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Heating of the Intracluster Medium by Quasar Outflows

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Abstract. We study the possibility of quasar outflows in clusters and groups of galaxies heating the intracluster gas in order to explain the recent observation of excess entropy in this gas. We show that radio galaxies alone cannot provide the energy required to explain the observations but the inclusion of Broad Absorption Line (BAL) outflows can do so, and that in this scenario most of the heating takes place at $z \sim 1$–4, the "preheating" epoch being at a lower redshift for lower mass clusters.

Key words. Cosmology: theory—Galaxies: intergalactic medium—X-rays: galaxies: clusters.

1. Introduction

Clusters and groups of galaxies contain a large amount of hot X-ray emitting gas called the intracluster medium, besides galaxies and the gravitationally dominant dark matter. Recent X-ray observations have provided evidences for non-gravitational heating of the ICM, in addition to the heating which occurs during the gravitational collapse. One of the first evidences was in the shape of the $L_x - T$ relation, which is steeper than the self-similar behaviour $L_x \propto T^2$ predicted in the case of only gravitational processes. Several authors like Kaiser (1991) and others have proposed that the missing element is the existence of a "preheated" high-entropy intergalactic gas prior to a cluster's collapse. Later, Ponman *et al.* (1999) and Lloyd-Davies *et al.* (2000) have found direct evidence of an entropy excess with respect to the level expected from gravitational heating in the centres of groups.

The candidate process which has been looked into as a source for this "preheating" are strong galactic winds driven by supernovae. However Valageas & Silk (1999) showed that the energy provided by supernovae cannot raise the entropy of intergalactic medium (IGM) up to the level required by current observations. The observed amount of required energy injection have been found to be in the range of 0.4 – 3 keV per gas particle (Wu *et al.* 2000; Lloyd-Davies *et al.* 2000 and others.)

An alternative source of heating, in the form AGN outflows in clusters, has been hypothesized by many authors to reconcile the observations. We have investigated the role of quasar outflows in this regard. We also try to constrain the epoch when this heating could have occurred.

2. Quasars inside clusters

For a proper evaluation of heat input from quasars inside clusters, one first needs to calculate their abundance and the dependence on the AGN mass, cluster mass, and the cluster formation redshift.

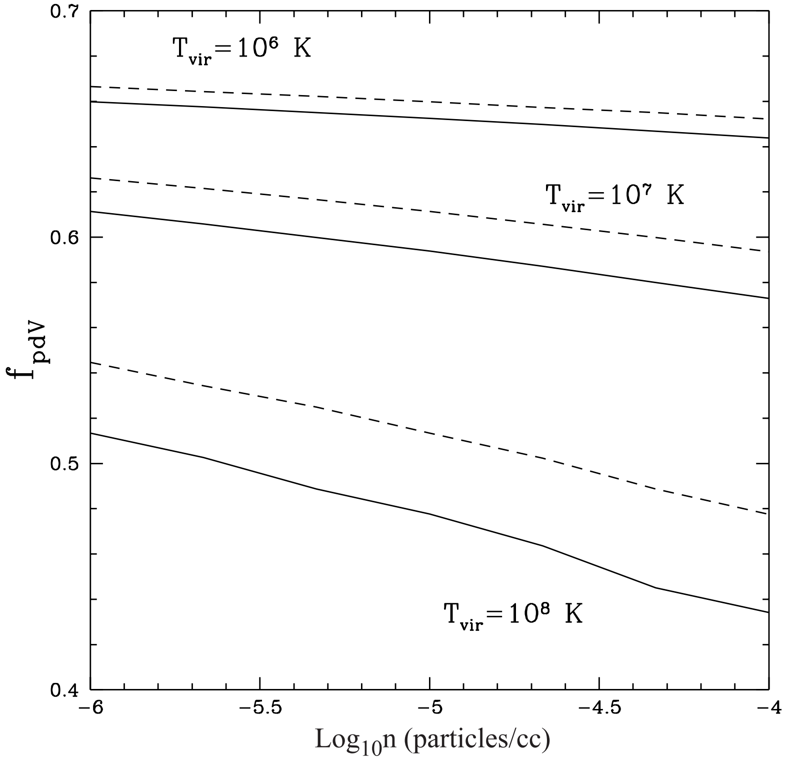

Figure 1(a). The dependence of f_{pdV} on the ambient density n is shown for various ambient temperatures T and kinetic luminosities of the jet, L_k (erg/s) . Solid and dashed lines are for $L_k = 10^{46}$ erg/s and 10^{47} erg/s respectively.

Following Yamada *et al.* (1999) (for $z = 0$), Haiman & Loeb (1998) and Furlanetto & Loeb (2001; FL01) at high redshift, we assume that the quasar abundance in clusters and low mass groups of galaxies is given by a fraction f_q of halos, where, $f_q \sim 0.1$ for $10^{13} \gtrsim M_h \gtrsim 10^{12}\ M_\odot$ and $f_q \sim 0$ for $M_h \gtrsim 10^{13}\ M_\odot$, & $M_h < 10^{12}\ M_\odot$. A life time of order 10^7 yr is assumed for the quasar (FL01).

To obtain the statistics of quasars *inside* clusters, that is, the rate of formation of quasars inside a future cluster of mass M_{cl}, one needs to have an extension of the Press-Schecter (PS) mass function which can predict the probability of a given halo merging into a bigger object later, or the probability of an object having had a projenitor of a given mass at an earlier epoch. Such extensions of the PS theory have been studied in detail by Bower (1991) and Lacey & Cole (1993)and others. The necessary growth factor in a cosmological constant dominated universe is taken from Kitayama & Suto (1996).

The above formalism leads to a *conservative* estimate of abundance of quasars in a cluster (and, therefore, the final heat input), because we ignore the increased pace of growth of perturbation and the merging rate inside a cluster. Our estimate of merging from the extended PS formalism is also conservative.

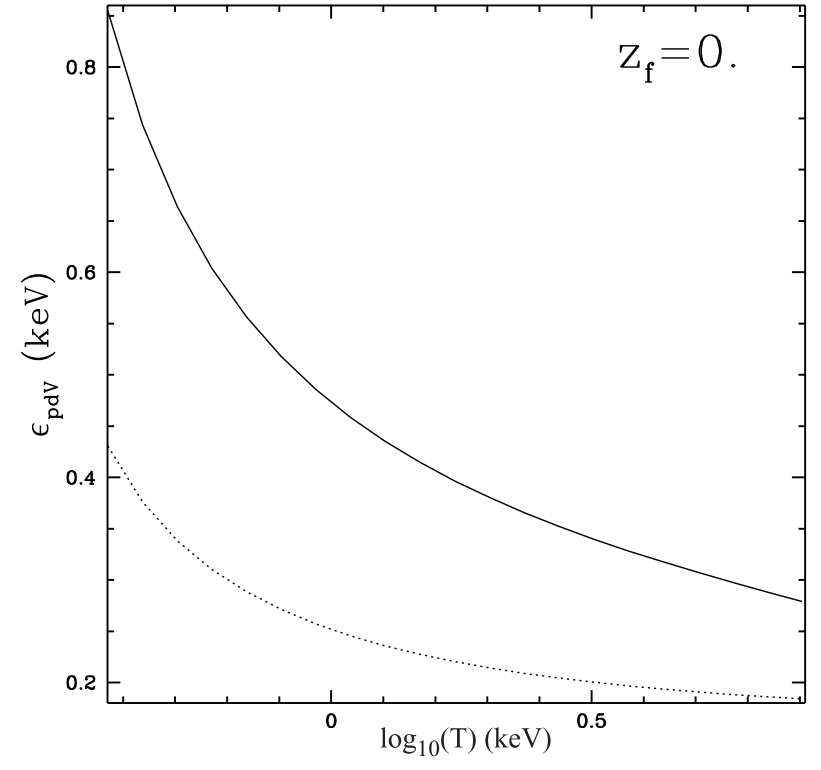

Figure 1(b). Excess energy (in keV) from BAL outflows is shown as a function of the cluster virial temperature (keV) for clusters with collapse redshift $z_f = 0$. The solid line shows the result of our calculation using the density and temperature dependent f_{pdV} and the dotted line shows the results when $f_{pdV} = 3/8$. (Bicknell *et al.* 1997)

3. Work done by quasar outflows

We then calculate the energy input from quasar outflows into the ambient medium. Two major types of outflows are considered: outflows from radio-loud quasars (RLQ) and broad absorption line (BAL) outflows. It has been assumed that during the active lifetime of the quasar, the energy output in the form of mechanical energy is given by the Eddington luminosity of the central black hole. We use the observed scaling between the central black hole mass and the halo mass (Magorrian *et al.* 1998; Gebhardt *et al.* 2000). Given the uncertainty in the geometry of the BAL outflows, we first calculate the work done by radio galaxy outflows and use similar values of the work done for BAL outflows. We also assume that all quasars go through the BAL outflow phase whereas the fraction of quasars being radio loud is of order ~ 0.1.

The standard scenario for outflows from radio loud quasars involves a 'cocoon' surrounding the core and the jet, and consisting of a shocked jet material (Scheuer 1974; Blandford & Rees 1974). We adopt the evolution of cocoons following the approach of Bicknell *et al.* (1997). Fig. 1(a) shows the dependence of the fraction of

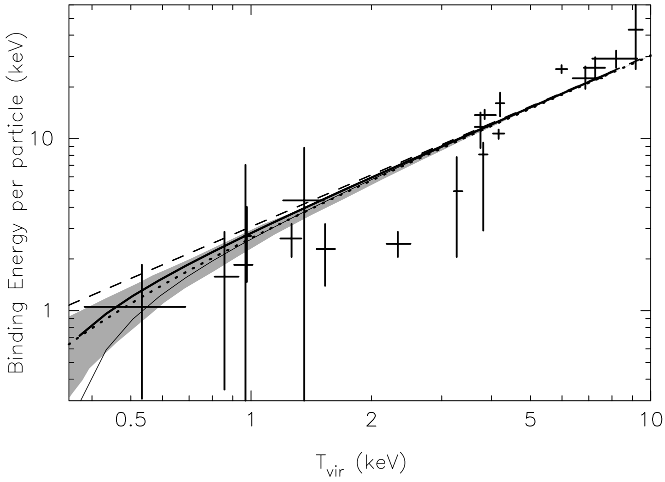

Figure 2. The prediction from our calculations is presented in the form of the final binding energy per particle of the central region of groups and clusters against the gas temperature. The data points are from the Figure 9 of Lloyd-Davies *et al.* (2000), and the dashed line refers to their fit $E \propto T$, derived from the data points for clusters with $T \geq 4$ keV. The dotted line refers to their second fit, with a constant excess energy of 0.44 keV per particle (subtracted from the binding energy) along with a formal 1 σ confidence interval shown by the shaded region. The darker and thicker solid line is the prediction of our calculation and the thinner and lighter solid line is the calculation using $f_{pdV} = 3/8$ (Bicknell *et al.* 1997).

energy of the jet lost through mechanical work f_{pdV} as a function of ambient density and ambient temperature.

4. Heating of the ICM

Equipped with the knowledge of the rate of formation of quasars in clusters and the fraction of total energy which is deposited as pdV work by the outflows from them, we now calculate the total amount on non-gravitational energy provided by quasar outflows in a cluster. Here we take the gas fraction of the total cluster mass, $f_{\rm gas} = 0.1$.

We present the results for the total non-gravitational energy input per gas particle as a function of cluster mass (or, equivalently, gas temperature) in the right panel of Fig. 1 (for a collapse redshift of $z_f = 0$). Recently, it has been shown by Lloyd-Davies *et al.* (2000) from observations of groups of clusters of galaxies that an excess energy of 0.44 ± 0.3 keV per particle suffices to explain the excess entropy in groups.

The solid curves in Fig. 1(b) and Fig. 2 show that the excess energy from pdV work done by the quasar outflows falls in this required range. Even if the fraction f_{pdV} is taken to be $3/8$ (dotted line in Fig. 1(b) and thin solid line in Fig. 2), the excess energy still satisfies the requisite range. The excess energy from radio galaxies alone would be one tenth of the excess we have calculated, and will fall short of the requirement. We also find that the epoch of heating is in the range of $z \sim 1 - 4$, where this epoch is at lower redshifts for low mass clusters (Nath & Roychowdhury 2002).

References

Bicknell, G. V., Dopita, M. A., O'Dea, C. P. O. 1997, *Ap. J.*, **485,** 112.
Blandford, R. D., Rees, M. J. 1974, *MNRAS*, **169,** 395.
Bower, R. G. 1991, *MNRAS*, **248,** 332.
Furlanetto, S., Loeb, A. 2001, *Ap. J.*, **556,** 619 (FL01).
Gebhardt, K. *et al.* 2000, *Ap. J.*, **543,** 5.
Haiman, Z., Loeb, A. 1998, *Ap. J.*, **503,** 505.
Kaiser, N. 1991, *Ap. J.*, **383,** 104.
Kitayama, T., Suto, Y. 1996, *Ap. J.*, **469,** 480.
Lacey, C., Cole, S. 1993, *MNRAS*, **262,** 627.
Lloyd-Davies, E. J., Ponman, T. J., Cannon, D. B. 2000, *MNRAS*, **315,** 689.
Magorrian, J. *et al.* 1998, *A. J.*, **115,** 2285.
Nath, B. B., Roychowdhury, S. 2002, *MNRAS*, **333,** 145.
Ponman, T. J., Cannon, D, B., Navarro, J. F. 1999, *Nature*, **397,** 135.
Scheuer, P. A. G. 1974, *MNRAS*, **166,** 513.
Valageas, P., Silk, J. 1999, *A&A*, **350,** 725.
Wu, K. K. S., Fabian, A., Nulsen, P. E. J. 2000, *MNRAS*, **318,** 889.
Yamada, M., Sugiyama, N., Silk, J. 1999, *Ap. J.*, **622,** 66.