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The missing soft X-ray luminosity in cluster cooling flows

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ABSTRACT

The gas temperature in the cores of many clusters of galaxies drops inward by about a factor of 3 or more within the central 100-kpc radius. The radiative cooling time drops over the same region from 5 or more Gyr down to below a few 10^8 yr. Although this indicates that cooling flows are taking place, *XMM-Newton* spectra show no evidence for strong mass cooling rates of gas below 1–2 keV. The soft X-ray luminosity expected from steady cooling flows is missing. Here we outline and test the energetics of a cold mixing model in which gas below 1–2 keV falls from the flow and is rapidly cooled by mixing with cold gas. The missing X-ray luminosity can emerge in the ultraviolet, optical and infrared bands, where strong emission nebulosities are commonly seen. We explore further the requirements for any heat sources that balance the radiative cooling in cluster cores.

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

1 INTRODUCTION

X-ray observations made with *Chandra* and *XMM-Newton* of clusters of galaxies with high surface brightness cores have confirmed some of the basic requirements for the presence of cooling flows (Fabian 1994), namely short central cooling times and low central temperatures. The radiative cooling times in many clusters drop to a few times 10^8 yr in the central few kpc and the temperatures drop from the cluster mean by about a factor of 3–5 (Fabian et al. 2000, 2001a; McNamara et al. 2000; Schmidt, Allen & Fabian 2001; Allen, Schmidt & Fabian 2001b; Ettori et al. 2002; Johnstone et al. 2002). However while the temperature profile is consistent with a simple single-phase cooling flow in many cases, the X-ray surface brightness profile is not. The emission is less centrally peaked than expected, which has been interpreted as distributed mass deposition throughout the flow (Fabian, Nulsen & Canizares 1984; White & Sarazin 1988) caused by multiphase gas (Nulsen 1986; Thomas, Fabian & Nulsen 1987).

The new data, which have much higher spatial and spectral resolution than was obtained previously, are not consistent with this picture. There is little spectral evidence for gas cooling out of a flow; the soft X-ray emission expected from the gas cooling below 1–2 keV is not detected at any radii (Peterson et al. 2001; Tamura et al. 2001; Kaastra et al. 2001; Molendi & Pizzolato 2001; Böhringer et al. 2002; Matsushita et al. 2002). Significant rates of gas cooling out of a flow are inferred only if excess intrinsic photoelectric absorption is introduced, so absorbing the emission below 1 keV (David et al. 2001; Schmidt et al. 2001; Ettori et al. 2002).

It appears that the peaked X-ray surface brightness profiles of clusters with short cooling times, $t_{\rm cool} < 10^9$ yr, are actually not peaked enough to represent simple single or multiphase cooling flows. What is missing is the additional soft X-ray peak expected from gas cooling below 1–2 keV. If cooling flows with gas cooling below 10^6 K occur at all in these clusters then there is a problem in the missing soft X-ray luminosity.

If the gas is not cooling then there must be some compensating heat flux. It has to be sufficient to stop gas from cooling below 1–2 keV but not so much that the gas heats up above the observed inner temperatures. Some form of feedback seems necessary, perhaps owing to a central active nucleus that is powered by the intracluster gas (Tucker & Rosner 1983; Binney & Tabor 1995; Soker et al. 2001; Böhringer et al. 2002). Of crucial importance is the requirement that the heat has to be spatially distributed, with much of it acting on gas at tens of kpc. Holes in the X-ray surface brightness of the cores of many clusters are probably bubbles of buoyant relativistic plasma produced by the central radio source (e.g. Böhringer et al. 1993; Churazov et al. 2001; Fabian et al. 2000; McNamara et al. 2000; Fabian et al. 2002). Whether these exist and can heat the gas sufficiently in very X-ray luminous clusters such as A1835 (Peterson et al. 2001; Schmidt et al. 2001) remains to be seen.

In this Letter, we discuss the missing soft X-ray luminosity in cooling flows further and point out that it could be related to the high luminosity of the optical/ultraviolet emission-lines, and also dust emission, common in these objects. When integrated from the far-infrared to the X-ray band, there is no shortage of luminosity.

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This implies that the gas below 1–2 keV could vanish by mixing with much cooler gas. The detection of O VI emission in A2597 with FUSE (Oegerle et al. 2001) tentatively supports this possibility. We also note that the temperature at which gas starts to appear missing is where magnetic pressure support owing to magnetic field amplification in the flow is expected to become important. This reduces the value of the missing luminosity.

We discuss further the heating requirements if there is no flow. Metallicity gradients seen in cluster cores (Fukazawa et al. 1994; Ezawa et al. 1997; De Grandi & Molendi 2001) limit the amount of large-scale convection and mixing that take place. This then limits the level at which heat is transported outward in any bulk manner. Heating may also result from the conversion of kinetic energy in the bulk motion of the gas as it moves within a cluster core. The discovery of cold fronts in clusters (Markevich et al. 2000) and their common occurrence supports the view that such motions are common.

2 COOLING-DOMINATED FLOWS

In this section we consider the missing soft X-ray luminosity problem and ignore heat sources. As noted above, luminous optical emission lines are common in cluster cooling flows (e.g. Heckman et al. 1989; Donahue & Stocke 1995; Crawford et al. 1999). The luminosity in Hα ranges from less than 10^{40} to above $10^{43}\,\mathrm{erg\,s^{-1}}$ and is 1000 s times more than that expected from gas cooling through 10^4–10^3 K at the rate inferred from the earlier X-ray data. The presence of a blue continuum in many of the line-luminous central cluster galaxies supports the idea that the line emission is powered by massive young stars, possibly formed from the cool gas (Johnstone, Fabian & Nulsen 1987; Allen 1995; Crawford et al. 1999). Whether this accounts for all the line emission is not clear. Photoionization models for the emission show that the total power emitted by the cool clouds is about 30 times that in Hα, with much radiated in the UV (e.g. Donahue & Voit 1991).

The optical line nebulosities range in size from a few kpc to more than 50 kpc (Heckman et al. 1989; Crawford et al. 1999; see Conselice, Gallagher & Wyse 2001 for spectacular images of the widespread filaments around NGC 1275 in the Perseus cluster). The Balmer decrement indicates that the gas is dusty; emission from dust has been detected in the submillimetre band with SCUBA (Edge et al. 1999; Irwin. Stil & Bridges 2001) and significant *IRAS* or *ISO* emission is sometimes found (e.g. Allen et al. 2001a; Hansen et al. 2000). Molecular hydrogen is also common (Jaffe & Bremer 1997; Donahue et al. 2000; Edge et al. 2002) with spectra indicating shock heating (Wilman et al. 2000) and recently large quantities of CO emission have been seen (Edge 2001).

Where the information is available, the total submillimetre to UV emission appears to be sufficient to account for the missing soft X-ray emission. Thus if gas decouples from a cooling flow when its temperature is 1–2 keV and rapidly mixes with cooler gas to say a few 10^5 K then the gross appearance could resemble what is observed. The gas at a few 10^5 K would radiate and cool strongly through UV emission which, we assume, is reprocessed by cooler gas into the observed spectrum.

To show the relationship more clearly we have converted the Hα luminosity of well-studied cooling flow nebulosities $L_{\mathrm{H}\alpha}$ into a mass cooling rate from 1 keV; $\dot{M}_{\mathrm{H}\alpha}$. A factor of 30 has been included to account for the UV emission etc. from the emission-line nebula. This factor is appropriate for the mixing situation since the major energy loss by the freshly mixed gas will be ionizing ultraviolet radiation, which is absorbed by surrounding cold gas to yield the observed emission-line nebula. Thus

$$\dot{M}_{\mathrm{H}\alpha} = \frac{2}{3}\frac{30 L_{\mathrm{H}\alpha}\mu m}{kT} = 2\left(\frac{L_{\mathrm{H}\alpha}}{10^{40}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{kT}{1\,\mathrm{keV}}\right)^{-1}\mathrm{M_{\odot}\,yr^{-1}}.$$

We ignore $P\,\mathrm{d}V$ work done on the cooling gas here and assume that it is cooled instantaneously by mixing.

In Fig. 1 we plot an estimate of the X-ray mass cooling rate $\dot{M}_{\mathrm{X}}$ against $\dot{M}_{\mathrm{H}\alpha}$. For $\dot{M}_{\mathrm{X}}$ we use the results from deprojection of *ROSAT* data from Peres et al. (1998) and Allen (2000). These rates assume that a flow has lasted for a Hubble time and so are *upper limits*. We take them as a useful reference value against which to scale. For the optical data we use only imaging results (Heckman et al. 1989), which cover the whole core, for clusters at redshifts $z < 0.1$ and slit luminosities (Crawford et al. 1999) for clusters at higher redshifts, which may underestimate the total luminosity but not as severely as at low redshifts. The figure shows that the rate at which gas can be cooled by mixing and optical–UV emission is comparable with the maximum X-ray rates inferred for the massive luminous clusters. Undoubtedly some of the optical line emission is powered by star formation, but there is room for a mixing component (see fig. 18 in Crawford et al. 1999).

For less powerful clusters agreement requires that $\dot{M}_{\mathrm{X}}$ be reduced by a factor of about 10. This can in part be accomplished by taking a shorter age for the flow, from about 4 down to 1 Gyr respectively. A few Gyr is a plausible age if flows are disrupted by infalling subclusters (Allen et al. 2001). We note too that some cooling flows, such as A2029, have no detected line emission (Johnstone et al. 1987).

A further low-frequency energy loss is dust emission, which can boost the cooling rate of the gas. This emission can occur either through reradiation of absorbed ultraviolet and optical emission, or during sputtering if dust becomes mixed into the hot gas. In cases where estimates, or limits, are available (Allen et al. 2001a; Edge et al. 1999) the infrared emission significantly exceeds the inferred total line emission (Fig. 1, lower panel). For example, in the case of A2199 (see Johnstone et al. 2002), the IR luminosity of $\sim 10^{44}\,\mathrm{erg\,s^{-1}}$ is sufficient to absorb a flow of $600\,\mathrm{M_{\odot}\,yr^{-1}}$, which far exceeds the likely flow of 50–$100\,\mathrm{M_{\odot}\,yr^{-1}}$. Only for M87, where the equivalent cooling rate $\dot{M}_{\mathrm{IR}}$ is about 5 times $\dot{M}_{\mathrm{H}\alpha}$, is there insufficient low-wavelength power seen.

We note that some of the observed infrared emission from the central cluster galaxies could also be due to a central active nucleus; a SCUBA study of NGC 1275 in A426 by Irwin et al. (2001) found core emission that they attribute to the nucleus plus extended emission with another origin. The important point to note from Fig. 1 is not that there is any particular correlation but that, apart from M87, the infrared detections (or upper limits, if so interpreted) are a factor of 3 to about 100 above the level required to account for the missing X-ray luminosity.

We conclude that mixing of hot gas with the observed cold gas and dust can account, on gross energetic grounds, for the missing soft X-ray luminosity in many cooling flows, particularly if their ages are only a few Gyr.

In order to answer why mixing might only take place for the cooler, 10^7 K, gas in a flow, we first note that it is spatially coincident with the cold gas. Secondly, we note that a flow is probably thermally unstable because embedded magnetic fields allow density contrasts to grow within the gas. This is because fields cause the gas to comove. However it is not clear that the fields can prevent slippage when the density contrasts are high,

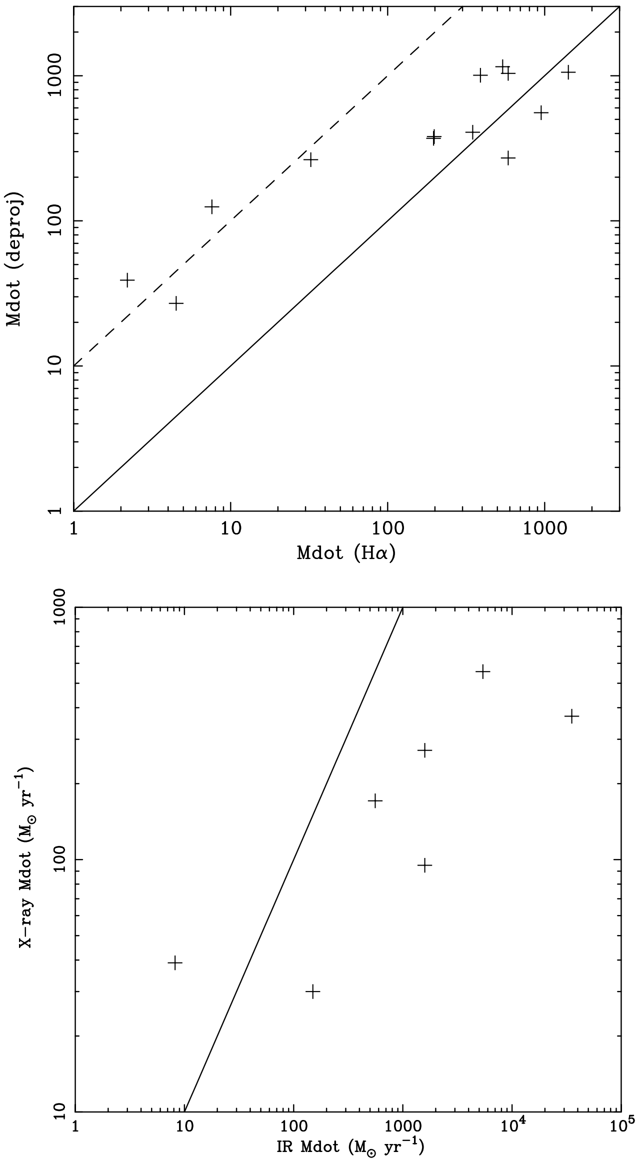

Figure 1. Maximum mass cooling rate inferred from X-ray observations (deprojection method assuming age is 13 Gyr) plotted against rate of gas cooling from 1 keV which would give (top) the observed Hα luminosity and (bottom) the observed infrared luminosity. Clusters from left to right in the top panel are M87, A262, A2052, Hydra A, A1795, A2390, A1068, A2204, A1835, PKS0745-191, A2597, A426, Zw3146. Those lying near the solid line have sufficient Hα luminosity to account for any missing soft X-ray luminosity from gas cooling below 1 keV in a flow at the rate derived from X-ray deprojection analysis, assuming a total cooling time of 13 Gyr (which is an unrealistic maximum time). The Hα emission from clusters lying near the dashed line can account for gas cooling at one tenth that rate. Clusters from left to right in the bottom panel are M87, Centaurus, A2199, A496 (lower – this may be an upper limit; see Allen et al. (2001a), A2597 (upper), A426, A1835 and A2390. There is clearly enough IR luminosity to account for and missing soft X-ray luminosity in all these clusters, apart from M87.

which occurs for the coolest gas. The gas may therefore be multiphase at all radii, with the temperature differences of comoving gas restricted to only a factor of say 1.5 to 2 at any radius. Denser, cooler clumps may fall ahead. If they mix with inner, X-ray-emitting, gas they could either heat it, causing cooling locally to slow down, or, if it is already cool, cause yet more gas to fall inward. We assume that the ultimate heat sink is the cold, atomic and molecular gas with which the gas eventually mixes. In this picture there would appear to be distributed mass dropout in the flow over the inner tens of kpc, with little sign of gas cooling radiatively below 1 keV.

Note that the strong increase in the cosmic cooling function below 10^7 K means that, at constant pressure, the power radiated per unit mass of gas at 10^5 K is about 1000 times greater than that at 10^7 K. If gas at 10^7 K is mixed with cold gas at a rate which enables the mixture to remain at 10^5 K, then the mixture need have only 1 per cent of the mass of the hotter gas, the soft X-rays from which will be only 10 per cent of the luminosity obtained had there been no mixing. Whether mixing can occur at a reasonable rate depends on the mixing process. Turbulent mixing layers (Begelman & Fabian 1990) yield a temperature for the mix which is at the geometric mean of the initial temperatures, so are a good candidate.

Direct evidence for the UV emission from the mixing region will be a good test of this hypothesis. As already noted, the FUSE data for A2597 support it, but similar data on A1795 do not (Oegerle et al. 2001). Cold gas and especially dust in the mixing region can absorb and complicate the predicted spectrum however. Deep searches for coronal lines (e.g. Fe X; see Yan & Cohen 1995 and references therein) can constrain the level of gas in the range $10^{5.5}–10^{6.5}$ K.

Magnetic fields have a further important effect if they are amplified in the flow by compression. At some point the magnetic pressure may dominate over thermal pressure and the flow change from (locally) being at constant pressure to constant density. This changes the work done on the gas by removing the $P\,\mathrm{d}V$ work meaning that the luminosity produced per unit mass cooling rate is reduced by a factor of 5/3. Inward of this point magnetic reconnection can heat the flow (Soker & Sarazin 1990) and also cause the magnetic topology to change (Norman & Meiksin 1996). We note that magnetic pressure cannot dominate the pressure beyond about 50 kpc in massive clusters with strong lensing since the mass estimates from strong lensing agree well with those based upon thermal hydrostatic pressure support for the gas (Allen et al. 2001).

3 HEATING SOURCES

We now discuss some constraints on any heat sources which balance cooling. As pointed out by Fabian et al. (2001b), a solution for the absence of gas cooling below 1–2 keV requires that the heat source either (i) stops the flow at all radii, or (ii) causes the coolest gas to vanish. Option (i) means that the heating has to be distributed over radius. Option (ii) is otherwise required because the emission measure distribution of the gas shows no sign of gas piling up at some small radius.

Some heating by a central radio source must be common. Whether it is sufficient is not yet clear. The X-ray data indicate that powerful sources blow a channel through the gas (e.g. Hydra A; David et al. 2001) or blow bubbles (e.g. Perseus cluster; Fabian et al. 2000a). A channel provides a geometry for expelling the coolest gas, but bubbles may be more difficult. They can lift up cooler gas (Böhringer et al. 1995; Churazov et al. 2001; Brüggen et al. 2002) but whether this provides the total means of expelling the coolest gas remains to be seen. We note that bubbles are expected to be in pressure equilibrium with their surroundings so only have enough energy to heat and double the temperature of a similar volume of gas (the internal energy of the relativistic component is $3PV$). The volume filling fraction occupied by the few observed bubbles in say the Perseus cluster appears to be small, so superficially it seems that the role of buoyant bubbles in heating gas is small.

For the Perseus cluster (Churazov et al. 2001; Fabian et al. 2002), the buoyancy time for a bubble to reach a radius of 50 kpc where the cooling time $\sim 10^9$ yr is $\sim 10^8$ yr so increasing the effective number of bubbles per cooling time by a factor of 10. What matters however is the (unknown) time-scale on which the bubbles lose their energy to the surroundings. The outer NW bubble has a similar energy to the inner ones so the loss time-scale may be long. If that time-scale is indeed long then the heating is small. If however the bubble energy loss time-scale is short, say a few 10^7 yr, then the effective number of bubbles is further increased by a few and the heating can be significant. The lifetime of the bubbles probably depends crucially on the magnetic fields in the bubbles and their interactions with the surroundings; such effects have not yet been modelled (Quilis et al. 2001). An important further issue is that radio sources have some axial symmetry which would imply axial symmetry in heating. This symmetry is generally not evident in the hot gas.

The heating rate per unit volume necessary to stop any flow can be deduced from the X-ray data. In the case of A2199 (Johnstone et al. 2002) the heating required in 10–20 kpc wide shells of increasing radii about the nucleus increases to values of about 10^{44} erg s^{-1} at about 100 kpc. This converts to a local heating rate of about $5 \times 10^{40} r^{-1.5}$ erg s^{-1} kpc^{-3}. The X-ray surface brightness distribution of A2199 has a similar shape to that of many cooling flows (i.e. the X-ray inferred mass deposition profiles of Peres et al. 1998 are similar) so we expect that the required heating rate variation with radius of approximately $r^{-1.5}$ is a general result. Of course it is only relevant within the region where the radiative cooling time of the gas is less than the age of the present cluster (typically out to radii of 30–100 kpc).

Cold fronts are common in cluster cores, including in some cooling flows (Markevitch et al. 2000; Markevitch, Vikhlinin & Mazzotta 2001; Mazzotta et al. 2001). They mark abrupt discontinuities in density and temperature over which the pressure is continuous. Presumably cooler and hotter clumps have yet to mix, presumably because transport processes and especially conduction are highly suppressed (Ettori & Fabian 2000). The profiles of some of the fronts indicate that the different gas phases are moving relative to each other at velocities which in some cases may be a significant fraction of the speed of sound. There is therefore considerable kinetic energy in the gas in many cluster cores. This could be the result of cool cores from infalling subclusters being decelerated without complete shocking (see e.g. Fabian & Daines 1991; Burns et al., private communication). The temperature drop at the centres of many clusters need not therefore be wholly caused by radiative cooling. The coolest and densest gas will of course sink to the central parts.

Provided the motions in the gas are subsonic, dissipation of its kinetic energy can change its cooling time by less than a factor of only 1.7: the thermal plus kinetic energy per ion in a gas of ionized H with 10 per cent He is given by

$$3.45 n_{\mathrm{H}} kT + 0.7 m_{\mathrm{p}} n_{\mathrm{H}} v^2 = 3.45 n_{\mathrm{H}} kT (1 + 5\mathcal{M}^2/9).$$

Unless there is a way to feed the kinetic energy into the innermost parts (e.g. by focusing sounds waves, Pringle 1989), this is not going to provide a solution to the problem. It may however cause the outer parts of the core to maintain a lower temperature than the rest of the cluster, yet not be cooling.

Finally we reiterate that the observed metallicity gradients limit the amount of convection and mixing that can occur. The gradients of iron in both the Centaurus (Sanders & Fabian 2002) and A2199 (Johnstone et al. 2002) clusters peak at values of about 1.5 and 0.7, respectively, at radii of about 30 kpc and may even decrease at smaller radii. Heating needs to extend out to radii of at least twice as far, where the cooling time is a few Gyr, in order be successful in stemming a cooling inflow. It also needs to be very specific in order to counter cooling which is proportional to the square of the local density.

4 RELEVANCE TO GALAXY FORMATION

A cooling flow phase occurs in the formation of massive galaxies (Nulsen & Fabian 1995) and what happens in this phase limits the mass of such galaxies. If all the gas that can cool does cool then there would be a significant tail of massive galaxies to the galaxy luminosity function, which is not observed. Simulations based on semi-analytic modelling of galaxy formation often recognize this by either truncating star formation when the circular velocity of the forming halo exceeds some value (e.g. Kauffmann et al. 1999; Somerville & Primack 1999) or making the star formation efficiency a function of the potential (e.g. Cole et al. 2000). Something prevents much of the gas in the cooling flow phase in massive galaxies from forming stars with a normal initial mass function. Either the gas is prevented from cooling down, or it does cool but does not make massive stars.

This problem appears similar to the one in clusters and may indeed have the same solution. If the gas is prevented from cooling down then there must be some heating. Accretion onto a central black hole is of course a potent source of energy. How that energy is transferred into heat in the gas is again not clear. If it is through radio jets forming bubbles, then we require that this is a common phase in the evolution of all massive galaxies, a phase that determines the final mass of those galaxies. This is contrary to what is usually assumed for radio sources, but not impossible. Further observations of cluster cores may shed light onto this important process.

5 DISCUSSION

Simple radiative cooling flows appear not to operate in clusters of galaxies, despite the large drops in gas temperature and short radiative cooling times seen in their central regions. The cores of observed clusters have insufficient soft X-ray luminosity. We have however shown here that there is in many clusters a possible excess of luminosity at longer wavelengths in the form of optical/UV line radiation and dust emission which can make up for much of this deficit. A model in which gas which has cooled from the mean cluster temperature by a factor of 3 or more falls and mixes, or conductively connects, with much colder gas near the cluster centre, is therefore viable on energetic grounds.

The prevailing explanation for the luminous examples of optical/UV/IR emission is massive star formation. The excess blue continuum light seen in these objects supports this, but the uncertainties in the level of agreement allow for a flux component from the mixing of gas.

We have noted that a heating explanation for the lack of cooling flows requires that the heating be widely distributed. Some heating by central radio sources must often occur, but whether it can on average balance radiative cooling to better than a factor of a few, particularly in massive clusters such as A1835, is unclear. A demonstration on energetic grounds that the radio source in M87 can heat the surrounding gas in the Virgo cluster does not establish that a similar process operates in cluster cores which are 100 times more luminous. Dissipation of gas motions is a further heat source but this is more likely to be important for the outer parts of a cluster core where a factor of 2 increase in cooling time can be very important, rather than for the coolest gas where it is relatively less important.

The minimum mean level of cooling flow in clusters is likely to be that which accounts for the formation of massive stars and molecular gas clouds seen in many objects. If it exceeds this value then the excess cooled gas forms either stars with a non-standard initial mass function or undetectable cold clouds. If some process stops the cooling of most of the gas below 1 keV, then this process limits the growth and final mass of massive galaxies.

Much deeper X-ray images and spectra are needed, together with further ultraviolet (e.g. FUSE) and infrared (e.g. SIRTF) spectra. ASTRO-E2 may enable important velocity measurements to be made of the intracluster medium in the inner parts of clusters.

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