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Hydrostatic equilibrium of a porous intracluster medium: implications for mass fraction and X-ray luminosity

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ABSTRACT

The presence of dilute hot cavities in the intracluster medium (ICM) at the cores of clusters of galaxies changes the relation between gas temperature and its X-ray emission properties. Using the hydrostatic equations of a porous medium, we solve for the ICM density for a given temperature as a function of the filling factor of dilute bubbles. We find that at a given temperature, the core X-ray luminosity increases with the filling factor. If the frequency of active galactic nuclei (AGN) in clusters were higher in the past, then the filling factor could correspondingly be significant, with implications for the cluster scaling relations at high redshifts. This is especially important for the core properties, including the temperature–luminosity (L_X–T) relation and estimates of the core gas mass. The results imply an epoch-dependent sensitivity of the L_X–T relation in the core to the porosity of the ICM. Detection of such an effect would give new insights into AGN feedback.

Key words: gravitation – cosmology: observations – cosmology: theory – dark matter – large-scale structure of Universe.

1 INTRODUCTION

X-ray observations of the intracluster medium (ICM) of massive clusters indicate the presence of cavities seen as depressions in the X-ray surface brightness (e.g. Boehringer et al. 1993; Fabian et al. 2000; McNamara et al. 2000; Bîrzan et al. 2004). These cavities or bubbles are believed to have been generated by active galactic nucleus (AGN) activity of central galaxies and possibly other galaxies in the cluster (Nusser, Silk & Babul 2006; Best et al. 2007; Martini, Mulchaey & Kelson 2007).

The observed properties of the X-ray emitting gas in clusters of galaxies provide strong constraints on the thermodynamic properties of the ICM. The most satisfactory model which accounts for the observed self-similar scaling properties of outer regions invokes galaxy formation by cooling gas (Suginohara & Ostriker 1998; Lewis et al. 2000; Pearce et al. 2000; Davé, Katz & Weinberg 2002; Ettori et al. 2004; Nagai, Kravtsov & Vikhlinin 2007), but this, in turn, leads to a major puzzle. Approximately twice as much cold gas is predicted as compared with the mass in stars. AGN feedback in the core can resolve this problem (e.g. Quilis, Bower & Balogh 2001; Babul et al. 2002; Dalla Vecchia et al. 2004; Ruszkowski, Brüggen & Begelman 2004; Brüggen, Ruszkowski & Hallman 2005; Roychowdhury, Ruszkowski & Nath 2005; Voit & Donahue 2005; Nusser, Silk & Babul 2006; Peterson & Fabian 2006; Sijacki & Springel 2006; Cattaneo & Teyssier 2007; McNamara & Nulsen 2007). Related discussions of the role of AGN heating of the ICM are given in semi-analytic modelling of galaxy formation (Croton et al. 2005; Bower et al. 2006). We point out here that AGN feedback drives porosity in the ICM and modifies the hydrostatic properties of cluster cores. A higher AGN activity in the past leads to a redshift evolution of the scaling relations.

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2 THE HYDROSTATIC EQUATION FOR THE AMBIENT MEDIUM

A formalism for following the evolution of bubbles statistically has been developed in Nusser et al. (2006). In this formalism, the hot dilute bubbles and the rest of the ICM are a two-fluid system that is best described as a single fluid which we term the *ambient medium*. The representation in terms of a single medium is applicable only if local pressure equilibrium between the bubbles and the residual ICM is established. Hereafter, quantities related to the ambient medium, the bubbles and the residual ICM (gas outside bubbles) are denoted by the subscripts, a, b and I, respectively. Suppose that the volume filling factor of bubbles at r is $F(r)$. The ambient density, ρ_a, at position r, is defined as

$$\rho_a = (1 - F)\rho_I + F\rho_b, \tag{1}$$

in terms of the density inside bubbles, ρ_b, and the density of the ICM, ρ_I, also at r. The local ambient energy, u_a, per unit mass is

$$u_a = \frac{(1 - F)\rho_I u_I + F\rho_b u_b}{\rho_a}, \tag{2}$$

where u_b and u_I are the energy per unit mass of the material inside the bubbles and of the residual ICM. If the pressure, p, is $p = (\gamma - 1)u\rho$ for both the ICM and the material inside the bubbles, the equation of state of the ambient medium is

$$p = (\gamma_a - 1)\rho_a u_a, \tag{3}$$

where

$$\gamma_a - 1 = \frac{(\gamma_I - 1)(\gamma_b - 1)}{(1 - F)(\gamma_b - 1) + F(\gamma_I - 1)}, \tag{4}$$

and we have assumed local pressure equilibrium between the bubbles and the ICM. Hydrostatic equilibrium of the ambient medium in a gravitational field $g(r)$ is described by

$$0 = g - \frac{1}{\rho_a}\frac{dp}{dr}. \tag{5}$$

We numerically integrate these equations assuming a NFW profile with a virial radius of 4 Mpc and a concentration parameter of seven (Neto et al. 2007). We assume that the gas outside the bubbles has a temperature of 6×10^7 K and that the core baryonic to dark mass ratio equals 0.14. We take a core radius, $r_c = 100$ kpc. This choice of the parameters yields reasonable temperature and density in the core. Of course, the choice is not unique. One can obtain similar characteristic of the central region for smaller virial radii at the expense of changing the concentration and the core radius. For simplicity, we assume that the mass in the bubbles is negligible.

3 RESULTS

The density averaged over the bubbles and residual core gas in the ambient medium, ρ_a, as a function of radius is plotted in Fig. 1 for various values of the filling factor. In each case, a constant filling factor is assumed. The profiles become flatter as the filling factor is increased. This can be seen analytically from the hydrostatic equation (5) as follows. Substituting $\rho_a = (1 - F)\,\rho_I$ and $P = (\gamma - 1)\rho_I u_I$ in this equation, we obtain, for u_I = constant and F = constant,

$$g = (\gamma - 1)u_I \frac{d \ln \rho_I^{1/(1-F)}}{dr}. \tag{6}$$

This implies that the density $\rho_I(F)$ as a function of the filling factor scales like $\rho_I(F) \sim \rho_I(F = 0)^{1-F}$ which, in turn, leads to a similar scaling for the ambient density plotted in the figure. Since $0 \leqslant F < 1$, this scaling yields flatter profiles for larger F.

The modification to the density profile causes a change in the corresponding core X-ray luminosity, $L_X \propto \int dr r^2 (1 - F)\rho_I^2(r) = \int dr r^2 (1 - F)^{-1} \rho_a^2(r)$. The X-ray luminosity (normalized to the value for $F = 0$) is plotted in Fig. 2. The luminosity is an increasing function of the filling factor. This is due essentially to the larger ambient density in the outer regions for a porous medium, amplified by the $(1 - F)^{-1}$ factor in the expression for L_X. The net result is a boost in the core X-ray luminosity.

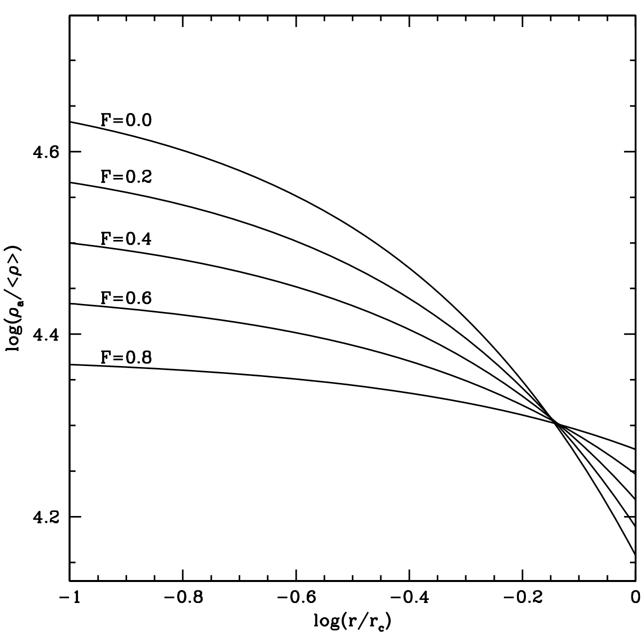

Figure 1. The ambient density, ρ_a, profiles (in units of the background value) as a function of radius (in units of r_c), for several values of the bubble filling factor.

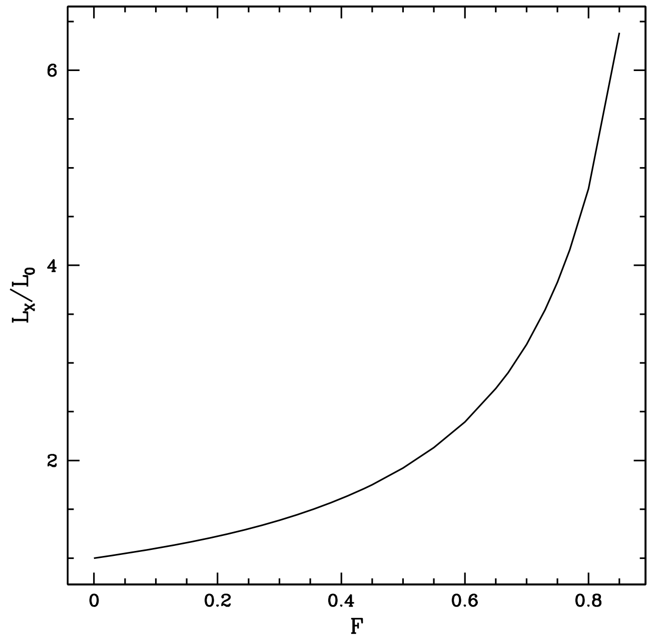

Figure 2. The normalized X-ray luminosity versus the filling factor.

4 DISCUSSION

Our results may be interpreted as follows.

(i) For a given observed X-ray emission and spectroscopic temperature of the residual ICM gas (outside the bubbles), hydrostatic equilibrium can yield erroneous mass estimates if the porosity of the medium is not properly included.

(ii) The temperature–luminosity L_X–T relation will depend on the porosity. The effect is enhanced if analysis is restricted to the core where the porosity is highest. This is, in addition, to changes resulting from gas cooling in the core (Allen & Fabian 1998; Markevitch 1998).

(iii) The ICM porosity is expected to be larger in the past due to an enhanced frequency of AGN activity. This leads to redshift dependence of a core L_X–T relation which is different from that seen for the outer parts of the cluster (Kotov & Vikhlinin 2005).

(iv) Porosity enhances the X-ray emission and hence shortens the cooling time. This leads to more AGN activity and the effect is only

Table 1. Filling factors of radio lobes in a few rich clusters (data taken from Bîrzan et al. (2004).

	Perseus	Hydra A	Cygnus A	MKW 3S	RBS 797	A2199
$F(R < 30\,\mathrm{kpc})$	0.006−0.036	0.07−0.14	0.11−0.25	0.12−0.23	0.023−0.14	0.006−0.03
$F(R < 40\,\mathrm{kpc})$	0.002−0.015	0.06−0.11	0.12−0.26	0.09−0.19	0.01−0.066	0.002−0.01

quenched when the porosity becomes sufficiently large, when only a little amount of gas remains available for feeding the AGN. At this point, the cold gas is all driven out of the core until there is time for a new episode of cooling and associated AGN activity.

Predictions of the modified hydrostatic equation should be compared against observations by the analysis of hydrostatic equilibrium of clusters. Porosity of individual clusters is needed for such a study. But reliable estimates of the porosity are not always possible using current data. One could alternatively proceed by solving the modified equation for assumed porosity as a function of cluster temperature and mass. The scatter in the relevant relations could then be minimized with respect to the assumed porosity values.

Rough estimates of porosity could be derived from the results of Bîrzan et al. (2004) (see also Dunn & Fabian 2004; Dunn, Fabian & Taylor 2005; Dunn & Fabian 2006). Using their table 2 for the sizes of prominent active bubbles (radio lobes), we compute the filling factors corresponding to some of their clusters. The filling factors within a distance of 30 and 40 kpc from the centre are listed in Table 1 here. The range of the filling factors corresponds to the uncertainty in projection effects (cf. Bîrzan et al.). Each cluster in Table 1 contains two radio lobes and the upper (lower) limiting value of the filling factor is obtained by summing the maximum (minimum) values of the sizes of both lobes. Table 1 demonstrates that the porosity resulting from active prominent bubbles could be significant. Note that low contrast bubbles remain undetected (Dunn & Fabian 2006) so that the porosity could be much higher than the estimate based on observed bubbles. Therefore, more rigorous estimates of the porosity, especially at larger radii and different redshifts, by detailed observational studies of higher signal-to-noise ratio are needed in order to test the evolutionary implications of the AGN feedback hypothesis.

The modified hydrostatic equation is valid for any two-component fluid where the density of one of the components is negligible. The generalization to multicomponent fluids of any densities could easily be done using the derivation described in Nusser et al. (2006).

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