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MAGNETIC FIELDS AND TURBULENCES IN CLUSTERS OF GALAXIES

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RESUMEN

Los campos magnéticos y la turbulencia se encuentran entre los componentes no térmicos más importantes en el medio intra-cluster (ICM por sus siglas en inglés). Se estima que su contribución sea de al menos un 10% de la energía térmica total. Estudiamos la influencia de campos magnéticos a gran escala agregando el componente de la presión magnética a la ecuación de equilibiro hidrostático. Así mismo, mediante un método perturbativo derivamos un nuevo perfil de densidad para el ICM, que toma en cuenta la magnitud del campo magnético. Las densidades que obtenemos varían por hasta un 20% en el núcleo de los cúmulos. De manera similar parametrizamos la turbulencia en el ICM suponiendo un componente a gran escala, generada por la historia de fusión, y un componente a escalas pequeñas, que depende de la distancia al centro del cúmulo, el cual se debe al movimiento de las galaxias en el centro del cúmulo. Estudiamos las dos contribuciones como función de los parámetros del modelo y señalamos su diferencia funcional.

ABSTRACT

Magnetic fields and turbulences are among the most important non-thermal components in the intra-cluster medium (ICM), estimated to be 10% or more of the total thermal energy. We study the influence of large-scale magnetic fields by completing the hydrostatic equilibrium equation with the magnetic field pressure component. In a perturbative approach we derive a new gas density profile for the ICM which takes into account the magnetic field strength. The new gas density varies by up to 20% in the cluster core. Similarly, we parametrize the ICM turbulences assuming a uniform large-scale component generated by the cluster merger history and a radius dependent small-scale component from the motion of galaxies in the cluster core. We study the two contributions as a function of the model parameters and we point out their functional difference.

Key Words: galaxies: clusters — galaxies: magnetic fields — turbulences

1. INTRODUCTION

Clusters of galaxies are the largest gravitationally bound objects in the Universe, with a typical total mass of $\mathcal{M} \sim 10^{15} M_{\odot}$, a temperature $T \sim 10^7 - 10^8$ K, a gas number density $n_g \sim 10^{-2} - 10^{-4}$ cm^{-3} and an extension of $1-2$ Mpc. Although often assumed to be virialized and in hydrostatic equilibrium, XMM and Chandra X-ray observations reveal an increasing number of substructures and dynamical merging processes in the ICM. X-ray observations of the Coma cluster core (Schuecker et al. 2004) show turbulences with Gaussian pressure fluctuations and a Kolmogorov-like power spectrum over relevant scales. The energy fraction is estimated to be 10–20% of the thermal energy. Magnetic fields have been the source of extended studies. Faraday rotation measurements in the radio (e.g. Clarke et al. 2001) have been obtained towards a fair sample of clusters of galaxies. Magnetic field power spectra have also been developed as a diagnostic tool in Vogt & Ensslin (2003). The different methods typically derive a central magnetic field strength $B_0 \sim 1 - 10\,\mu G$ and a (large-scale) magnetic field coherence length of $5 - 20$ kpc. Very little is known about small-scale tangled magnetic fields. Based on these observations, magnetic fields and turbulences (possibly together with cosmic rays) are estimated to account for about 20% of the total cluster thermal energy budget and they are believed to be the major non-thermal cluster components. In the following we aim at deriving new cluster gas density profiles based on the magnetic field an turbulence contributions.

2. ANALYTICAL MODEL: A PHENOMENOLOGICAL APPROACH

Our goal is to build a simple analytical but realistic model in order to make predictions which can be tested against observations. The model should further depend on only a few parameters which can be calibrated by observations and which have a clear physical interpretation. A hydrodynamical treatment for magnetic fields and turbulences is analytically impossible. We therefore choose a thermodynamical approach where both magnetic fields

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and turbulences are handled as additional pressure components. Strictly speaking, this requires local thermodynamical equilibrium among the different constituents, as it is discussed in detail in Stothers (2002). We further assume homogeneous isotropic pressure contributions (on large enough scales), which simplifies the problem to a spherical symmetrical case. Any cluster radial gas pressure profile $P_g(r)$, resulting from a hydrostatic equilibrium, is then completed with:

$$P_g(r) \rightarrow P_g(r) + P_B(r) + P_T(r), \tag{1}$$

where $P_B(r)$ and $P_T(r)$ are the additional magnetic field and turbulence radial pressure contributions, respectively. We also assume:

$$P_B(r), P_T(r) \ll P_g(r), \tag{2}$$

which justifies the use of perturbative methods in the following calculations. Observations and numerical simulations (Norman & Bryan 1999; Dolag et al. 2001) support this assumption.

The hydrostatic equilibrium equation for a spherical symmetrical cluster with an isothermal temperature ($T_g(r) \equiv T_g$) and an ideal gas law ($P_g(r) = n_g(r)kT_g$, n_g: gas number density, k: Boltzmann constant) is:

$$\frac{1}{\rho_g(r)} \cdot \frac{d\,P_g(r)}{d\,r} = -\frac{G\,\mathcal{M}(r)}{r^2}, \tag{3}$$

where $\mathcal{M}$ is the total cluster gravitating mass within a radius r including dark matter and the ICM. G is the gravitational constant, $\rho_g(r)$ is the ICM gas density profile. In order to build our model, we need observationally motivated profiles for $P_B(r)$ and $P_T(r)$.

2.1. *Additional magnetic field pressure*

The case with an additional magnetic field pressure support term, $P_g(r) \rightarrow P_g(r) + P_B(r)$ has been studied in Koch et al. (2003) with:

$$P_B(r) = B(r)^2/(8\pi) \quad \text{and} \quad B(r) \sim \rho_g(r)^\gamma, \tag{4}$$

where γ typically is between 0.6 and 0.9. This magnetic field profile $B(r)$ is motivated by both simulations and observations (Dolag et al. 2001). Expressing the total mass $\mathcal{M}$ in equation (3) once with $P_g(r)$ only and once with $P_g(r) + P_B(r)$, and then setting $\mathcal{M}$ equal for both cases, leads to an integro-differential equation for a new modified gas profile $\rho_B(r)$ in the presence of the additional pressure support $P_B(r)$. Assuming an equal total mass $\mathcal{M}$ (dominating dark matter component) and specifying the boundary condition with a vanishing magnetic field strength at the cluster limiting radius r_l leads to:

$$\rho_B(r) = \rho_g(r) \left[1 + \frac{1}{\rho_{B,0}^{\prime 2\gamma}} \cdot \frac{B_0^2}{8\pi} \cdot \frac{\mu m_{\mathrm{H}}}{kT_g} \int_r^{r_l} \frac{(\rho_B^{2\gamma})'(\tilde{r})}{\rho_g(\tilde{r})} d\tilde{r} \right], \tag{5}$$

where μ, m_{H} and B_0 are the mean molecular weight, the hydrogen mass and the central magnetic field strength, respectively. In a perturbative solution, $\rho_B(r)$ is finally expressed as a function of the unperturbed profile $\rho_g(r) = \rho_{g,0} \cdot f(r)$:

$$\rho_B(r) \approx \rho_{g,0} \cdot f(r) \left[1 + \frac{B_0^2}{8\pi} \cdot \frac{1}{n_{g,0} kT_g} \int_r^{r_l} \frac{(f^{2\gamma})'(\tilde{r})}{f(\tilde{r})} d\tilde{r} \right], \tag{6}$$

where $\rho_{g,0}$ is the cluster central gas density.

2.2. *Additional turbulence pressure*

In a similar approach, $P_g(r) \rightarrow P_g(r) + P_T(r)$, the additional support pressure from turbulences is modeled. Motivated by earlier studies, Brunetti et al. (2001); Kuo et al. (2003), we adopt the following parametrization for the turbulence pressure profile:

$$P_T(r) = a_0 + a_1 \left(1 + (\frac{r}{r_{G,c}})^2 \right)^{-3\beta_G/2}, \tag{7}$$

where the first term on the right hand side accounts for a uniform turbulent background from the cluster merger history and the second term represents a radius dependent contribution from the motion of galaxies. $r_{G,c}$ and β_G are the core radius and β-parameter for a β-profile[2] galaxy density. The two contributions are calibrated with the two parameters a_0 and a_1. An identical functional form to equation (7) has been used by Brunetti et al. (2001); Kuo et al. (2003) in order to model the time-independent electron re-acceleration due to turbulences in clusters. The relativistic electrons are originally injected by merger shocks. Since this model has reasonably well reproduced the radio and hard X-ray excess emission in the Coma cluster, we adopt it here for the turbulence pressure profile. The same argument as in the previous section holds, which then also leads[3] to another integro-differential equation for the gas

[2]The commonly used β-profile for the ICM gas density is written as: $\rho_g(r) = \rho_{g,0} \left(1 + \left(\frac{r}{r_c} \right)^2 \right)^{-3/2\beta}$, where $\rho_{g,0}$, r_c and β are the central gas density, the core radius and the β-parameter, respectively.

[3]In deriving equations (6) and (8) we have set, without loss of generality, $T_B \equiv T_g$ and $T_T \equiv T_g$.

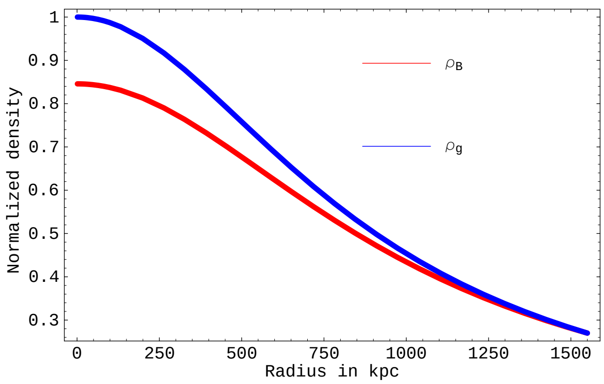

Fig. 1. The modified profile $\rho_B(r)$ compared to the β-profile $\rho_g(r)$ for A119. The profiles are normalized by the central gas density $\rho_{g,0}$. For an isothermal β-model, the cluster parameters are: $\beta_{\rm Fit} = 0.56$, $\gamma = 0.9$, $B_0 = 7.5\,\mu G$, $T_g = 5.92 \cdot 10^7$ K, $n_{g,0} = 2.593 \cdot 10^{-3}$ cm^{-3}, $r_c = 800$ kpc, $r_l = 1550$ kpc, $\mu = 0.63$.

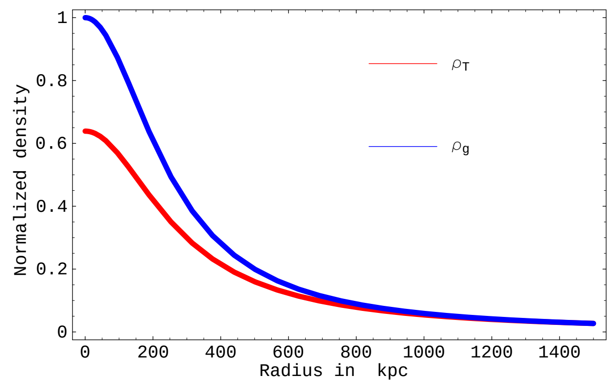

Fig. 2. The original gas β-profile $\rho_g(r)$ and the turbulence modified profile $\rho_T(r)$ with a 10% central turbulence pressure term. The profiles are normalized by the central gas density $\rho_{g,0}$. Standard cluster parameters have been adopted: $\beta = 2/3$, $T_g = 2 \cdot 10^7$ K, $n_{g,0} = 1.2 \cdot 10^{-2}$ cm^{-3}, $r_c = 250$ kpc, $r_l = 1500$ kpc.

profile modified by the turbulence pressure support:

$$\begin{aligned}\rho_T(r) &= \rho_g(r) \cdot \frac{1}{\rho_{g,0}} \left[\frac{\rho_{g,0}}{\rho_g(r_l)} (\rho_g(r_l) + a_0) \right. \\ &\quad \left. - \frac{\mu\, m_H}{k\, T_g} \int\limits_r^{r_l} \frac{P_T'(\tilde{r})}{\rho_g(\tilde{r})}\, d\tilde{r} \right] . \qquad (8)\end{aligned}$$

We limit the discussion here to the case with the boundary condition $a_0 \equiv 0$ which yields:

$$\rho_T(r) = \rho_{g,0} \cdot f(r) \left[1 - \frac{1}{n_{g,0}\, k\, T_g} \int\limits_r^{r_l} \frac{P_T'(\tilde{r})}{\rho_g(\tilde{r})}\, d\tilde{r} \right] . \quad (9)$$

3. RESULTS

The modified and original gas profiles in the presence of additional magnetic field pressure are illustrated for the cluster A119 in Figure 1, where the cluster parameters following Mohr et al. (1999) and Dolag et al. (2001) have been used.

As an immediate consequence of $P_B(r)$ we note: The modified gas density profile $\rho_B(r)$ is not following a β-profile any more. In particular, the central gas density is lower, proportional to B_0^2, which consequently leads to weaker X-ray and Sunyaev-Zeldovich effect (SZE) fluxes. In Koch et al. (2003) the integrated SZE is estimated to be reduced by up to 15% for a central magnetic field strength of up to $10\,\mu G$.

Similarly, Figure 2 shows the modified profile $\rho_T(r)$ for a 10% central turbulence pressure term, $a_1 = 0.1 \cdot n_g k T_g$, for a standard cluster. Turbulence contributions at this level are expected from numerical simulations (Norman & Bryan 1999) and have

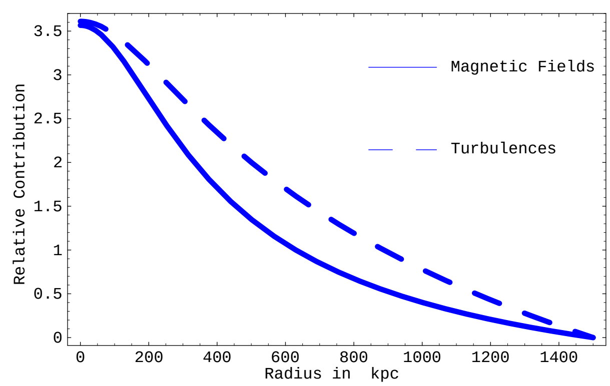

Fig. 3. The functional difference between the magnetic field and the turbulence contributions for a standard cluster ($\gamma = 0.7$, $r_c = 250$ kpc, $r_l = 1500$ kpc) with the same central pressure contributions, $B_0^2/(8\pi) \equiv a_1$, and a vanishing contribution towards the cluster outer region. Shown are the relative contributions given by the equations (12) and (13) with their numerical constants set equal and neglected.

also been reported from first X-ray observations of the Coma cluster core (Schuecker et al. 2004).

It is worthwhile investigating the difference between the magnetic field and the turbulence contributions. Although both reduce the original gas density profile $\rho_g(r)$, there is a functional difference in between them, resulting in different contribution levels at different radii. This originates from the different exponential dependences of P_B and P_T on the underlying gas and galaxy density profiles, respectively. Figure 3 illustrates this for a standard cluster ($\gamma = 0.7$, $r_c = 250$ kpc, $r_l = 1500$ kpc) with identical

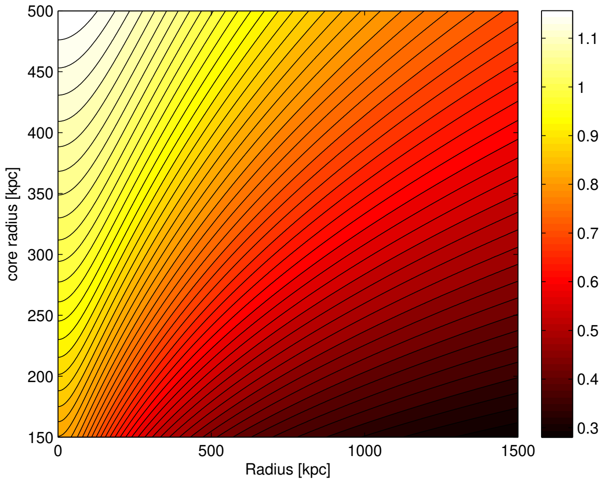

Fig. 4. The ratio P_B/P_T for equal central pressure contributions as a function of radius and cluster core radius for $\gamma = 0.7$ and $r_l = 1500$ kpc.

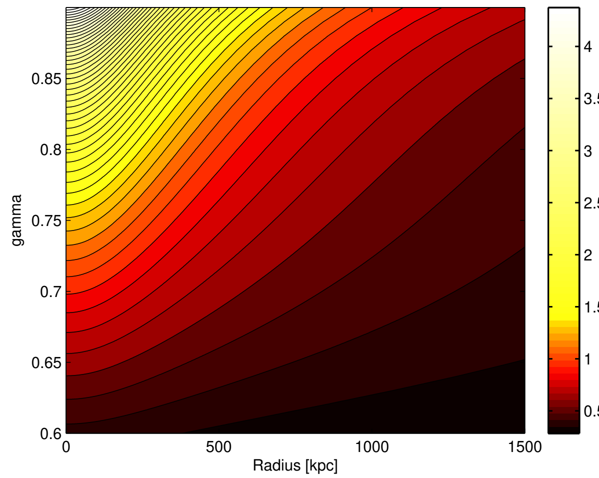

Fig. 5. The ratio P_B/P_T for equal central pressure contributions as a function of radius and γ for $r_c = 250$ kpc and $r_l = 1500$ kpc.

central pressure contributions, $B_0^2/(8\pi) \equiv a_1$, and a vanishing effect towards the cluster outer region.

In order to further analyze the functional difference, we write the new profiles $\rho_B(r)$ and $\rho_T(r)$ from the equations (6) and (9) as:

$$\rho_B = \rho_g(r)[1 + h_B(r)], \quad (10)$$
$$\rho_T = \rho_g(r)[1 + h_T(r)], \quad (11)$$

where the perturbation terms $h_B(r)$ and $h_T(r)$ can be analytically expressed, assuming a β-profile for $\rho_g(r)$ and assuming $\beta_G \equiv \beta$, $r_{c,G} \equiv r_c$ for the galaxy density profile:

$$h_B = \frac{B_0^2/(8\pi)}{n_{g,0}\, k\, T_g} \cdot \frac{2\gamma}{\gamma - 1} \times \times \left(\left[1 + \frac{r_l^2}{r_c^2}\right]^{1-2\gamma} - \left[1 + \frac{r^2}{r_c^2}\right]^{1-2\gamma} \right), \quad (12)$$

$$h_T = \frac{a_1}{n_{g,0}\, k\, T_g} \ln\left(\frac{r_c^2 + r_l^2}{r_c^2 + r^2}\right). \quad (13)$$

The contour plots in the Figures 4 and 5 show the ratio P_B/P_T as a function of different combinations of parameters.

4. CONCLUSION

We propose an analytical model where additional, observationally motivated, magnetic field and turbulence pressure terms are added in the hydrostatic equilibrium equation. The new equilibrium gas density profiles are solved in a perturbative approach assuming a known unperturbed gas profile as an input. Although the discussion here has been limited to the β-profile, this is valid for any gas profile. Both the magnetic field and the turbulence pressure terms lead to a smaller central gas density and a generally shallower profile in the cluster core. At different radii their individual contributions depend on the exact parameters. Nevertheless, there is a trend (Figures 4 and 5) that the magnetic field term dominates the turbulence pressure term in the cluster core, whereas the turbulence term gains towards the cluster outer region. With larger γ the magnetic field is the dominant pressure contribution out to larger radii.

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