Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 13 January 2005 (MN LATEX style file v2.2)

On viscosity, conduction and sound waves in the intracluster medium

A.C. Fabian, C.S. Reynolds, G.B. Taylor and R.J.H. Dunn
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA

13 January 2005

ABSTRACT

Recent X-ray and optical observations of the Perseus cluster indicate that the viscous and conductive dissipation of sound waves is the mechanism responsible for heating the intracluster medium and thus balancing radiative cooling of cluster cores. We discuss this mechanism more generally and show how the specific heating and cooling rates vary with temperature and radius. It appears that the heating mechanism is most effective above 10^7 K, which allows for radiative cooling to proceed within normal galaxy formation but will stifle the growth of very massive galaxies. The scaling of the wavelength of sound waves with cluster temperature and feedback in the system are investigated.

Key words: galaxies: clusters – cooling flows – X-rays: galaxies

1 INTRODUCTION

The Hα-emitting filaments surrounding NGC 1275 in the core of the Perseus cluster (Lynds 1970; Conselice et al 2001) appear to act as streamlines revealing flows in the intracluster medium (Fabian et al 2003b). Many of the outer filaments are reasonably straight and stretch over 10s kpc. One dubbed the horseshoe (Conselice et al 2001) folds back on itself just behind a large spherical-cap shaped depression in the X-ray intensity of the gas, suggestive of the flow on Earth seen behind rising spherical-cap bubbles in water (Fabian et al 2003b). Together these observations indicate that the intracluster medium is not turbulent and so is probably viscous, with a viscosity approaching the Spitzer-Braginskii (1956) value for an ionized plasma.

Further evidence for the medium being viscous is provided by the *shape* of detached buoyant bubbles, seen most clearly in the Perseus cluster (Fabian et al 2003a). Simulations of bubbles rising in an intracluster medium show that viscosity enables bubbles to remain intact for longer than a crossing time (Reynolds et al 2004).

If the intracluster medium is viscous then sound waves produced for example by radio bubbles from the central active galaxy, as seen in the Perseus cluster (Fabian et al 2003a), can be rapidly dissipated. This provides an efficient mechanism for transferring energy produced by a massive black hole in a central cluster galaxy into the surrounding medium in a reasonably isotropic manner. Although the energy flow passes through highly directional jets, the resultant bubbling produces approximately spherical sound waves which propagate into the cluster.

Energetic outflows from black holes do not otherwise couple well to surrounding gas. Electromagnetic ones pass through the gas which, being ionized, is mostly transparent. Collimated outflows, which tend to be the most energetic, are often too violent and bore right through the gas along the collimation direction (e.g. Cygnus A). Uncollimated winds might work but would tend to give strong shocks, which are not observed in the inner intracluster gas. Viscous dissipation can provide continuous, gentle, distributed heat, as is required (Voigt & Fabian 2004).

Here, we examine the viscous dissipation of sound wave energy in intracluster and intragroup gas. It has a strong temperature dependence which means that such heating dominates over radiative cooling above about 10^7 K. Radiative cooling dominates below that temperature. This provides a clue as to why heating appears to stifle the cooling in clusters and groups (the cooling flow problem, see Fabian et al 2001) yet most galaxy formation, where much of the stellar component is a consequence of radiative cooling of baryons which have fallen into dark matter wells, has taken place. Indeed the process which stifles cooling in massive systems probably is responsible for truncating the upper mass range of galaxies (Fabian et al 2002; Benson et al 2003; Binney 2004).

2 VISCOUS AND CONDUCTIVE HEATING

We now consider the heating rate of sound waves propagating through the intracluster medium. The viscosity will be assumed to be close to the Spitzer-Braginskii (1956) value for an ionized gas. Cluster cores do have significant magnetic fields (e.g. Carilli & Taylor 2002) which may of course alter the viscosity. What effect this has is unclear.

There is, however, evidence from Faraday rotation measures (RMs) observations (Carilli & Taylor 2002 and references therein) that the field is coherent in patches larger than the ion mean free path. Typical values of the cell size estimated from RM distributions and quoted in the literature are 5-10 kpc. A power-spectrum analysis of Hydra A, a bright radio galaxy and one of the best cases for probing a cooling core cluster as it provides a probe of the RM distribution on scales from 0.2 to 40 kpc, has been carried out by Vogt & Esslin (2004, in prep), who find a magnetic autocorrelation length of $3\pm0.5\,\mathrm{kpc}$. This autocorrelation length can be compared to the ion mean free path (mfp) of $0.23T_{\rm c}^2n_{\rm c}^{-1}\,\mathrm{kpc}$ for typical cluster core parameters of $T_{\rm c}=3\times10^7\,\mathrm{K}$ and $n_{\rm c}^{-1}=0.01\,\mathrm{cm}^{-3}$. Since the mfp is smaller than the dominant scale size of the magnetic field, the viscosity will be high for much of the volume under consideration. This is also relevant to the issue of conduction, which can also dissipate the energy in sound waves (Landau & Lifshitz 1987), but is not strong enough to offset cooling in many clusters by itself (Voigt & Fabian 2004; Kaastra et al 2004).

Consider a simple model in which the intracluster medium consists of many magnetically isolated blobs of gas, each of size ranging over a few kpc. Within a blob the field is fairly coherent. Conduction of heat from the outside of the core to the centre is inhibited by the boundaries between the blobs. The energy in sound waves propagates freely across the boundaries and can be dissipated within the blobs by both conduction and viscosity.

2.1 Sound wave heating and radiative cooling rates

Suppose the ICM possesses a kinematic viscosity ν and a thermal conductivity of κ. The absorption coefficient for the passage of sounds waves is given by (Landau & Lifshitz 1987)

$$\gamma=\frac{2\pi^2f^2}{c_{\rm s}^3}\left[\frac{4}{3}\nu+\frac{\kappa}{\rho}\left(\frac{1}{c_{\rm V}}-\frac{1}{c_{\rm p}}\right)\right], \qquad (1)$$

where f is the frequency of the sound waves, $c_{\rm s}$ is the sound speed, ρ is the density of the ICM, and $c_{\rm V}$ and $c_{\rm p}$ are the specific heats at constant volume and pressure, respectively. The dissipation length (i.e., the length scale over which the energy flux of the sound wave decrease by a factor of e) is given by $\ell=1/2\gamma$. Noting that $c_{\rm p}/c_{\rm V}=5/3$ for a fully ionized gas, we can write

$$\ell=\frac{3c_{\rm s}^3}{8\pi^2f^2\left[2\nu+\kappa/\rho c_{\rm p}\right]}. \qquad (2)$$

Suppose that the viscosity and thermal conductivity are fixed fractions, ξ_ν and ξ_κ, of their unmagnetized values. For a fully ionized hydrogen plasma, we get

$$\nu = 1.4\times10^{25}T_7^{5/2}n^{-1}\xi_\nu, \qquad (3)$$

$$\frac{\kappa}{\rho c_{\rm p}} = 5.6\times10^{26}T_7^{5/2}n^{-1}\xi_\kappa, \qquad (4)$$

where $T_7=T/(10^7\,\mathrm{K})$, and n is number density, and we have taken the Coulomb logarithm to have a value of 30. Substituting the numerical values into eqn. 2, we get

$$\ell=154\,\frac{nT_7^{-1}f_{-6}^{-2}}{\left(\frac{\xi_\nu}{0.1}\right)+20\left(\frac{\xi_\kappa}{0.1}\right)}\,\mathrm{kpc} \qquad (5)$$

where we have expressed the sound wave frequency in units of per megayear (i.e., $f_{-6}=f/(10^{-6}\,\mathrm{yr}^{-1})$ and have normalized to plausible values of viscosity and thermal conductivity (following the arguments of Narayan & Medvedev 2001). Hereafter, we shall use denote

$$\bar{\xi}=\frac{\xi_\nu}{0.1}+20\frac{\xi_\kappa}{0.1} \qquad (6)$$

We note that, since temperature and density vary with radius in the cluster, the dissipative effects of viscosity and thermal conductivity vary but maintain a fixed ratio (as a consequence of assuming that ξ_ν and ξ_κ are constant). We also note that thermal conduction is over an order of magnitude more effective at dissipating sound wave energy if $\xi_\nu\approx\xi_\kappa$.

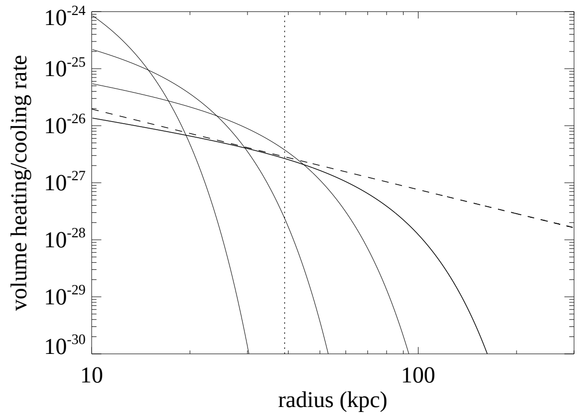

Figure 1. Dissipative volume heating rates (solid lines) and radiative volume cooling rate (dashed line), using the temperature and density profile of A 2199 (Johnstone et al. 2002). The heavy solid line is for the following set of illustrative set of parameters for which the heating and cooling approximately balance; $L_{44}=1$, $f_{-6}=0.1$, $\xi_\nu=0.1$, $\xi_\kappa=0$. Other choices of the acoustic power (L_{44} will simply rescale this line in the vertical direction. Other choices of f_{-6}, $\xi_\nu=0.1$, and $\xi_\kappa=0$ change the dissipation lengthscale as well — the family of additional (thin) solid lines shows the effect of successive doublings of frequency ($f_{-6}=0.2$, $f_{-6}=0.4$, and $f_{-6}=0.8$.

We now model the central AGN as a source of acoustic energy at the center of the cluster. Suppose that the AGN injects an acoustic luminosity of $L_{\rm inj}$ into the ICM at an inner radius of $r=r_{\rm in}$. If $L_s(r)$ is the acoustic luminosity at radius $r>r_{\rm in}$, the definition of dissipation length gives

$$\frac{dL_s}{dr}=-\frac{L_s}{\ell}, \qquad (7)$$

which has the solution

$$L_s(r)=L_{\rm inj}\exp\left(-\int_{r_{\rm in}}^{r}\frac{1}{\ell}\,dr\right). \qquad (8)$$

The volume heating rate due to viscous and conductive dissipation is

$$\epsilon_{\rm diss}=\frac{L_s(r)}{4\pi r^2\ell}, \qquad (9)$$

which, for $r\ll\ell$ is approximately

$$\epsilon_{\rm diss}\approx\frac{2\pi f^2L_{\rm inj}\left[2\nu+\kappa/\rho c_{\rm p}\right]}{3c_{\rm s}^3r^2}, \qquad (10)$$

which can be evaluated to give

$$\epsilon_{\rm diss}\approx1.9\times10^{-28}T_7n^{-1}f_{-6}^2r_2^{-2}L_{44}\bar{\xi}\,\mathrm{erg\,cm^{-3}\,s^{-1}}, \qquad (11)$$

where $L_{44}=L_{\rm inj}/(10^{44}\,\mathrm{erg\,s^{-1}})$ and $r_2=r/(100\,\mathrm{kpc})$.

As an illustration of the radial dependence of the viscous and conductive dissipation, we compute $\epsilon_{\rm diss}$ using the temperature and density profile of Abell 2199 from Johnstone et al. (2002); $T=4.4r_2^{0.3}\,\mathrm{keV}$ and $n=6.0\times10^{-3}r_2^{-0.75}\,\mathrm{cm^{-3}}$. We compare this with the radiative cooling as derived from the formula of Tozzi & Norman (2001) which, expressed in our units, becomes;

$$\epsilon_{\rm rad}=10^{-24}n_in_e\left[1.13T_7^{-1.7}+5.3T_7^{0.5}+6.3\right] \qquad (12)$$

As shown in Fig. 1, the dissipative heating closely balances the radiative cooling within the cooling radius (defined as the radius within which the cooling time $\tau = 3nkT/2\epsilon_{\rm rad}$ exceeds 1 Gyr) for the following choice of parameters; $L_{44} = 1$, $f = 0.1$, $\xi_\nu = 0.1$, $\xi_\kappa = 0$. The dissipation lengthscale is approximately 100 kpc, and the heating rate displays power-law radial profile within this radius (reflecting the simple power-law forms of the assumed temperature and density). A sharp (exponential) cutoff in the heating rate is seen for radii larger than the dissipation length. Varying the acoustic luminosity of the AGN simply changes the normalization of this heating rate. On the other hand, varying the frequency of the sound waves leads to dramatic changes in the dissipation lengthscale. In particular, increasing the sound frequency while leaving the other parameters at the values listed above rapidly brings the dissipation lengthscale within the cooling radius. A detailed balance of heating and cooling is then no longer possible — the innermost regions can be strongly heated while radiative cooling occurs unchecked at the cooling radius.

For a given suppression factor (ξ_ν and ξ_κ), thermal conduction is significantly more important than viscosity at dissipating sound wave energy. Indeed, if thermal conduction occurred at the level suggested by Narayan & Medvedev (2001),

$$\xi_\kappa \approx 0.2, \qquad (13)$$

the dissipation lengthscale would be extremely short for all but the lowest frequency soundwaves ($\ell \approx 3.9nT_7^{-1}f_{-6}^{-2}\,{\rm kpc}$).

The theory outlined above only strictly applies to the case of linear sound waves; this imposes a radius dependent maximum acoustic luminosity to which this theory can be applied. Expressed in terms of pressure fluctuations, δp, the acoustic luminosity crossing a shell at radius r is,

$$L_s \approx 4\pi r^2 \frac{\delta p^2}{\rho c_s}. \qquad (14)$$

The acoustic waves become strongly non-linear when $\delta p \approx p$. Thus, the maximum acoustic luminosity for which our model applies is

$$L_{s,max} \approx 4\pi r^2 \frac{p^2}{\rho c_s} \approx 3.1\times 10^{46} nT_7^{1.5} r_2^2\,{\rm erg\,s^{-1}}\,. \qquad (15)$$

Using this equation, we see that the fiducial model described above for A 2199 ($L_{44} = 1$, $f = 0.1$, $\xi_\nu = 0.1$, $\xi_\kappa = 0$) is only valid for radii greater than about 20 kpc. Within that radius, the energy must be transported within the form of weak shocks and/or convective motions.

3 THE WAVELENGTH AND FREQUENCY OF SOUND WAVES

Subcluster mergers are common in clusters and these will generate large pressure discontinuities and sound waves. The wavelengths of sound waves remaining after shocks have passed will presumably be on the scale of cluster cores or hundreds of kpc. On these scales the gas may be turbulent so the motions may degrade down to scales of tens of kpc where viscous dissipation can operate. The outer gas in a cluster may therefore be noisy with a wide spectrum of wavelengths. Pringle (1989) noted that the dense regions of a cluster core can focus sound waves inward, meaning that significant heating may result at the centre. Establishing the energetics and efficiency of such processes requires numerical calculations beyond the scope of this Letter.

A central active nucleus giving rise to jets will inflate cavities of relativistic radio-emitting plasma within the intracluster medium. Such cavities or bubbles are seen in the Perseus cluster (Böhringer et al 1993; Fabian et al 2000; Fabian et al 2003a), Virgo cluster (Wilson et al 2002; Forman et al 2003), A2052 (Blanton et al 2001, 2003), A2597 (Nulsen et al 2002), A4059 (Heinz et al 2002) and Hydra A (McNamara et al 2000). Such bubbles inflate and then break away due to buoyancy (Churazov et al 2000, 2001) and so even a constant jet will lead to a bubbling effect. This generates a repetitive pressure excess and thus a sound wave with a period equal to the repetition time of the bubbles.

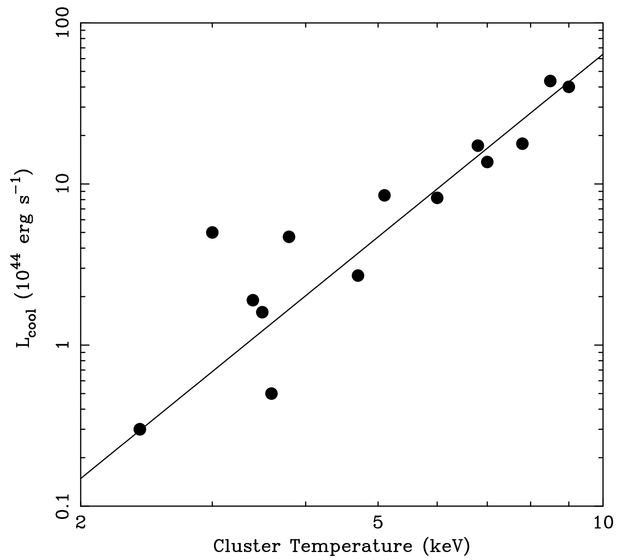

Figure 2. The X-ray luminosity within the cooling radius plotted against the cluster temperature, using results for cooling flow clusters taken from Peres et al (1998). The best fitting power law is shown, with index 3.8.

A bubble expands because of its excess pressure relative to the intracluster medium at a rate which varies as $t^{1/3}$, where t is time. It detaches from the jet when buoyancy dominates which is roughly when its expansion velocity drops to about one half of the local Keplerian velocity due to the local gravitational field of the central galaxy and cluster, $v_{\rm K}$ (Churazov et al 2000). A new bubble then begins to grow. This gives a natural bubbling period $f \propto L^{-1/2}P^{1/2}v_{\rm K}^{3/2}$, where P is the pressure of the intracluster gas and L is the power of the jet. Now the central cooling time of many clusters with cool cores levels off at about 10^8 yr within a radius of 10 kpc (Voigt & Fabian 2004) which implies that (between clusters) $P \propto T^{3/2}$. If we also assume that $v_{\rm K} \propto T^{1/2}$ where the gas temperature is T. Then $f \propto L^{-1/2}T^{3/2}$ and further scaling depends on L.

The dependence of L on T is probably fairly steep. If we assume that the jet power L does balance cooling then it is proportional to the X-ray luminosity $L_{\rm cool}$, within the cooling radius (where the cooling time equals the cluster age). $L_{\rm cool}$ is tabulated for nearby clusters by Peres et al (1998) and using these values and the cluster temperatures we find (Fig. 2) that $L \propto T^\alpha$ with $\alpha \sim 4$. Therefore $f \propto T^{-1/2}$. As a rough check, the scaling predicts that radius R when a bubble separates, $R \propto L^{1/2}P^{-1/2}v_{\rm K}^{-1/2} \propto T$. This scaling result is shown in Fig. 3 with results for individual clusters drawn from the compilation of Dunn & Fabian (2004).

The luminosity drops out of the dissipation formula (11) which now varies steeply with temperature; $\epsilon_{\rm diss} \propto T^{7/2}r^{-2}$ and at a given radius $\epsilon_{\rm diss}/\epsilon_{\rm rad} \propto T^2$.

Although we have in this Section identified the bubbling frequency as the dominant one, it is likely that the underlying vari-

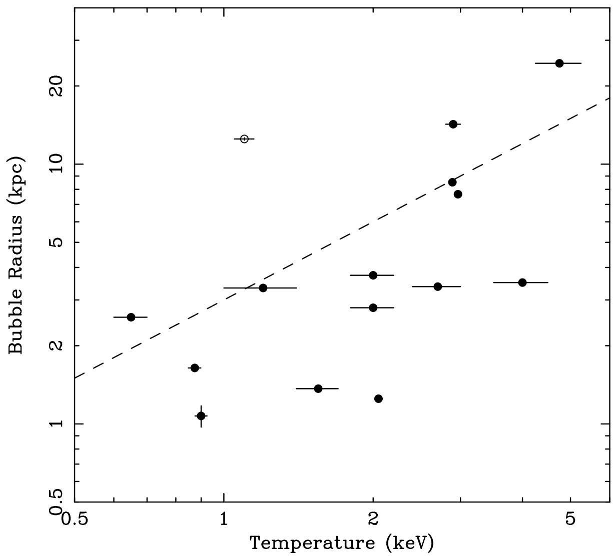

Figure 3. The radius of bubbles is shown as a function of the surrounding temperature. Data are for attached bubbles from the compilation of Dunn & Fabian (2004). The open point is for A2052 where there appears to be much cool gas accumulated around the rims (Blanton et al 2003) so the points may reasonably shift to the right. The dashed line is not a fit but indicates the $R \propto T$ relation tentatively derived in the text for the rough radius, R, at which bubbles detach from the nucleus. Bubbles should therefore only exist below, or close to, the line.

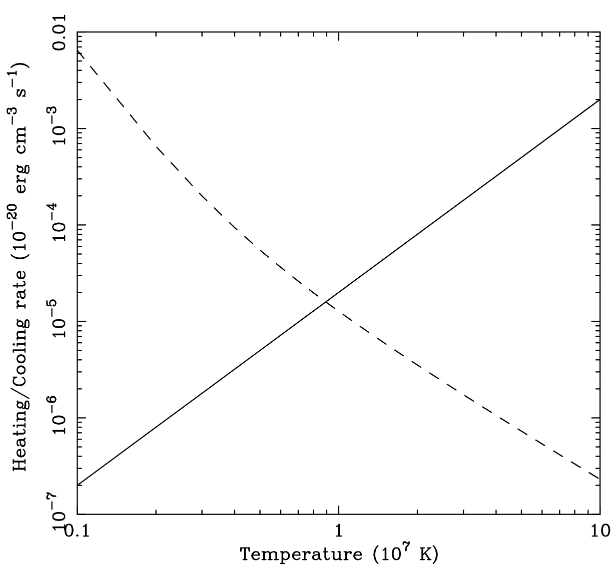

Figure 4. Heating and cooling rates plotted as a function of temperature for a pressure $nT = 10^6\,\mathrm{cm}^{-3}\,\mathrm{K}$ and radius of 10 kpc. For the heating rate, $f_{-6}^2 L_{44}\bar{\xi} = 1$.

ability of the radio jets occurs at higher frequencies. Most jets are not constant as shown by repeated outbursts on small scales (e.g., in Perseus A=3C84, Taylor & Vermeulen 1996, see also Reynolds & Begelman 1997, and in general Zensus 1997). These variations will be transmitted through to the surface of the bubble leading to its growth being erratic and a spectrum of high frequency sound waves being present at small radii, with the bubbling frequency being the low-frequency cutoff. The steep dependence on frequency means that higher frequency waves are damped most easily.

As an indication of the temperature dependence of the dissipation versus radiative cooling we show $\epsilon_{\rm diss}$ and $\epsilon_{\rm rad}$ as functions of temperature in Fig. 4. We assume that $f_{-6}^2 L_{44}\bar{\xi} = 1, r = 10\,\mathrm{kpc}$ and $P = nT = 10^6\,\mathrm{cm}^{-3}\,\mathrm{K}$ which means that if the above scaling is correct, the heating rate in real objects is steeper. The plot shows that sound wave dissipative heating dominates above about 10^7 K and radiation dominates below. The process is therefore relevant as an explanation for the truncation of cooling, and thus of star formation and the total stellar mass, in massive galaxies.

4 DISCUSSION

We have shown that viscous heating of intracluster or intragroup gas can effectively compete with radiative cooling above gas temperatures of about 10^7 K. Sound waves produced by jets from a central black hole can thereby shut off cooling in the surrounding gas and prevent further growth of the central galaxy by accretion of radiatively cooled gas. This mechanism may explain the upper-mass cutoff in galaxies since it operates best at high temperatures.

If cooling initially dominated in a cluster core then the temperature profile would have dropped to the local virial one, which for a NFW potential (Navarro, Frenk & White 1997) approaches $T \propto r^{1/2}$ for the central cusp (i.e. within the central 100 kpc). Steady heating then applied to this gas will tend to push the gas outward, lowering its density whereas continued cooling means that gas flows inward, in both circumstances following close to the virial temperature profile. This roughly explains the observed temperature profiles, given that much of the inner few kpc are occupied by bubbles.

The prevalence of the central X-ray surface brightness peak characteristic of short radiative cooling times (Peres et al 1998; Bauer et al 2004)and the remarkable similarity of the cooling time profiles in many clusters (Voigt & Fabian 2004) suggests that a good heating / cooling balance is commonly established. This presumably requires feedback with the central power source, the accreting black hole. How that is established so that the properties of the gas at say 50 kpc are attuned to those at the black hole accretion radius of say 100 pc, is not completely clear.

A partial answer can be seen from the following. If the radio source becomes too vigorous, then most of its power will be deposited at large radii beyond the cooling radius both if it becomes an FRII (as in Cygnus A) or remains an FRI when the associated giant bubbles (as in Hydra A, Nulsen et al 2004, or MS0735.6+7421, McNamara et al 2004) create low frequency global disturbances which dissipate poorly. If the radio source shuts off due to lack of fuel, then the inner gas will cool and, angular momentum permitting, accrete and provide that fuel. Rapid variations in jet power will lead to high frequency disturbances which dissipate rapidly heating those inner regions. A trickle of cooling and accretion explains the prevalence of warm optical nebulosity (Crawford et al 1999 and references therein) and cold gas (Edge 1991) near the centres of these objects. The inner cooling time of these objects at $\sim 10^8\,\mathrm{yr}$ (Voigt & Fabian 2004) is similar to the dynamical timescale of the central galaxy.

Continued heating by a central AGN in cluster and group cores means that the central black hole continues to grow. The total accreted mass can be considerable (see Fabian et al 2002; Fujita & Reiprich 2004). This may skew the mass – velocity dispersion relation ($M - \sigma$) for massive black holes upward at the highest black hole masses, such as expected of the massive black holes in groups and clusters.

Finally, we note that a viscous intracluster medium means that motions in the cores of relaxed clusters will be damped and, apart from the regions directly around the inflating and rising bubbles, or where the dark matter potential or galaxy are sloshing around, fluid motions should be small and highly subsonic. Measurements of iron-K emission-line widths with ASTRO-E2 will distinguish such laminar motions from turbulence (see Inogamov & Sunyaev 2003 for predictions of turbulent profiles).

5 ACKNOWLEDGMENTS

CSR gratefully acknowledges support from the *Chandra* Cycle-5 Theory & Modelling program under grant TM4-5007X. ACF thanks the Royal Society for support.

REFERENCES

Bauer, F.E., *et al*, 2004, MNRAS, submitted.
Benson, A.J., Bower, R.G., Frenk, C.S., Lacey, C.G., Baugh, C.M., and Cole, S., 2003, ApJ, 599, 38
Binney, J., 2004, MNRAS, 347, 1093
Blanton E.L., Sarazin C.L., McNamara B.R., Wise M.W., 2001, ApJ,
Blanton, E.L., Sarazin, C.L. and McNamara, B.R., 2003, ApJ, 585, 227
Böhringer, H., Voges, W., Fabian, A. C., Edge, A. C. and Neumann, D. M., 1993, MNRAS, 264, 25
Braginskii S.L., 1958, Sov. Phys. JETP, 6, 358
Carilli C. L., Taylor G. B., 2002, ARAA, 40, 319
Churazov, E., Forman, W., Jones, C., and Böhringer, H., 2000, A&A, 356, 788
Churazov E., Brüggen M., Kaiser C.R., Böhringer H.,Forman W., 2001, ApJ, 554, 261
Conselice C.J., Gallagher J.S. and Wyse R.F.G., 2001, AJ, 122, 2281
Crawford, C. S., Allen, S. W., Ebeling, H., Edge, A. C. and Fabian, A. C, 1999, MNRAS, 306, 857
Dunn, R. J. H.; Fabian, A. C., 2004, MNRAS, 355, 862
Edge, A. C., 1991, MNRAS, 250, 103
Fabian, A. C., Sanders, J. S., Ettori, S., Taylor, G. B., Allen, S. W., Crawford, C. S., Iwasawa, K., Johnstone, R. M. and Ogle, P. M., 2000, MNRAS 318, L65
Fabian, A. C., Mushotzky, R. F., Nulsen, P. E. J. and Peterson, J. R., 2001, MNRAS, 321, 20.
Fabian, A. C., Voigt, L. M. and Morris, R. G., 2002, MNRAS, 335, 71
Fabian, A.C., Sanders, J.S., Allen, S.W., Crawford, C.S., Iwasawa, K., Johnstone, R.M., Schmidt, R.W., and Taylor, G.B., 2003(a), MNRAS, 344L, 43F
Fabian, A.C., Sanders, J.S., Crawford, C.S., Conselice, C.J., Gallagher, J.S., and Wyse, R.F.G., 2003(b), MNRAS, 344L, 48F
Forman, W., Nulsen, P., Heinz, S., Owen, F., Eilek, J., Vikhlinin, A., Markevitch, M., Kraft, R., Churazov, E., Jones, C., astro-ph/0312576
Fujita Y., Reiprich T.H., 2004, ApJ, 612, 797
Heinz, S., Choi, Y., Reynolds, C.S., and Begelman, M.C., 2002, ApJ, 569, 79
Johnstone R. M., Allen S.W., Fabian A. C., Sanders J.S., 2002, MNRAS, 336, 299
Kaastra, J. S., Tamura, T., Peterson, J. R., Bleeker, J. A. M., Ferrigno, C., Kahn, S. M., Paerels, F. B. S., Piffaretti, R., Branduardi-Raymont, G., and Böhringer, H., 2004, A&A, 413, 415
Landau, L.M., Lifshitz, E.M., 1987, *Fluid Mechanics*
Lynds R., 1970, ApJ, 159, 151
McNamara, B.R., Wise, M., Nulsen, P.E.J., David, L.P., Sarazin, C.L., Bautz, M., Markevitch, M., Vikhlinin, A., Forman, W.R., Jones, C., and Harris, D.E., 2000, ApJ, 534, 135
McNamara, B. R., Nulsen, P. E. J., Wise, M. W., Rafferty, D. A., Carilli, C., Sarazin, C. L. and Blanton, E. L., astro-ph/0411553
Narayan R., Medvedev M. V., 2001, ApJ, 562, L129
Navarro J. F., Frenk C. S., White S. D. M., 1997, ApJ, 490, 493
Nulsen P. E. J., David L. P., McNamara B. R., Jones C., Forman W. R., Wise M., 2002, ApJ, 568, 163
Nulsen, P. E. J., McNamara, B. R., Wise, M. W. and David, L. P., 2004, astro-ph/0408315
Peres C. B., Fabian A. C., Edge A. C., Allen S. W., Johnstone R. M., White D. A., 1998, MNRAS, 298, 416
Pringle, J. E, 1989, MNRAS, 239, 479
Reynolds, C.S., McKernan, B., Fabian, A.C., Stone J.M., and Vernaleo,J.C., 2004, MNRAS, accepted
Spitzer L., 1956, Physics of Fully Ionized Gases, 1st Ed., New York: Wiley-Interscience
Taylor G.B., Vermeulen 1996, ApJ, 457, L69,
Tozzi, P. and Norman, C., 2001, ApJ, 546, 63
Voigt, L.M. and Fabian, A.C., 2004, MNRAS, 347, 1130
Wilson, A. S., Yang, Y., 2002, ApJ, 568, 133
Zensus J. A., 1997, ARA&A, 35, 607