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.

Keywords: 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; Birzan et al. 2004). These cavities or bubbles are believed to have been generated by active galactic nuclei (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; Brüggen, Ruszkowski & Hallman 2005; Roche, 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.

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, $\rho_a$, at position $r$, is defined as

$$\rho_a = (1 - F)\rho_i + F\rho_b,$$

in terms of the density inside bubbles, $\rho_b$, and the density of the ICM, $\rho_i$, also at $r$. The local ambient energy, $u_a$, per unit mass is

$$u_a = \frac{(1 - F)\rho_i u_i + F\rho_b u_b}{\rho_a},$$

where $u_i$ and $u_b$ are the internal energies of the ICM and bubbles, respectively. 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.
where $u_0$ and $u_1$ 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

$$p = (\gamma_a - 1)\rho a u_a,$$

where

$$\gamma_a - 1 = \frac{(\gamma_1 - 1)(\gamma_b - 1)}{(1 - F)(\gamma_b - 1) + F(\gamma_1 - 1)},$$

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

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

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 $6 \times 10^7$ 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, $\rho_a$, 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 $\rho_a = (1 - F) \rho_1$ and $P = (\gamma - 1)$

$$\rho_1 u_1$$

in this equation, we obtain, for $u_1 = \text{constant}$ and $F = \text{constant},$

$$g = (\gamma - 1)u_1 (\frac{1}{\rho_1} \frac{d\ln(1-F)}{dr}).$$

This implies that the density $\rho_1(F)$ as a function of the filling factor scales like $\rho_1(F) \sim \rho_1(F = 0)^{1-F}$ which, in turn, leads to a similar scaling for the ambient density plotted in the figure. Since $0 \leq F < 1$, this scaling yields flatter profiles for larger $F$.

The modification to the density profile causes a change in the corresponding core X-ray luminosity, $L_\text{X} \propto \int dr r^2 (1 - F) \rho_1^2 (r) = \int dr r^2 (1 - F)^{-1} \rho_1^2 (r)$. 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 $L_\text{X}$. The net result is a boost in the core X-ray luminosity.

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 $L_\text{X} - T$ 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 $L_\text{X} - T$ 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

Figure 1. The ambient density, $\rho_a$, 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.
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Table 1. Filling factors of radio lobes in a few rich clusters (data taken from Birzan et al. (2004)).

| Cluster     | $F(R < 30\text{kpc})$ | $F(R < 40\text{kpc})$ |
|-------------|-----------------------|-----------------------|
| Perseus     | 0.006−0.036           | 0.020−0.015           |
| Hydra A     | 0.07−0.14             | 0.06−0.11             |
| Cygnus A    | 0.11−0.25             | 0.12−0.26             |
| MKW 3S      | 0.012−0.23            | 0.09−0.19             |
| RBS 797     | 0.023−0.14            | 0.01−0.066            |
| A2199       | 0.006−0.03            | 0.002−0.01            |

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