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CLUSTER CORES AND COOLING FLOWS

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RESUMEN

La temperatura del gas en la región central (100 kpc de radio) de muchos cúmulos de galaxias disminuye hacia el centro por un factor de 3 o más. En esa región, el tiempo de enfriamiento radiativo disminuye de 5 o más giga-años a menos de 10^8 años. Si bien podría pensarse que el enfriamiento ocurre por flujos, los espectros del XMM-Newton no muestran evidencia de tasas altas de enfriamiento de masa por abajo de 1 - 2 keV. Las imágenes del Chandra muestran hoyos coincidentes con los lóbulos en radio y frentes fríos, lo cual indica que las regiones centrales son complejas. Se describe la situación observacional. Es probable que alguna forma de calentamiento sea importante para reducir las tasas de enfriamiento de la masa por factores de hasta diez. Se analiza la conducción de calor del gas caliente exterior, o el calentamiento por una fuente central, junto con posibles maneras de que pueda continuar el enfriamiento. Se exploran algunos paralelismos con la formación de la parte bariónica de las galaxias.

ABSTRACT

The gas temperature in the cores of many clusters of galaxies drops inward by about a factor of three 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 it would seem that cooling flows are taking place, XMM-Newton spectra show no evidence for strong mass cooling rates of gas below 1–2 keV. Chandra images show holes coincident with radio lobes and cold fronts indicating that the core regions are complex. The observational situation is reviewed. It is likely that some form of heating is important in reducing the mass cooling rates by a factor of up to ten. Conduction of heat from the hot outer gas or heating from a central radio source are discussed, together with possible ways in which continued cooling might occur. Parallels with the formation of the baryonic part of galaxies are explored.

Key Words: **CLUSTERS OF GALAXIES — COOLING FLOWS — GALAXY FORMATION**

1. INTRODUCTION

The gas density within the central 100 kpc or so of the centre of most clusters of galaxies is high enough that the radiative cooling time of the gas is less than 10^{10} yr. The cooling time drops further at smaller radii, suggesting that in the absence of any balancing heat source much of the gas in the central regions is cooling out of the hot intracluster medium. In order to maintain the pressure required to support the weight of the overlying gas, a slow, subsonic inflow known as a cooling flow develops.

X-ray observations made before Chandra and XMM-Newton were broadly consistent with the cooling flow picture (see Fabian 1994 for a review), although several issues remained unresolved. The first issue was the observed X-ray surface brightness profile, which was not as peaked as expected from a homogeneous flow. Instead, a multiphase gas was assumed, dropping cold gas over a range of radii. The second was the fate of the cooled gas. At the rates of 100s to more than $1000\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$ found in some clusters, the central galaxies should be very bright and blue if the cooled gas forms stars with a normal intial-mass-function. In many cases they do have excess blue light indicative of massive star formation (Johnstone, Fabian & Nulsen 1987; Allen 1995; Cardiel et al 1998; Crawford et al 1999; Bayer-Kim et al 2002), but at rates which are a factor of 10 to 100 times lower than the X-ray deduced mass cooling rate. It has also been argued (e.g. O'Dea et al 1994) that there is no significant sink in terms of cold gas clouds. A third issue involved the shape of the soft X-ray spectrum, which was inconsistent with a simple cooling flow. Absorption intrinsic to the flow was found to be a possible explanation (Allen & Fabian 1997; Allen et al 2001). A final issue was whether the neglect of heating was justified. The effect of gravitational heating as the gas flows was taken into account, but the effects of any central radio source, which pumps energy into the surrounding gas via jets, together with disturbances due to subclusters plunging into the core every few Gyr were not included due to a lack of quantitative information. Heat flow due to thermal conduction was also assumed negligible.

The situation with cluster cooling flows has been clarified over the past two years, particularly by the high spatial resolution imaging of Chandra and the high spectral resolution of the XMM-Newton Reflection Grating Spectrometer (RGS). Chandra images show much detail in the cores of clusters, with bubbles from radio sources (e.g. McNamara et al 2000; Fabian et al 2000; Blanton et al 2001) and cold fronts (Markevitch et al 2000; Vikhlinin et al 2001) seen. RGS spectra (Peterson et al 2001; Tamura et al 2001; Kaastra et al 2001) confirm the presence of a range of temperatures in cooling flow clusters but fail to show evidence of gas cooling below 1–2 keV. Simply put, the data are consistent with gas cooling at a high rate to about one third of the gas temperature beyond 100 kpc, but then vanishing.

At about the same time, the evidence for both warm (Jaffe & Bremer 1997; Donahue et al 2000; Edge et al 2001; Wilman et al 2002) and cold (Edge 2001; Salomé & Combes 2002) molecular gas (H_2 and CO) at the centres of cooling flows clusters has become widespread. In some extreme cases there may be over $10^{11}\,M_\odot$ of cold gas (Edge 2001).The presence of dust in these regions is also widespread, from evidence of the Balmer decrement in the optical/UV nebulosities commonly seen (e.g. Heckman et al 1989; Crawford et al 1999), dustlanes, and submm and IR detections (Edge et al 1999; Allen et al 2001; Irwin, Stil & Bridges 2001). It is therefore possible that some more star formation, and in particular cold gas clouds, may be found in and around central cluster galaxies. There has also been the detection of OVI emission from A2597 with FUSE at a level consistent with a moderate cooling flow (Oegerle et al 2001). Lastly, recent numerical simulations of evolving cluster which include radiative cooling of the gas predict cooling flows (e.g. Pearce et al 2000).

Some form of heating may balance radiative cooling but the source of heating remains unsolved, although several good candidates have been identified (e.g. Tucker & Rosner 1983; Binney & Tabor 1995). Heating from radio sources and infalling subclusters must occur at some level, but whether they can balance radiative cooling over the required spatial scales to better than a factor of a few is not yet clear. Thermal conduction is another candidate. Cooling probably does account for the observed star formation and cold gas clouds, but this may be confined to just the inner 10 kpc or so. Whether the mass cooling rates

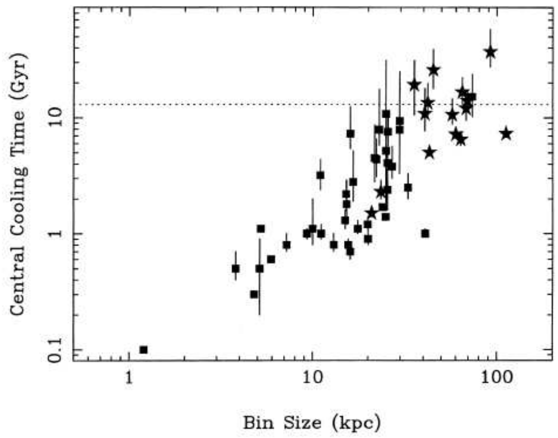

Fig. 1. Radiative cooling time inferred from ROSAT images of the brightest 50 clusters in the Sky (Peres et al 1997). The bin size depends on the quality of the data and is smallest for nearby peaked clusters. Note that most clusters have central cooling times less than a Hubble time (dashed line).

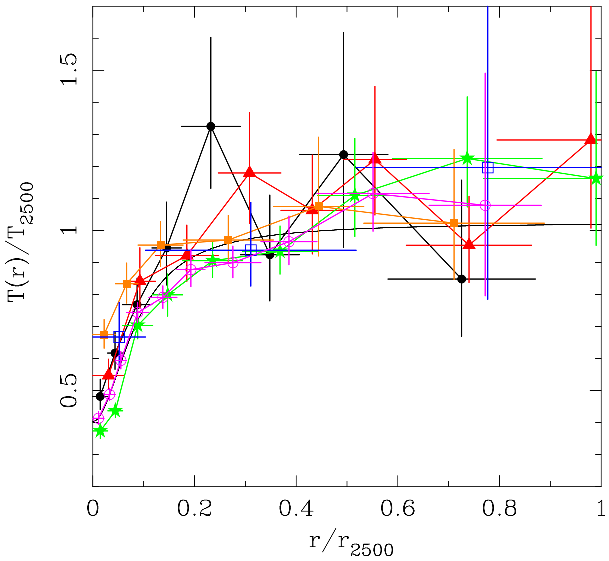

Fig. 2. Chandra temperature profiles for six massive clusters: PKS0745-191, A2390, A1835, MS2137-2353, RXJ1347-1145 and 3C295, from Allen et al (2001). Note the temperature drop within $\sim 0.2r_{2500} \sim 120\,\mathrm{kpc}$.

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are reduced from the earlier X-ray deduced rates by a factor of a few, ten or a hundred is unclear.

Some form of feedback is probably required to prevent all of the gas from being heated up. If feedback does occur we have a good chance to observe how it works, since the region is spatially resolved and optically thin. The process is of wide importance, since feedback modulated cooling is a key ingredient in the baryonic part of galaxy formation.

This is an updated and extended version of Fabian (2002d).

2. CHANDRA RESULTS

Chandra images show structure in cluster cores. The X-ray emission is steeply peaked into the centres of many clusters but there are holes and fronts in the peak. Markevitch et al (2000) found sharply defined cold fronts on A2142, across which the pressure is continuous yet the temperature changes by a factor of about 2. Ettori & Fabian (2000) note that thermal conduction must be heavily suppressed at the fronts in order that such sharp features can last long enough to be common. The fronts probably indicate that the gas of subclusters does not readily mix with the existing intracluster medium, presumably because they are separate magnetic structures. Also the cores of infalling subclusters need not be strongly shocked in decelerating into the core (see Fabian & Daines 1992).

2.1. *The Perseus, Centaurus and Virgo clusters*

Holes in the X-ray surface brightness are seen to coincide with some radio lobes. Good examples are in the Perseus cluster (Figs. 3 and 4), and were first seen with ROSAT (Böhringer et al 1993). Chandra shows that they have bright rims of X-ray *cool* gas (Fabian et al 2000a; Schmidt et al 2002). This is contrary to the work of Heinz et al (2000) who predicted that the rims would signify shocks. Other holes coincident with radio lobes are found in Hydra A (McNamara et al 2000; David et al 2001; Nulsen et al 2002) and many other clusters (e.g. A2052, Blanton et al 2001; A2597, McNamara et al 2002). The puzzling aspect if radio sources are heating the cooling gas is that in all cases reported the *coolest* gas seen is that closest to the radio lobes. Of course there is much energy going into the lobes, but the energy from the PdV work expended in forming the holes can propagate away as sound waves, and the relativistic energy stored in the bubbles (Fabian et al 2002a) can be lifted away and out of the immediate core by buoyancy.

The Centaurus cluster (Fig. 5; Sanders & Fabian 2002) shows a swirly structure of X-ray cooler gas.

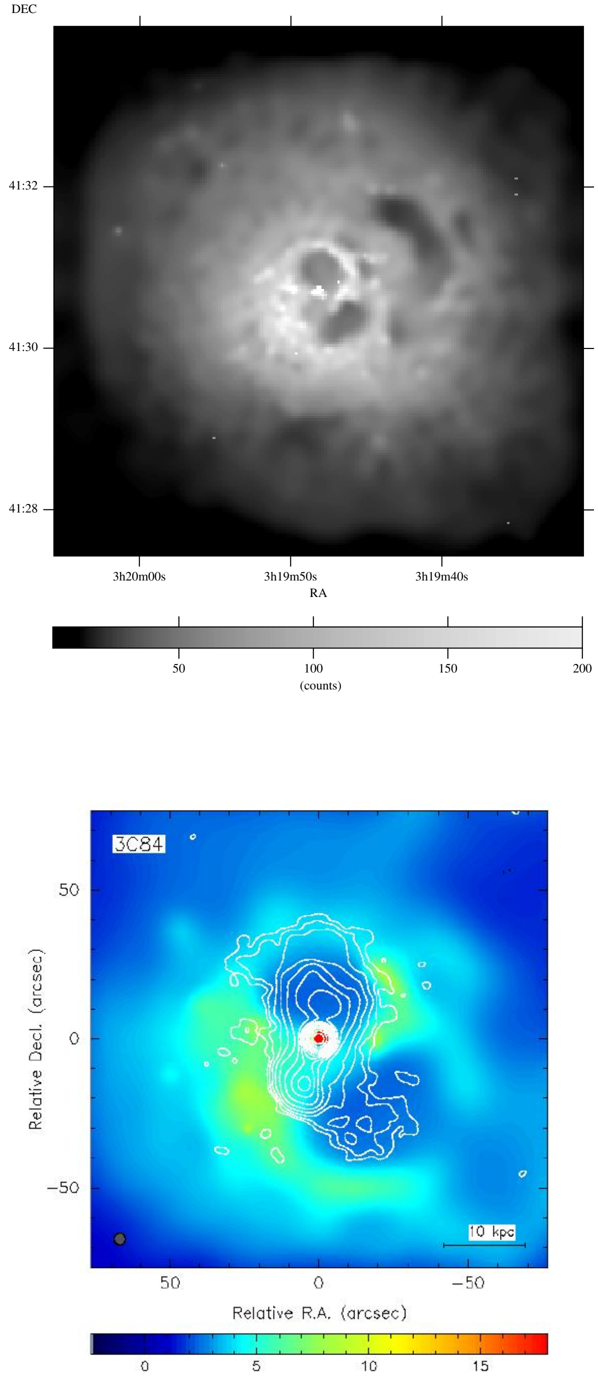

Fig. 3. (Top) Adaptively-smoothed 0.5–7 keV ACIS-S X-ray image of the Perseus cluster; (Bottom) Radio image (1.4 GHz restored with a 5 arcsec beam, produced by G. Taylor; see Fabian et al 2000a) overlaid on an adaptively smoothed 0.5–7 keV X-ray map. See color Plate 7.

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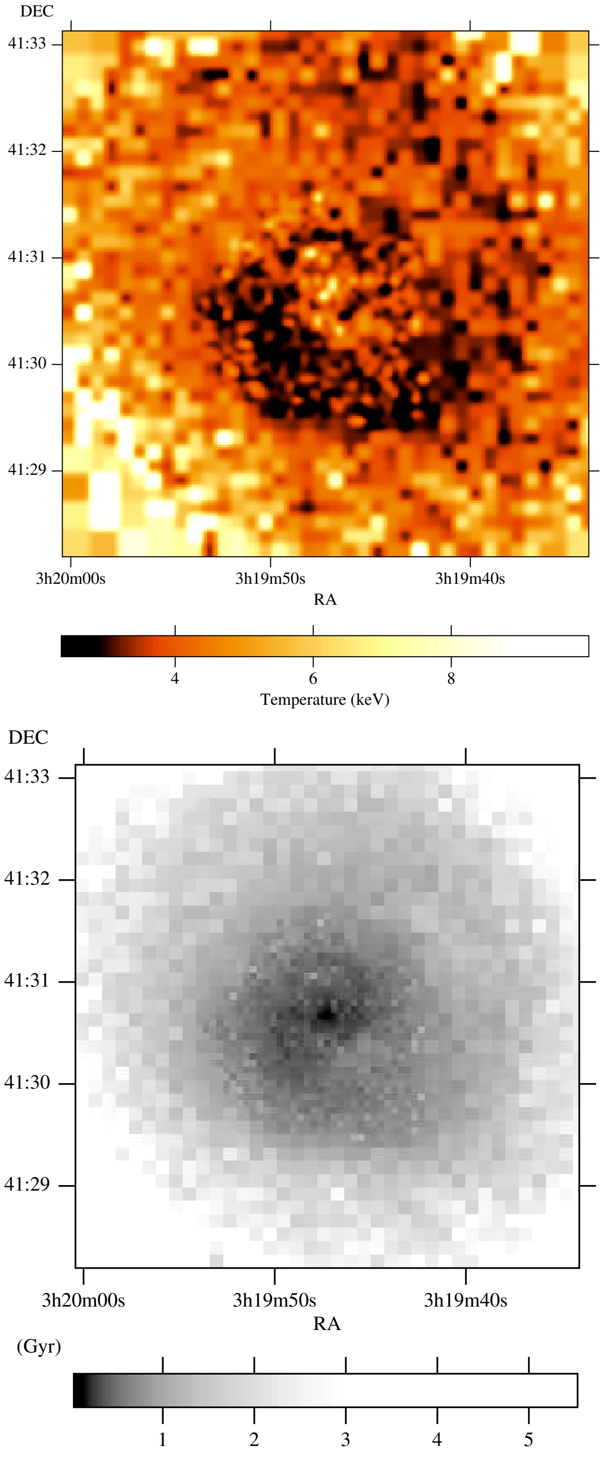

Fig. 4. (Top) Temperature and (Bottom) radiative cooling time maps of the Perseus cluster (Fabian et al 2000a). Note that the coolest gas ($T \sim 2.5\,\mathrm{keV}$) with the shortest cooling time (~ 0.3 Gyr) lies in the rim around the N lobe, and the swirl to the temperature map. Single-phase gas has been assumed for the analysis. See color Plate 7.

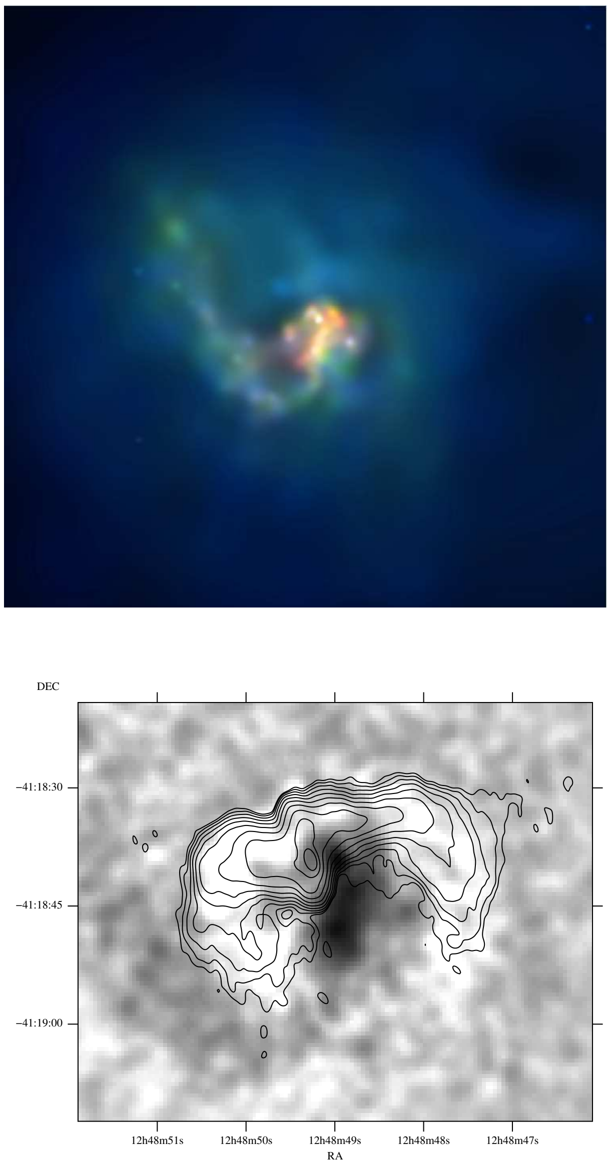

Fig. 5. (Top) Colour image of the Centaurus cluster, with red indicating the coolest gas (see color Plate 8). (Bottom) radio contours on an unsharp mask of the X-ray image, showing that the radio source has displaced the X-ray gas.

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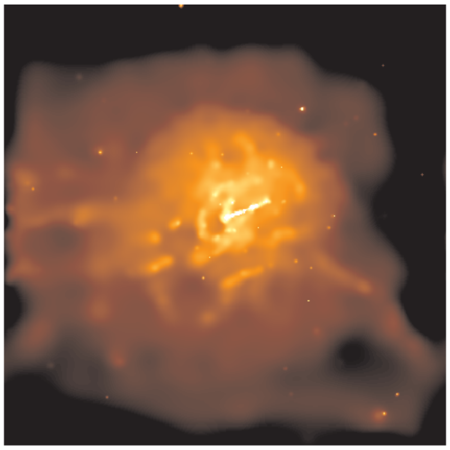

Fig. 6. 40 ks Chandra image of the core of the Virgo cluster (Young, Wilson & Mundell 2002). The famous M87 jet is seen pointing at 2 o-clock in the centre. See color Plate 8.

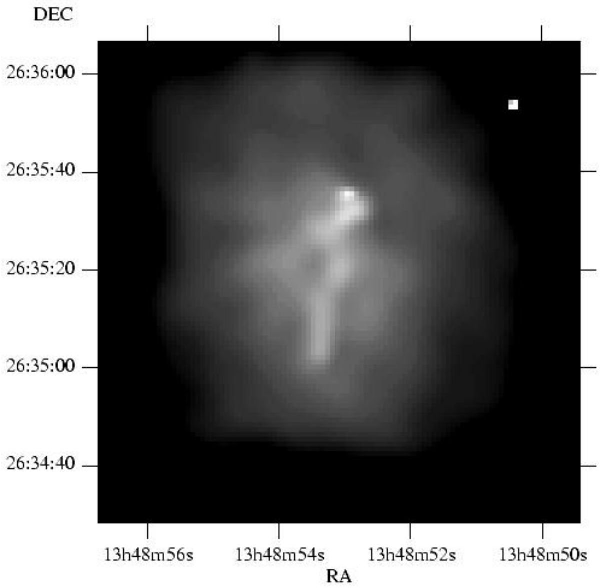

Fig. 7. Adaptively-smoothed X-ray image of the centre of A1795 (Fabian et al 2000b).

The radio source sits around the cooler central blob, displacing the X-ray emission. Strong Faraday Rotation is seen in the radio source (Taylor et al 2002), indicating significant magnetic fields in the surrounding gas. Field amplification could result from the inflow associated with a cooling flow.

The Virgo cluster (Fig. 6; Young, Wilson & Mundell 2002) shows ridges to the N of the nucleus coincident with optical filaments and some bubble-like features. Cool structures extend along the outer radio lobes to the E and SW (see also ROSAT and XMM-Newton; Böhringer et al 1995; 2001). The Eastern one is likened to a mushroom cloud following an explosion by Churazov et al (2001).

2.2. *A1795 and A2199*

The Chandra image of A1795 (Fabian et al 2000b; Ettori et al 2002) shows an 80 kpc long soft X-ray feature coincident with an Hα filament found by Cowie et al (1982). It is plausibly a cooling wake trailing behind the central galaxy, which is at the head of the filament. The galaxy is moving around in the core of the cluster at a few hundred $\mathrm{km\,s^{-1}}$. There is no evidence from the temperatures of the gas that this motion has heated the gas significantly. The central galaxy in A2199 may also be oscillating, as deduced from the unusual morphology of its radio source (Burns et al 1983) and X-ray emission. Again, the coolest gas appears to be close to both the radio source and the central galaxy (Johnstone et al 2002).

The (deprojected) temperature and metal abundance profiles in A2199 are shown in Fig. 9 (from Johnstone et al 2002). As is now seen to be typical for such objects, the temperature drops by about a factor of three. The radiative cooling time of the gas is around 10^{10} yr at 100 kpc, 7×10^{8} yr at 10 kpc and $\sim 10^{8}$ yr within 2 kpc. The heating rate required to maintain the gas in thermal equilibrium is also shown in Fig. 9. It is clear from this plot that the heating must be distributed and cannot just occur at the very centre. What is required is roughly equal amounts of power per kpc around the centre.

The emission measure distribution of the gas in the core of A2199 is also compared with that for a cooling flow in Johnstone et al (2002). This distribution increases with radius, whereas that expected from a single-phase cooling flow is weakly decreasing. So although the temperature profiles resemble those of cooling flows, the emission measure distribution (and thus the gas density distribution) does not.

3. XMM-NEWTON RESULTS

The most striking results have come from the RGS data which show little evidence for gas cooling below 1–2 keV (Fig. 10; Peterson et al 2001, 2002; Tamura et al 2001; Kaastra et al 2001). These grating spectra of the inner 30 arcsec of cluster cores are at higher spectral resolution than previous observations, and clearly show the Fe-L lines of Fe XXII-XXIV at 10–13A from gas at about one third the outer cluster temperature. Emission lines from FeXX and XVII at 13–18A should however be bright

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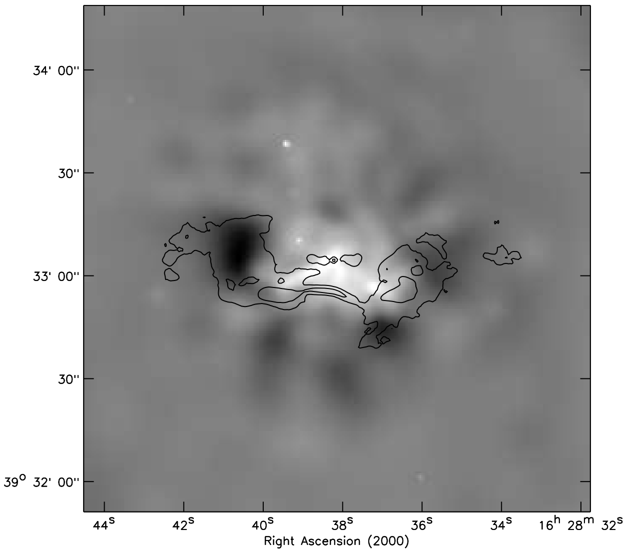

Fig. 8. X-ray image of A2199 with overlaid radio contours (Johnstone et al 2002).

and easily seen if a continuous cooling flows is taking place, but they are absent. EPIC CCD spectra (e.g. Böhringer et al 2001; Molendi & Pizzolata 2001) confirm this result. For a range of objects the upper limits on the mass cooling rate are about one fifth of that previously proposed.

In summary, the data for a typical relaxed cluster show that the radiative cooling time of the gas is about 10^{10} yr at 100-200 kpc from the centre, decreasing monotonically by one to two orders of magnitude inward to the centre. The gas temperature decreases to the centre by at least a factor of three. The spectrum of the whole region is consistent with gas cooling steadily from the outer temperature to about one third of that value at a rate which may be high ($\dot{M} \sim 100 - 1000\,\mathrm{M_\odot\,yr^{-1}}$ in massive clusters), but the limit on gas cooling below one third of the outer temperature is only 20 per cent of that level of $\dot{M}$. The surface brightness is not as peaked as expected from a single phase cooling flow (i.e. a single temperature at each radius) but would require a multiphase flow (i.e. a range of temperatures at each radius). There is little evidence for any extreme multiphase gas with temperatures ranging over an order of magnitude (see Molendi & Pizzolato 2001 and Johnstone et al 2002 for limits on multiphase gas) but it would be difficult to rule out a factor of two range variation.

It seems likely that the temperature drop is due to cooling (although gas from incoming cool subclus-

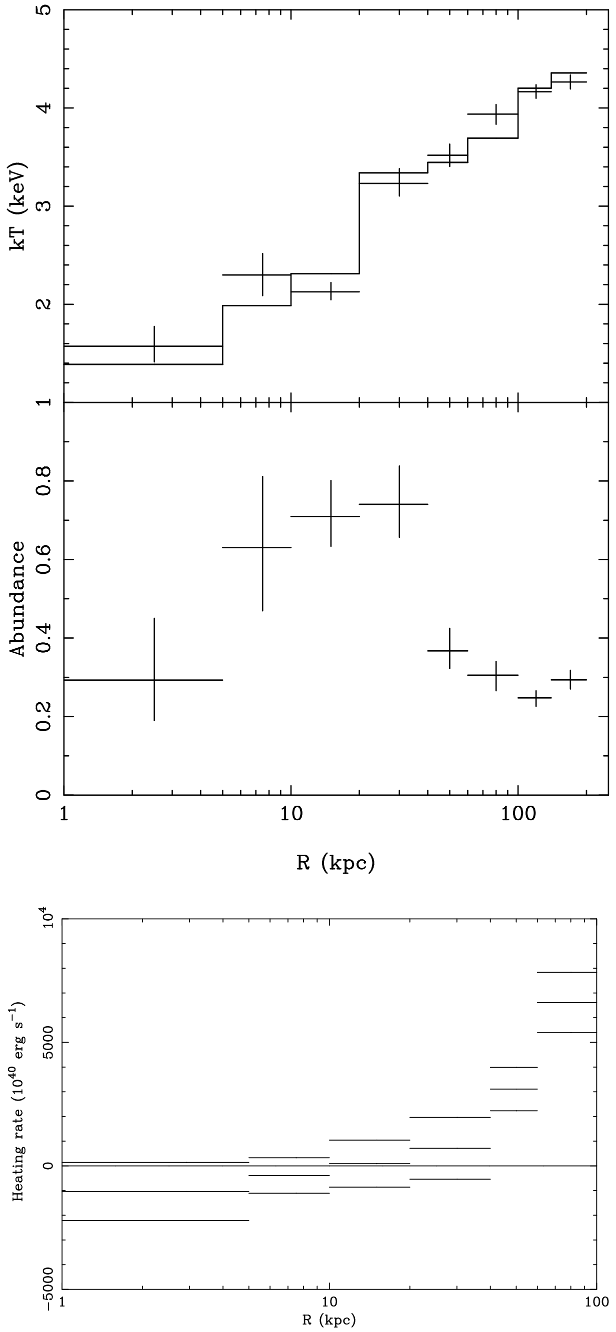

Fig. 9. (Top) Deprojected temperature and (Middle) Abundance profiles for A2199. (Bottom) Heating rate required to maintain mass flow rates of 0 (top set of lines), 50 (middle set) and 100 (lower set) $\mathrm{M_\odot\,yr^{-1}}$ in A2199.

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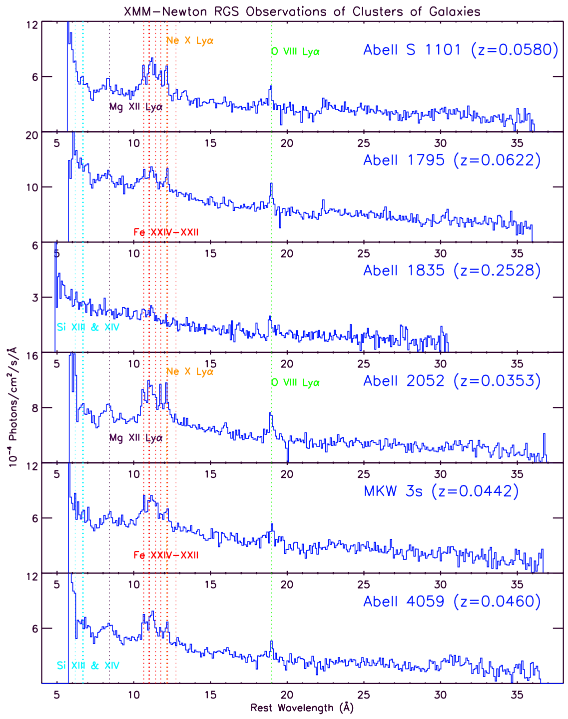

Fig. 10. RGS spectra of 6 cooling flow clusters, kindly provided by J. Peterson and J. Kaastra. Emission lines between 10-13 A indicate the presence of cooler gas in these clusters (at 1–3 keV), but the lack of lines between 13 and 18 A shows that gas is not radiatively cooling below 1–2 keV at high rates in any simple unobscured manner.

ters may contribute). This raises the problem of why the gas does not appear to cool below about one third of the outer temperature.

4. HEATING AND COOLING

Various explanations have been discussed (e.g. Peterson et al 2001; Fabian et al 2001; 2002b; Böhringer et al 2002). They can be split according to whether heating plays a major role or not.

4.1. *Solutions without heating*

The gas may be cooling and yet appear to vanish when it reaches say 2 keV. Clouds of cold gas may, for example, photoelectrically absorb the soft X-rays. So far no exhaustive testing of this possibility has been carried out but it is unlikely to work unless the absorbing gas is intimately related to the cooling gas blobs.

The gas may have become dense enough to separate from the flow and mix in with surrounding hotter gas (Norman & Meiksin 1996). In this category are also some models involving a central radio source which is merely required to drag the coolest gas from the very centre out to larger radii (David et al 2001; Nulsen et al 2002). Such rearrangement of the gas does not of course change the long term cooling rate of the whole region. Taking the cooler gas rapidly to larger radii may adiabatically cool it, possibly reducing the observed emission from the 0.2–1 keV temperature range, but the gas would still cool (for bremsstrahlung the cooling time goes as pressure$^{-0.4}$ and is roughly constant with pressure for line-dominated cooling; the pressure changes by about a factor of 10 over the inner 100kpc). Only if the gas can be dragged out well beyond the inner 100 kpc would the total cooling flow rate to below 10^6 K be significantly reduced.

Alternatively, it may mix in with colder gas (for example, that associated with the optical filaments or the molecular gas, which would explain why the filaments are so bright; Fabian et al 2002b). The problem is then best seen as one of missing soft X-ray luminosity (i.e. that of the X-ray coolest gas). The missing luminosity may emerge in the FUV or infrared bands.

Another possibility is that the metals in the gas are not uniformly mixed in, but have a bimodal distribution (Fabian et al 2001; Morris & Fabian 2002). Gas in which ten per cent has a metallicity of 3 times solar and 90 per cent has zero metallicity has the same spectrum as gas at 0.3 solar if cooling is unimportant. When it does cool, however, the metal emission lines cool only 10 per cent of the gas and so are much reduced as compared with the situation if they were responsible for cooling all the gas. This model has not yet been thorughly tested (assuming that the inhomogeneities occur on scales much less than a kpc). It could account for the puzzling central metallicity decrease seen in A2199 (Fig. 9, Johnstone et al 2002) and in the Centaurus cluster (Sanders & Fabian 2002), since the innermost gas will have been depleted of metal rich gas.

Solutions with little heating, at least within the inner tens of kpc, remain of interest as they seem best able to explain the FUSE detection of OVI (Oegerele et al 2001) in A2597.

4.2. *Solutions with heating*

Two main heating solutions have been proposed, making use of two large sources of energy; a central black hole and the outer cluster gas. The first uses a central radio source, which is a common constituent of such clusters and the other invokes conduction of heat from the outer parts of a cluster.

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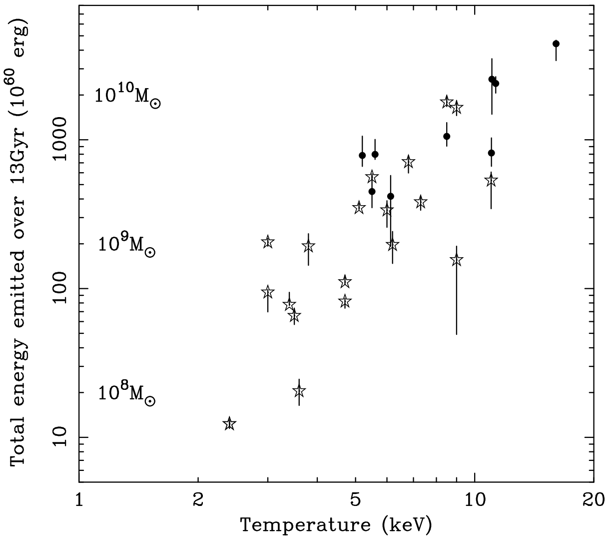

Fig. 11. Energy requirement in order to balance the radiative cooling of cluster cores (Fabian et al 2002). The energy radiated within the region where the cooling time is 10^{10} yr is shown for about 25 clusters. The total black hole mass accumulated assuming an efficiency of 10 per cent is indicated.

First, let us look at the level of heating required. It cannot just be some low level of heat which stops the gas at 1–2 keV, since that would cause an accumulation at that temperature, contrary to observation. It has to halt the cooling over the full range of temperatures, and thus radii. How this can happen is a puzzle. If the radio source is responsible, then it may be intermittent. Maybe we do not see the heating phase, which is short lived. The power required to stem the flow during the heating phase then goes up to high values. There may not be any problem in the Virgo cluster around M87 (e.g.Churazov et al 2002) where the energy requirements are relatively small, but in a massive cluster like A1835 (Peterson et al 2001; Schmidt et al 2001) the necessary power may exceed $10^{46}\,\mathrm{erg\,s^{-1}}$.

The energy requirement is shown in Fig. 11 (Fabian et al 2002c). For massive high temperature clusters, energy balance requires that most of the accretion energy of a massive central black hole go into heating the surrounding gas. This probably has to happen in a radiationless manner around the black hole, with little of the accretion energy appearing as radiation which couples very poorly with the intracluster medium, and most of it as jet energy which is then required to couple well. Radiation-inefficent flows such as ADAFs (e.g. Narayan et al 1995) are not appropriate for such large implied accretion rates (this is a problem for the feedback model for M87 of

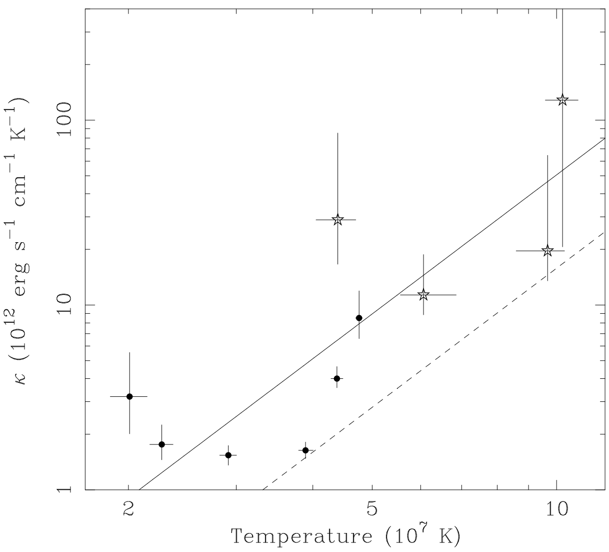

Fig. 12. The effective conductivity required to balance cooling in A2199 (solid circles) and A1835 (stars; Voigt et al 2002). The solid line represents conduction at the Spitzer rate and the dashed one is one third of that rate.

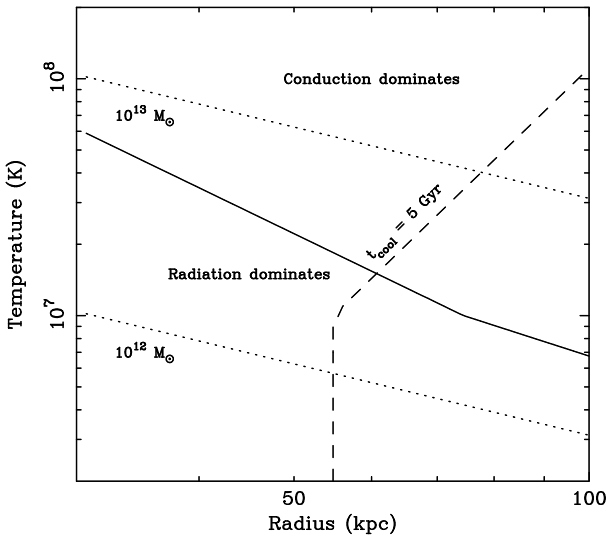

Fig. 13. Conduction-dominated regime, where conduction can balance radiative cooling, for gas in an isothermal dark matter potential well (Fabian et al 2002). The gas fraction is 10 per cent.

Churazov et al 2002, which requires that at least 99 per cent of the accretion energy goes into a jet). Only if the energy being tapped is the spin energy of the black hole, could the low radiation, high jet power, constraints be met.

Radio source models must do the heating in a manner that leaves the surroundings of the inner radio bubbles cool. Various simulations have shown that some heating does take place, and have presumed that it is sufficient (Churazov et al 2000; Quilis et al 2001; Brüggen & Kaiser 2001; Reynolds et al 2002). There seems to be enough power in the FRI jets to balance the cooling in modest cooling flows (as noted by e.g. Pedlar et al 1990) if it can be effectively targetted. What has yet to be shown is that the jet power can heat the intracluster medium in a distributed manner leaving it looking like observed clusters. If too much power is used then presumably the jets break through as in Cyg A and dump most of their power at large radii beyond the cooling region.

There is no doubt that the radio sources push the gas around and ought to do some heating, but the level of heating has yet to be determined. Note that the gas must not be stirred to the extent that the abundance gradients are destroyed. Feedback models where some accretion is followed by a heating phase seem most promising.

The other large heat source is the outer intracluster medium. The cooling region within 100 kpc is only a few per cent of the total mass of gas in a cluster and the outer gas is hot. Narayan & Medvedev (2001) have noted that the level of conductivity required to offset cooling is similar to the Spitzer value expected in a plasma. Indeed, they have shown that in a turbulent magnetized plasma a value of about one quarter of the Spitzer one could be appropriate.

Voigt et al (2002) have used deprojected temperature and emission measure profiles of clusters to determine the effective conductivity required. Interestingly, for A2199 and A1825 it is less than the Spitzer value over a significant temperature (and thus radius) range (Fig. 12). Further work by Zakamska & Narayan (2002) indicates that there are clusters for which Spitzer conductivity may not be sufficient.

Conduction is suppressed in cold fronts and may be suppressed throughout most cluster cores. Different parts of the gas may have, for example, different magnetic structures. Conduction may be time variable and intermittent. Perhaps an intital cooling flow leads to a radial magnetic field structure which enables efficient conduction to operate. Conduction is an interesting, but unproven, component.

5. GALAXY FORMATION

Much of the gas in the formation of massive galaxies behaves as in a cooling flow (White & Frenk 1991). Some form of feedback is required to prevent everything from cooling at the earliest times, and cooling must be switched off in the most massive objects (Kauffmann et al 1999). If we cannot understand what is going on in cluster cores, then why should we believe models for galaxy formation which rely on a similar process?

The feedback in galaxies is assumed to be due to supernovae, but it is plausible that a central black hole is also important, especially given the correlations between black hole and galaxy mass (Gebhardt et al 2000; Ferrarese & Merritt 2000). Only a few per cent of the accretion energy of a central black hole is sufficient to unbind the host galaxy. It is then puzzling why cooling should proceed in galaxies (giving their stellar mass) but fail in clusters.

The conduction solution to cooling flows gives one answer to this, since conduction works best at high temperatures, whereas cooling works best at low temperatures. The regimes where conduction and radiative cooling dominate in gas trapped in an isothermal dark matter well are shown in Fig. 13 (from Fabian et al 2002c). This shows that if conduction does proceed unsuppressed in galaxy formation then it moulds the upper mass limit for galaxies.

6. SUMMARY

The central 100 kpc radius region in most clusters has a radiative cooling time shorter than 5 Gyr and many have cooling times which drop to the centre to a value of only 10^8 yr or so. The gas temperature drops by a factor of 3 or more over this radius range. It is plausible that the temperature drop and short radiative cooling times are related and that the low temperatures are caused by radiative cooling.

It is then a puzzle as to why gas which has lost two thirds of its thermal energy, and for which the radiative cooling time is very short, is not seen to cool further.

There are two obvious solutions, both of which have some difficulties. The first solution is that the gas does cool, but either the soft X-ray emission is absorbed or the cooling is non-radiative and due, say, to mixing. The problem of the fate of cooled gas then remains, although significant masses of cold gas have been found in some objects. The second solution is that some heating balances cooling. The problem here is that the heating has to balance cooling over a wide range of radii and a wide range of timescales. Observations of radio lobes which are a likely source of heat indicate that they coincide with the coolest gas in cluster cores. Heating by conduction is promising for some clusters, although it requires that conduction proceed at close to the Spitzer rate.

The data are consistent with modest levels of cooling ($\dot{M}$ of tens rather than hundreds $\mathrm{M_{\odot}\,yr^{-1}}$) continuing in the inner tens kpc in many clusters but with some heating, perhaps intermittent, balancing most of the radiative cooling at large radii.

7. ACKNOWLEDGEMENTS

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