) and the temperature,

\[
U \geq \frac{3 k_B T}{2 m_H}
\]

\( (k_B \) is the Boltzmann’s constant, \( m_H \) is the hydrogen atom mass and \( \mu = 0.62 \) is the mean molecular weight of 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), i.e., \( M(r) = M_g(r) + M_{cl}(r) \). \( M_{cl}(r) \) follows

\[
\rho_{cl}(r) = \rho_0 \left( 1 + \frac{r^2}{a^2} \right)^{-\frac{3}{2}}
\]
in which \( \rho_0 \) and \( a \) (the cluster core radius) are related to \( \sigma \) (the line-of-sight velocity dispersion) via: \( 9\sigma^2 = 4\pi G a^2 \rho_0 \).

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 \( \sim 700 b_{22}^{1/3} \text{ kpc from the cluster center}. \) Along this paper we will use mostly the ratio between magnetic and thermal pressures, or the \( \beta \)-parameter, \( \beta = p_B / p \).

The sink term \( \omega \rho \) in the mass equation describes the removal of mass from the gas flow by thermal instabilities. The importance of the gas removal was studied in detail by friaca (1993) following the \( q \)-description described by white & Sarazin (1987). The sink is particularly important when one searches for a steady state solution of the cooling flow without an implausible huge accumulation of mass at the center. In fact, the condensations formed by the sink will probably give rise to stars, planetary bodies or cold dense clouds which in turn will constitute a halo surrounding the central dominant galaxy. We assume isobaric removal, so that the sink does not introduce any additional term in the energy equation. Summing up the physics contained in this term one can say that the specific mass removal rate is \( \omega = q t_c \), where the denominator is the instantaneous isobaric cooling time, such that the removal efficiency \( q \) relates the cooling time to the growth time scale of the thermal instability in the cooling flow. We assume \( q \) between 1.0 and 1.5, which are the \( q \)-values found to be more consistent with the observations (friaca 1993).

The cooling function adopted \( \Lambda(T) \) is the cooling rate per unit volume. Since there is no ionization equilibrium for temperatures lower than \( 10^6 \) K, we adopt a non-equilibrium cooling function for the gas at \( T < 10^6 \) K (the recombination time of important ions is longer than the cooling time at these temperatures). The cooling function was calculated with the atomic database of the photoionization code AANGABA (Gruenwald & Viegas 1992). The adopted abundances are sub-solar as appropriate for the ICM (Edge & Stewart 1991; Fabian 1994; Grevesse & Anders 1989).

Despite the presence of steep temperature gradients we did not consider thermal conduction in our models. This can be justified using the fact that on a global scale cooling flow clusters contain cooler gas near the center and hotter gas further out. Therefore, the presence of cooling flows is itself a proof that thermal conduction effect is, at least, reduced in the ICM. Models show that thermal conduction would erase the observed density and temperature gradients in cooling flows, unless it is inhibited (see, for instance, friaca 1986; david & Bregman 1989). It is well known that even weak magnetic field, if it is tangled, can inhibit the thermal conduction perpendicular to the field lines. More recently it has been argued that electromagnetic instabilities driven by temperature gradients (or electric currents in other situations) also can cause this inhibition in cooling flows (Pistinner et al. 1996), even for non-tangled field lines.

A spherically symmetric Eulerian code is employed for the calculations, which are solved via the finite-difference scheme based on Cloutman (1980). The grid points are spaced logarithmically, with a grid of 100 cells, with the first being 50 pc wide. The innermost cell edge is located at 100 pc and the outer boundary at twice the tidal radius of the cluster. The artificial viscosity for the treatment of the shocks follows the formulation of Tscharnuter & Winkler (1979) based on the Navier-Stokes equation. The outer boundary conditions on pressure and density are derived by including an outer fictitious cell, the density and pressure in which are obtained from extrapolation of power laws over the radius fitted to the five outermost real cells. The inner boundary conditions are adjusted according to whether inflow (velocity at the inner boundary is extrapolated from the velocities at the innermost cell edges) or outflow (velocity is set zero) prevails locally. The initial conditions for the gas are an isothermal atmosphere \( (T_0 = 10^7 \text{ K}) \) with 30% solar abundances and density distribution following that of the cluster dark matter. The evolution is followed until the age of 14 Gyr.

The initial \( \beta \) value used here was derived from the magnetic field observations (using, for instance, bagchi et al. 1998; ge & Owen 1993, 1994; enslin & Biermann 1998; ruy & Biermann 1998). We assume: frozen-in field; spherical symmetry for the flow and the cluster itself; and that at \( r > r_c \) (the cooling radius, see below), the magnetic field is isotropic, i.e.,

\[
B_r^2 = B_t^2 / 2 = B_t^2 / 3
\]

and \( l_r = l_t \equiv l \) (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. \( M_t \neq M \) varies with \( r \)). Therefore, the two components of the field are then given by

\[
\frac{D}{Dt} \left( B_r^2 r^4 \dot{M}^{-2} \right) = 0
\]

and

\[
\frac{D}{Dt} \left( B_t^2 r^2 a^2 \dot{M}^{-1} \right) = 0.
\]

In our models we take as reference radius 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 \( 10^{10} \text{ yr} \) (usually adopted as the condition for the development of a cooling flow). Therefore, our condition to assume a non-isotropic field is \( t_{cool} \equiv 3k_B T / 2u m_H \Lambda(T) \rho \leq 10^{10} \text{ yr} \). After the formation of the cooling flow, in the inner regions of the ICM, the magnetic field geometry is changed, following the enhancement of the radial component of the field, due to the enhancement of the density.

3 MODELS AND RESULTS

In this section we present the results of our models. There are four parameters to consider in each one of the models: \( \sigma \), the cluster velocity dispersion; \( \rho_0 \), the initial average mass density of the gas; \( a \), the cluster core radius; and \( \beta_0 \), the initial magnetic to thermal pressure ratio. We adopted the removal efficiency \( q = 1.5 \).

The most important results of our models are shown on figures we describe below, for which we assume: \( \sigma = 1000 \text{ km s}^{-1} \) and \( a = 250 \text{ kpc} \). 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 will compare the results with the very recent study based on ROSAT observations of the cores of clusters of galaxies, by Peres et al. (1998), focusing on cooling flows in a X-rays flux-limited sample (containing the brightest 55 clusters over the sky in the 2–10 keV band). Comparing the present models with Peres et al. (1998) deprojection results, we see that the central cooling time here adopted as our cooling flow criterion, e.g. $t_{cool} \lesssim 10^{10}$ yr, is typical for a fraction between 70% and 90% of their sample. They also discuss briefly the cooling flow age, remembering that in hierarchical scenarios for the formation of structures in the Universe, clusters are formed by smaller substructures by mergers, and therefore the estimation of the cooling flows ages (and the cluster ages themselves) is complicated. Anyway they determine the fraction of cooling flow clusters in their sample considering a factor of two in the ages and concluding that the fraction do not vary that much (from 13 Gyr to 6 Gyr, the fraction varies from 70% to 65%). This allow us conclude that our models, which present cooling flows since the cluster has the age of $\sim 7 - 9$ Gyr, are typical for their sample. As a matter of fact, the time in which the cooling flow structure is formed depends strongly on the initial density we adopted. For models with $\rho_0 = 1.25 \times 10^{-28}$ g cm$^{-3}$ it rises on $\sim 9$ Gyr, while the models with $\rho_0 = 1.5 \times 10^{-28}$ g cm$^{-3}$ have it formed on $\sim 7$ Gyr. We will come back to this point later while analyzing the field anisotropy.

The characteristics of our models are summarized using four typical set of initial parameters, and discussing some details which came up of the study of a larger grid of parameters. Therefore, each model is characterized by its position in the $(\rho_0, \beta_0)$ parameter space: model I ($\rho_0 = 1.5 \times 10^{-28}$ g cm$^{-3}$, $\beta_0 = 10^{-2}$); model II ($\rho_0 = 1.5 \times 10^{-28}$ g cm$^{-3}$, $\beta_0 = 10^{-3}$); model III ($\rho_0 = 1.25 \times 10^{-28}$ g cm$^{-3}$, $\beta_0 = 10^{-2}$); and model IV ($\rho_0 = 1.25 \times 10^{-28}$ g cm$^{-3}$, $\beta_0 = 10^{-3}$).

Figure 1 shows the evolution of density and temperature profiles corresponding to model I, 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. In order to better understand how the magnetic field geometry is modified after the cooling flow formation, e.g., after the steepness on the temperature and density gradients, we follow the evolution of the degree of anisotropy, using the concepts previously defined on Section 2, concerning the geometry of the magnetic field. Hereafter we called ‘degree of anisotropy’ the ratio $B_l/B_r$, noting that for the isotropic case it results $\sqrt{2}$ and the more anisotropic the field geometry the smaller is this ratio. Therefore, we present on Figure 2 the evolution of the degree of anisotropy since $\sim 3.3$ Gyr, comparing models I and III, in which one can see, clearly, that the anisotropy begins decreasing on earlier times for models with higher $\rho_0$ (model I) than for the ones with lower values of $\rho_0$ (model III). From Figure 2 we are allowed to conclude that the degree of anisotropy can be seen as a sensor of the presence of the cooling flow. In another words, the change in the degree of anisotropy can be used as another criterion to indicate the epoch, on the ICM evolution, in which the cooling flow appear.

These results can also be discussed in the light of some observational works in which the limits to the magnetic field strength on large and small scales of the cooling flow clusters are given. Following such a kind of observations, as previously seen in the introduction section, we chose two values of magnetic field strength derived by the authors below. The first one is presented in Bagchi et al. (1998) who estimated, from inverse Compton X-ray emission with the synchrotron emission plasma, a cluster-scale (700 kpc) magnetic field strength of $(0.95 \pm 0.10)$ $\mu$G for Abell 85 (a cooling flow cluster with a central dominant cD galaxy and $M \simeq 100$ $M_\odot/yr$). The second one is presented in two papers of Ge & Owen (1993, 1994), in which they present and discuss rotation measures and the related intensity of the magnetic field, giving a range of this intensity at scales of 10 kpc. Therefore, our results for the magnetic field strength and also for pressures, on large and small scales, are compared to the chosen observed ones, in Figures 3 and 4. Reminding that the time on which the cooling flow arises is closely related to $\rho_0$, one can expect distinct results on the evolution of the field intensity from, for instance, model I to model III. However this evolution can be better explained comparing model I (Figure 3) to model II (Figure 4), since these two models have the same initial density but distinct $\beta_0$.  

![Figure 1. Evolution of the density and temperature profiles. Curves represent early and late stages of the ICM evolution, as labeled, for model I. Noting the steep gradients of these quantities, i.e., the presence of the cooling flow, at inner regions of the cluster, on later stages of the ICM evolution.](image-url)
Our best model, in terms of the magnetic field strength compared with observations, is model I ($\rho_0 = 1.5 \times 10^{-28}$ g cm$^{-3}$, $\beta_0 = 10^{-2}$). From Figure 3 it is possible to see that on scales of 700 kpc the magnetic field expected for the model is higher than the observed one (considering, of course, the profile correspondent to redshift zero, or evolution times on the order of 13 – 14 Gyr), while on scales of 10 kpc the model gives a value lower than the observed one. Meanwhile, at least on scales of 700 kpc, the situation is inverted if one takes a look on Figure 4, for which $\rho_0 = 1.5 \times 10^{-28}$ g cm$^{-3}$, but $\beta_0 = 10^{-3}$. Given the uncertainties characteristics of the observations, we can say that our models are in agreement with the magnetic field estimations available.

On Figures 5 and 6 we show the magnetic and thermal pressures evolution, or in another words, $\beta$-evolution, for models I and II respectively, on later times of the ICM evolution, in order to analyze when and where magnetic pressure reaches equipartition. Obviously the magnetic pressure 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, on 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. Here again model I appears being the best one, with ($\beta_0 = 10^{-2}$), but the values expected from model II are not far away from the observed ones as well. Noting also that magnetic pressure and/or magnetic intensity does not change very much after 12 Gyr, for both cases. Results presented on Figures 3 - 6 would indicate that we should adopt an intermediate initial value for $\beta$ (like $\beta_0 = 5 \times 10^{-3}$) in order to obtain a magnetic field intensity in better agreement with the observations, at least on scales of 700 kpc. Nevertheless such an exercise should not solve the match of models and observations on smaller scales, since $\beta_0 \simeq 5 \times 10^{-3}$ should decrease magnetic pressure on scales of 10 kpc, at the present time, as a result of the present modelling assumptions (see Figure 4).

Other proposals for the amplification of the magnetic field in the center of the cooling flow clusters are: i) rotational driven mechanisms, in which the twisting of the magnetic flux tubes and/or the operation of fast $\alpha - \omega$ dynamo are the responsible for the increase of the magnetic strength (Godon et al. 1998); ii) turbulence induced am-
plification (Eilek 1990; Mathews & Brighenti 1997). However, these processes can not account for the strong magnetic fields observed in the center regions, confirming the expectations previously discussed by authors like Goldshmidt & Rephaeli (1993) and Carvalho (1994).

4 DISCUSSIONS AND CONCLUSIONS
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 homogenous cooling flow. Since we consider inhomogeneous cooling flow (i.e. $\dot{M}$ decreases with decreasing $r$) the amplification of $B$ is smaller in our models. As a matter of fact the magnetic pressure reaches equipartition only at radius as small as $\gtrsim 1$ kpc (model I) or $\gtrsim 0.5$ kpc (model II), 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 intrachannel medium, even on regions as inner as few kpc, is small. Tribble (1993) studying the formation of radio haloes in cooling flow clusters from the point of view of the cluster evolution via mergers, suggested typical magnetic field strengths of $\sim 1 \mu$G. In addition, Zoabi et al. (1996), studying a completely different characteristic of the ICM (magnetic fields on the support of X-rays clumps and filaments), adopted the usually assumed magnetic to pressure ratio, at few scales of 10 – 20 kpc, of 0.1, and following a simple geometry of the field in which it is amplified by the radial inflow, this ratio become $\sim 1$ at

$\sim 5$ kpc. Again our results are more or less compatible with the above ones (for the cluster scale magnetic field), but the equipartition condition is reached at smaller scales.

There are a number of papers discussing heating processes on the inner part of the cooling flow clusters, in particular mechanisms to power the emission lines of optical filaments, which use the magnetic energy transformed in optical emission via magnetic reconnection (Jafelice & Friaça...
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Figure 7. $\beta$ profiles on 14 Gyr for models I - IV. The profiles are quite similar, except for the fact that models with $\beta_0 = 10^{-3}$ have final $\beta$-values lower. From the figure is also clear that the equipartition condition occurs at outer radii for higher $\beta_0$ models, and that anyway this condition is reached only on radii smaller than $\sim 1$ kpc.

Figure 8. Profiles on 14 Gyr for models I - IV. The profiles are quite similar, except for the fact that models with $\beta_0 = 10^{-3}$ have final $\beta$-values lower. From the figure is also clear that the equipartition condition occurs at outer radii for higher $\beta_0$ models, and that anyway this condition is reached only on radii smaller than $\sim 1$ kpc.

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REFERENCES

Allen S.W., 1998, MNRAS, 296, 392
Allen S.W., Fabian A.C., 1994, MNRAS, 269, 409
Bagchi J., Pislar V., Lima Neto G.B., 1998, MNRAS, 296, L23
Carvalho J.C., 1994, A&A, 281, 641
Cloutman L.D., 1980, Los Alamos Report, LA - 8452 - MS
David L.P., Bregman J.N., 1989, ApJ, 337, 97
Edge A.C., Stewart A.C., 1991, MNRAS, 252, 414
Eilek J., 1990, in Clusters of Galaxies, ed. M.J. Fitchett, W.R. Goldshmidt O., & Rephaeli Y., 1993, ApJ, 411, 518
Ensslin T.A., 1997, A&A, 324, 449
Friaça A.C.S., 1986, A&A, 164, 6
Friaça A.C.S., 1993, A&A, 269, 145
Friaça A.C.S., Gonçalves D.R., Jafelice L.C., Jatenco-Pereira V., Opher R., 1997, A&A, 324, 449
Ge J.P., Owen F.N., 1993, ApJ, 411, 518
Grevesse N., Anders E., 1989, in Waddington C.J., ed., Cosmic Abundances of Matter. AIP, New York, p.183
Gruenwald R.B., Viegas S.M., 1992, ApJS, 78, 153
Heckman T.M., Baum S.A., Van Breugel W.J.M., McCarthy P., 1989, ApJ, 338, 48
Jafelice L.C., Friaça A.C.S., 1996, MNRAS, 280, 438
Kim J.P., Butcher J.A., Stewart G.C., Tanaka Y., 1990, ApJ, 335, 29
Lieu R. et al. 1996, Science, 274, 1335
Loeb A., Mao S., 1994, ApJ, 435, L109
Loewenstein M., 1994, ApJ, 431, 91
Mathews W.G., Brighenti F., 1997, ApJ, 488, 595
Miralda-Escudé J., Babul A., 1995, ApJ, 449, 18
Nulsen P.E.J., Böhringer H., 1995, MNRAS, 274, 1093
Peres C.B., et al., 1998, MNRAS, 298, 416
Pistinner S., Levinson A., Eichler D., 1996, ApJ, 467, 162
Rephaeli Y., Gruber D.E., 1988, ApJ, 333, 133
Rephaeli Y., Gruber D.E., Rothschild R.E., 1987, ApJ, 320, 139
Ryu D., Biermann P.L., 1998, A&A, 335, 19
Smail I., Ellis R.E., Dressler A., Couch W.J., Oemler A., Sharples R.M., Bucther H., 1997, ApJ, 479, 70
Sarazin C.L., 1992, in “Clusters and Superclusters of Galaxies”, ed. A.C. Fabian, NATO ASI Series, p. 131
Soker N., Sarazin C.L., 1990, ApJ, 348, 73
Sreekumar et al., 1996, ApJ, 464, 628
Taylor G.B., Perley R.A., 1993, ApJ, 416, 554
Tribble P.C., 1993, MNRAS, 263, 31
Tscharnuter W.M., Winkler K.H., 1979, Comp. Phys. Comm., 18, 171
White III R.E., Sarazin C.L., 1987, ApJ, 318, 612
Wu X.P., Fang L.Z., 1996, ApJ, 467, L45
Wu X.P., Fang L.Z., 1997, ApJ, 483, 62
Wu X.P., Chieuh T., Fang L.Z., Xue Y.J., 1998, MNRAS, 301, 861
Zoabi E., Soker N., Reveg O., 1996, ApJ, 460, 244