On the soft X-ray spectrum of cooling flows

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Abstract

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ABSTRACT

Strong evidence for cooling flows has been found in low-resolution X-ray imaging and spectra of many clusters of galaxies. However, high-resolution X-ray spectra of several clusters from the Reflection Grating Spectrometer on *XMM-Newton* now show a soft X-ray spectrum inconsistent with a simple cooling flow. The main problem is a lack of the emission lines expected from gas cooling below 1–2 keV. Lines from gas at about 2–3 keV are observed, even in a high-temperature cluster such as A1835, indicating that gas is cooling down to about 2–3 keV, but is not found at lower temperatures. Here we discuss several solutions to the problem: heating, mixing, differential absorption and inhomogeneous metallicity. Continuous or sporadic heating creates further problems, including the targeting of the heat at the cooler gas and also the high total energy required. So far there is no clear observational evidence for widespread heating, or shocks, in cluster cores, except in radio lobes which occupy only part of the volume. Alternatively, if the metals in the intracluster medium are not uniformly spread but are clumped, then little line emission is expected from the gas cooling below 1 keV. The low-metallicity part cools without line emission, whereas the strengths of the soft X-ray lines from the metal-rich gas depend on the mass fraction of that gas and not on the abundance, since soft X-ray line emission dominates the cooling function below 2 keV.

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

1 INTRODUCTION

X-ray spectra of the cores of clusters with cooling flows made with the Reflection Grating Spectrometer (RGS: den Herder et al. 2001) on *XMM-Newton* show a remarkable lack of emission lines from gas at 1 keV or below. For the cluster A1835, at redshift $z = 0.2523$, both *Chandra* (Schmidt, Allen & Fabian 2001) and *XMM-Newton* (Peterson et al. 2001) CCD spectra show a strong temperature decrease towards the cluster centre from about 9 keV down to about 3 keV. RGS spectra (Peterson et al. 2001) are well fitted by a model of gas cooling over that energy range, at a rate of about $1000 \, M_\odot \, yr^{-1}$, but not to lower temperatures. There is clear evidence for emission lines from Fe XXIV, but not from lower ionization stages such as Fe XX–XXII and in particular Fe XVII which characterize gas cooling through temperatures of 1 keV and below, respectively. The limit on the rate of gas cooling below 1 keV is about $150 \, M_\odot \, yr^{-1}$. A similar temperature decrease inward is seen in *Chandra* (Fabian et al. 2001) and *XMM-Newton* (Tamura et al. 2001) CCD spectra of A1795 ($z = 0.063$), again

with no emission lines from gas cooling through and below 1 keV apparent in the RGS spectra (Tamura et al. 2001). The low-temperature cooling rate limit in this case is about $140 \, M_\odot \, yr^{-1}$, which is close to the total cooling rate inferred from *ASCA* spectra (Fabian et al. 1994; Allen et al. 2001a).

Various explanations for this disagreement with simple cooling flow expectations (see Fabian 1994 for a review) are given by Peterson et al. (2001). Just invoking a heat source is not sufficient, unless it has very specific properties, since gas does not appear to accumulate at 3 keV; it appears to cool down to that temperature and then vanish. Moreover, since gas at 3 keV occupies less than 6 per cent of the volume of gas at 9 keV, any heating needs to be targeted. It is possible that the 3-keV gas mixes with hotter or much colder gas, or absorption becomes important for cooler gas. We discuss these problems and possibilities here in more detail.

Finally we advance a new possibility involving strong metallicity variations in the intracluster gas. The line radiation from intracluster gas above 3 keV is proportional to its metallicity, but if it cools to lower temperatures where line radiation dominates the cooling function, the predicted line strengths depend on the mass fraction of the gas that is metal-rich. That fraction may be small.

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2 HEATING

Many authors have suggested that radiative cooling in cluster cores is offset by some form of heating. Some scenarios invoke conduction with the hot gas being the heat source (Tucker & Rosner 1983; Bertschinger & Meiksin 1986; Gaetz 1989). Others suggest that activity from the nucleus of the central galaxy is responsible (Rosner & Tucker 1989; Böhringer & Morfill 1989; Loewenstein, Zweibel & Begelman 1991; Binney & Tabor 1995; Tucker & David 1997; Soker et al. 2000; David et al. 2000).

We note that the mass of gas at about 3 keV in A1835 is consistent with that expected from radiative cooling of the hotter 9-keV gas. The radiative cooling time, t_c, of gas at 3 keV is about 20 per cent of that at 9 keV [for bremsstrahlung cooling at constant pressure $t_c \propto T^{3/2}$; $t_c(3\,\mathrm{keV}) \sim 1\,\mathrm{Gyr}$ or less in A1835], so in a steady flow the mass of gas below 3 keV is only 20 per cent of that below 9 keV, within the flow. If gas were accumulating at 3 keV for the lifetime of the flow, then there would be five times more of it than expected from steady cooling alone. This is inconsistent with the observed mass fractions. If steady heating is responsible then it has to be some form of 'complete' heating which takes the gas back up to the higher temperature, since there is no evidence for significant amounts of gas at other temperatures.

One mechanism for this has been suggested by Norman & Meiksin (1996). They propose that the magnetic topology of the gas changes as it cools down and at some point, say 3 keV, reconnection enables rapid thermal conduction to occur between the cooler gas and the hotter surrounding gas. Why this should happen throughout the flow at 3 keV is unclear. It could be that magnetic fields pin cooling blobs into comoving with the flow until the density contrast becomes so great that they fall and mix into the surrounding hotter gas, or perhaps this is when magnetic fields dominate the pressure (for a cooling spherical cloud, magnetic pressure $P_B \propto T^{-4/3}$). As noted by Norman & Meiksin (1996), mechanisms such as 'hot mixing' do not actually stop the cooling flow altogether since energy is being lost, unless the hotter phase is thermally coupled by conduction to the outer hot gas beyond the cooling flow. *Chandra* images of 'cold fronts' in some clusters (Markevitch et al. 2000; Vikhlinin, Markevitch & Murray 2000) indicate that conduction there is highly suppressed (Ettori & Fabian 2000).

Note too that the volume occupied by gas below temperature T in a cooling flow $\propto T^{5/2}$ if bremsstrahlung dominates; below a few keV where line cooling dominates then the dependence is steeper. This means that gas below 3 keV in a flow originating at 9 keV occupies less than 6 per cent of the volume of the hotter gas. Heating must be targeted at this small volume if cooling down to 3 keV is to take place. The volume is yet smaller if we allow for gravitational work done on the gas.

Thermal conduction also has a steep temperature dependence ($T^{5/2}$ if proportional to the Spitzer rate) which means that it will operate principally in the hotter gas rather than in the cooler gas in the system (see also the discussion by Bregman & David 1988).

An alternative to steady heating is sporadic heating. The nucleus, for example, may have short intervals of strong activity interspersed with periods of relative quiescence. Several heating models have been proposed along these lines (Rosner & Tucker 1989; Binney & Tabor 1995; Tucker & David 1997; Soker et al. 2000). In an analysis of *Chandra* data of the Hydra A cluster, David et al. (2000) find from spectra that the rate at which gas cools to low temperatures in the inner 30 kpc is inconsistent with the rate of gas flow into this region, and invoke sporadic heating by the radio source to heat the remainder.

Problems with this scenario are (i) the large energy input required, and (ii) efficient coupling of that energy to the gas. For example, the thermal energy of the gas within 100 kpc of the centre of A1835 is about 3×10^{61} erg. To heat two-thirds of this (i.e. to take the gas back from 3 keV to 9 keV) requires a power of 2×10^{46} erg s^{-1} for 3×10^7 yr if the coupling efficiency is 100 per cent. This exceeds the total power of an extreme (and rare) radio source such as 3C 295 (Allen et al. 2001b, where the radio emission is assumed to be only 10 per cent of the radio power). Most of the power of such sources is, however, deposited beyond the core, since the lobes propagate through the intracluster medium rapidly [$\sim 10^7$ yr to cross 100 kpc for 3C 295, using the radio hotspot speed of Perley & Taylor (1991)].

Lower powers could be used for longer times, but then the probability of seeing a cooling flow being heated becomes significant and no such example has yet been identified. Observations of cooling flows around radio sources, e.g. 3C 295 (Allen et al. 2001b) and 3C 84 (Fabian et al. 2000), show no evidence for heating taking place beyond the radio lobes, which occupy only a small fraction of the volume. Indeed, in the case of 3C 84 in the Perseus cluster the data show that the *coolest* gas in the core lies immediately around the radio lobes (Fabian et al. 2000; see also Böhringer et al. 1995 for M87, where the gas close to the radio lobes is cooler than the surrounding gas). Nevertheless, heating of some of the gas (at least that in the lobes) in cluster cores by radio sources must take place. Whether it can be sufficient to offset cooling in a massive system such as A1835 is unknown. A major problem is that no cluster yet shows the heating taking place in a widespread manner; no strong shocks, which Soker et al. (2000) invoke as the main distributed heat source set up by radio jets, have been found in cluster cores. If heating is the solution then jets may be considerably more powerful than their radio luminosity implies.

If a cluster is heated from near to its centre, the details of the heating process do not have a major effect on the structure of the heated gas. The principal issue is the rate of heating relative to the size of the region that is heated appreciably. In a heating event where the heating rate exceeds the thermal energy of the gas divided by its sound crossing time, a shock forms and the heated gas will usually be left in a convectively unstable state. The hottest gas may then rise well outside the heated core as the atmosphere returns to convective equilibrium in a few free-fall times. Lower heating rates do not produce a shock, although they still tend to make the heated gas convectively unstable. However, for low heating rates convective motion has time to maintain near-convective equilibrium while the gas is being heated, so that the whole of the region that is heated significantly becomes nearly isentropic. This means that in order for slow heating to prevent deposition of cold gas from a cooling flow, the whole of the region that would otherwise be the cooling flow becomes isentropic. This is not consistent with the data if the temperature declines towards the centres of these clusters are due to radiative cooling. Fast heating would also result in a nearly isentropic core between heating events, but need not make the whole of the region where there is net heating isentropic (David et al. 2000). Observed abundance gradients (Ezawa et al. 1997) are also inconsistent with a convective core.

We have previously argued that wind power from accreting black holes may have been responsible for heating the intracluster medium in all clusters, in order to explain the observed

luminosity–temperature relation (Wu, Fabian & Nulsen 2000). We envisage this process happening at earlier times (redshifts greater than one) than the heating in the present discussion, and also originating from most of the cluster galaxies. Heating by the nucleus of the central cluster galaxy could be seen as the remnant of a continuum of heating activity by galactic nuclei, provided that the problems discussed above can be overcome.

A merger with another cluster may also disrupt a cooling flow [see discussion in Allen et al. (2001a) and Gomez et al. (2000)]. For the mean age of cooling flows to be about 1 Gyr or less, as is required from the typical cooling time of gas at 2–3 keV at the pressure near the centre of a cluster, the merger rate must be high. Small clusters or groups are the only plausible merger partners (no evolution is seen in the cluster luminosity function within $z = 0.3$: Ebeling et al. 1997). Again, how such a process could apparently target the coolest X-ray-emitting gas in a cluster core is unclear.

3   MIXING

If cooling does take some gas down to say 10^4 K then 'cold mixing' of hotter gas with that cold gas could cause the hotter gas to be undetectable in the X-ray band. In the case of A1835 there are considerable amounts of gas at 10^3–10^4 K within a radius of 20 kpc from the centre seen in optical line emission (Allen 1995; Crawford et al. 1999), and over 10^{11} M$_\odot$ of molecular gas have been reported (Edge 2001).

The mixing process could resemble a mixing layer as discussed by Begelman & Fabian (1990). Momentum constrains the relative quantities of gas at high ($T_{\rm h}$) and low ($T_{\rm l}$) temperatures which mix such that the final temperature is approximately $\sqrt{(T_{\rm h} T_{\rm l})}$. This means that gas at 3×10^7 K mixing with gas at 3×10^3 K ends at a temperature of $\sim 3 \times 10^5$ K. Such gas will cool very rapidly and add to the gas mass at the lower temperature.

Gas cooling within a blob is likely to be thermally unstable, with the denser cooler gas falling, shredding and mixing into the surrounding less dense parts. This too could lead to much of the thermal energy of a blob being radiated in the extreme-ultraviolet, rather than in soft X-rays.

The relevance of cool mixing may be testable by ultraviolet observations of the strong line emission expected from gas at 10^5–10^6 K and optical observations of coronal line emission. Mixed gas in A1795 would have to be below $10^{5.5}$ K in order to be consistent with the results of Yan & Cohen (1995). Reprocessing of UV emission by colder gas could explain some of the optical emission lines from the central regions of cooling flows (Heckman et al. 1989; Crawford et al. 1999; Donahue et al. 2000). The total power radiated in these lines [which is about 20 times that detected in Hα, for which the luminosity $L({\rm H}\alpha)$ ranges from 10^{41} to 10^{43} erg s^{-1}] is similar to that associated with the gas cooling from about 1 keV. There is not, therefore, any problem here with the energetics; indeed, there is a good correspondence with the missing energy from gas cooling below 1 keV and the total power radiated by the optical nebulosity, although ionization by massive young stars presumably accounts for some of $L({\rm H}\alpha)$.

4   DIFFERENTIAL ABSORPTION

The deficit of emission below 1 keV seen with *ROSAT* (Allen & Fabian 1997) and *ASCA* (Fabian et al. 1994; Allen et al. 2001a) has often been ascribed to absorption internal to the cooling flow. The models used have, however, generally been very simple

screens across the whole flow. If instead the absorption only operated on the cooler gas, say that below 3 keV which, as noted above, occupies only a few per cent of the volume, then the X-ray emission lines from cooler gas could be rendered undetectable. The required column densities would be in the range of a few $\times 10^{21}$ to 10^{22} cm^{-2}.

If the flow were not highly multiphase, then much of the cooler gas would be near the centre which is also where most of the absorbing gas would need to lie. This gas could be in either sheets and filaments of cooled gas, or cooled parts of cooling clouds. The implied mass of absorbing gas is similar to that assumed to be deposited by the cooling flow over a few Gyr (Allen et al. 2001a). Again, the optical nebulosity commonly seen in this region may also be involved. Observation of patches of absorption, in both soft X-ray lines and continuum, would test this possibility.

Resonance scattering may also be important for soft X-ray resonance lines. The 15.01-Å emission of Fe XVII, which is produced by gas at around 4×10^6 K, is a key line missing from the observed spectra. This line is weakened in solar spectra by resonance scattering (see e.g. Rugge & McKenzie 1985). Using the formula presented by Rugge & McKenzie (1985), we find that the optical depth for that line in a large flow such as in A1835 could exceed 100. (The mass of gas around 4×10^6 K is obtained from the product of the cooling time at that temperature, $t_{\rm c} \sim 3 \times 10^6$ yr, and the mass cooling rate, ~ 1000 M$_\odot$ yr^{-1}; the column density is then obtained using the pressure, $\sim 2 \times 10^6$ cm^{-3} K.) Such a high optical depth can increase the total path-length of the resonant line photons by a factor of 2–3, making them more prone to absorption by cold gas. Also, if there is a widespread distribution of cooling gas, then some line emission can be scattered beyond the 1-arcmin effective field of view of the RGS.

5   METALLICITY VARIATIONS

Consider that the intracluster medium is highly inhomogeneous, not principally in density or temperature but in Z, the metallicity. Although there is little evidence for this, it is not obvious that the metals ejected from galaxies and supernovae should mix into a magnetized hot gas very easily. The strong continuous shear in the disc of a spiral galaxy may mix gas fairly well there, but the situation is far different in the intracluster medium. We assume that the scale of the metal-rich clumps is very small ($\ll 1$ kpc) so is spatially unresolved.

Let 90 per cent of the gas have zero metallicity ($Z = 0$) and 10 per cent have 2 times solar ($Z = 2$), i.e. the metallicity is bimodal. The spectrum of such gas then looks on average just like one with $Z = 0.2$. The iron ions, for example, radiate in the same way wherever they are located in the optically thin intracluster medium.

What happens now as the gas cools, i.e. in the central cooling flow? If the gas starts at $kT = 10$ keV, bremsstrahlung cooling dominates in all the gas. Line cooling only dominates the cooling function below about 2 keV for gas around solar metallicity (see Böhringer & Hensler 1989; the temperature at which it happens increases with metallicity). The metal-rich gas cools together with the metal-poor gas until about 2 keV, below which it cools much faster and drops out. The line emission from the cooling flow is only from the metal-rich gas, which has only one-tenth of the mass and energy of the total flow.

The line strengths are not 10 times what they would have been for that gas if it had $Z = 0.2$, since the gas only has so much
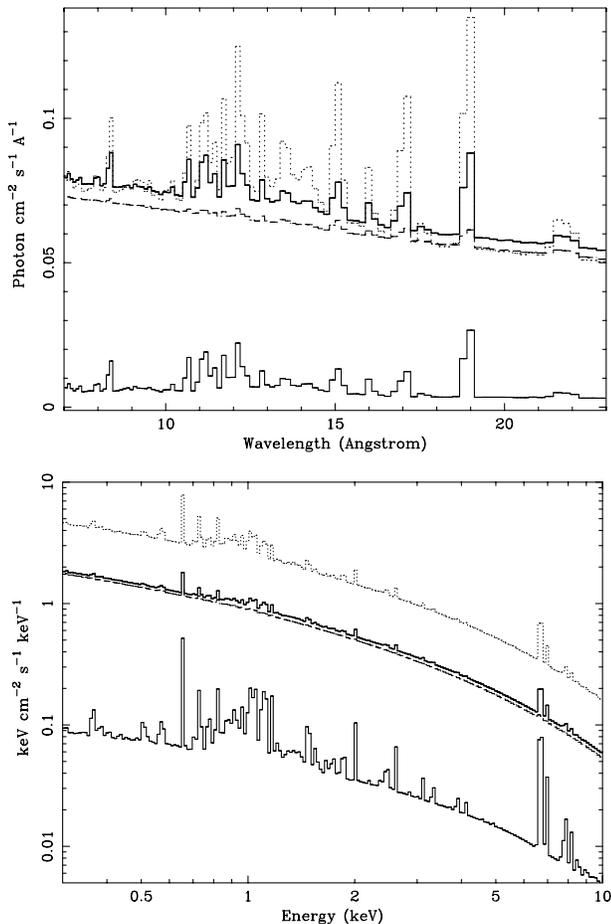
Figure 1. Comparison of cooling flow spectra from gas with differing metallicities. All have an upper temperature of 9 keV. Upper panel: the bottom spectrum is $10 \, M_\odot \, yr^{-1}$ of gas with $Z = 2$, then successively above are $100 \, M_\odot \, yr^{-1}$ at $Z = 0.01$, the sum of these two (bold solid line), and finally $110 \, M_\odot \, yr^{-1}$ at $Z = 0.2$ (dotted line). Much of the line emission from 11 to 17 Å is iron L-shell emission (Fe XXIV to XVII roughly going from left to right in the figure; Fe XVII accounts for the emission at 15 and 17 Å); O VIII emission is at 19 Å. Lower panel: similar to the upper panel but plotted against energy and with a range showing the iron K lines; the top curve (dotted line) is for a $Z = 0.2$ flow with a higher rate of $330 \, M_\odot \, yr^{-1}$ so there is no overlap. The spectra of non-cooling hot gases corresponding to the top two models (a 10:1 mixture of gas at $Z = 0.01$ and 2, and gas at $Z = 0.2$) would be indistinguishable.

thermal energy, most of which comes out from the lines. The line intensity depends on $\dot{M}$ rather than Z where line cooling dominates (it does depend on Z at higher temperatures). The net effect is that the cooling lines from the whole flow are much weaker than they would be were the gas fully mixed. In summary, when the gas is not cooling it looks like gas with $Z = 0.2$. When it is radiatively cooling, however, particularly below 2 keV, it looks like much lower metallicity gas.

The X-ray emission from such an inhomogeneous-metallicity flow resembles the sum of a metal-poor one and a metal-rich one. This is illustrated in Fig. 1. If the gas is simply of two varieties, one with metallicity 0 and the other with mass fraction f and metallicity Z, then the cooling flow will approximate a standard (mixed) one of mass cooling rate $\dot{M}$ down to where the lines dominate cooling in the metal-rich gas, with metallicity fZ (the lower panel in Fig. 1 shows that the iron K lines are close in

relative strength to those from the mixed gas). Below that temperature the soft X-ray lines will be appropriate for a flow of only $f\dot{M} = Z_{obs}\dot{M}/Z$, where Z_{obs} is the observed (average) metallicity (Fig. 1 shows that the iron L lines are much weaker than those from the mixed gas). The precise reduction in metallicity depends on the fraction of the power at the temperatures relevant to the detected lines, which is due to line emission relative to bremsstrahlung.

Note that if the oxygen abundance is high in a flow (or there were regions with enhanced oxygen abundance which cool separately) and it became an important coolant in the X-ray range then the oxygen line fluxes depend on the cooling rate, not the abundance too. Determinations of abundance from cooling flows are inherently complicated, more so if the metallicities of different elements are inhomogeneous. This is also relevant to the hot gas commonly seen in elliptical galaxies.

If the metal-rich gas begins cooling at a larger radius than the metal-poor gas (the line emission will help to do this, but the metal-rich gas could also be slightly denser) then the X-ray emission spectrum will be complicated to analyse. The innermost parts of the flow might then be metal-poor, as is indeed found in M87 (Böhringer et al. 2001, where resonant scattering is invoked). It is possible that some of the larger scale abundance gradients seen in the cores of some cooling flow clusters (e.g. Ezawa et al. 1997) could be due to these effects.

A possible way to test the inhomogeneous metallicity solution is to search for metallicity variations in the intracluster medium using high spatial resolution images (*Chandra* and *XMM-Newton*). Also, if the optical line-emitting nebulosity at the centres of cooling flows is due to the metal-rich gas then abundance determinations of that gas may provide a clue.

6   DISCUSSION

We have shown that the *XMM-Newton* RGS soft X-ray spectra of cooling flows are difficult to interpret. There are problems with many solutions. Sporadic heating, mixing, differential absorption and inhomogeneous metallicity offer possible solutions. If the last proves correct then it has wide implications for the enrichment of both the intracluster medium, and the intergalactic medium which presumably would also have a patchy metallicity. Some issues related to whether or not the metals from the first stars are mixed uniformly into the intergalactic medium are discussed by Rees (1997). The chemical evolution of galaxies might also become complex, with bimodal populations.[1]

One possible advantage with a heating explanation is that there is no, or little, mass deposition. This means that the problem of the fate of the cooled gas in a standard cooling flow is avoided. As already mentioned, however, there is strong evidence for massive star formation and cooled gas in many cooling flows.

If hot mixing or heating solutions apply to cooling flows then they may well apply to the formation of all galaxies by cooling. There has long been an assumption that the visible matter in galaxies is that which could cool on an infall time (Rees & Ostriker 1977; White & Rees 1978). Massive galaxies do, however, accrete large hot envelopes of gas where the cooling time exceeds the infall time but is still less than the age of the Universe

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[1] The globular cluster population of M87 has a bimodal colour distribution which has been interpreted as being due to the later merger of a metal-rich galaxy (Kundu et al. 1999). Formation from gas with bimodal metallicity is an alternative possibility.

– i.e. they have cooling flows (Nulsen & Fabian 1995). Whether such gas cools and builds galaxies further or is heated and prevented from cooling is not known. Heating by a central engine is one solution. The consequence of this is that the central engine (the growth of the central black hole) then has a profound influence on the final state of the galaxy.

Further observations of the soft X-ray phenomenon in cooling flows therefore have potential implications for our understanding of cooling and heating generally, as well as for the uniformity of metal enrichment of hot gas, the energy content of jets, and galaxy formation.

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