IS THE GAS IN COOLING-FLOWS MULTI-PHASE?

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ABSTRACT

Employing XMM-Newton EPIC data we perform a detailed comparison between different spectral models to test whether the gas in cooling-flows is multi-phase or not. Our findings all point in the same direction, namely that gas in cooling-flows does not show the wide distribution of temperatures expected from standard multi-phase models. This result has profound implications for cooling-flow models. Firstly, the large absorption column depths inferred by previous analysis of cooling-flow spectra are most likely an artifact following from the application of an incorrect spectral model to the data. Secondly, the mass deposition and mass flow are likely to be much smaller than previously thought. Last, but perhaps not least, the term “cooling-flow” cluster is probably no longer appropriate, as it describes a phenomenon of smaller entity and impact than previously thought. We propose to substitute it with that of “cool-core” cluster. The latter definition is less ambitious than the first, as it reflects only an observational fact rather than an inferred physical property, the flow, but has the undeniable advantage of being firmer.

Subject headings: X-rays: galaxies — Galaxies: clusters

1. INTRODUCTION

A large fraction of the clusters which have been imaged with X-ray telescopes show clear evidence of a centrally peaked surface brightness profile. The gas properties derived by deprojecting the X-ray images of these systems imply central cooling timescales which are substantially smaller than the Hubble time. In the absence of heating mechanisms, or of other forms of support, the cooling gas must flow inwards and give rise to a phenomenon known as cooling-flow.

Further evidence in favor of cooler gas in the core of clusters has come from X-ray spectra. ASCA (e.g. Virgo/M87, Matsumoto et al. 1996; Centaurus, Fukazawa et al. 1994) and BeppoSAX (e.g. Perseus/NGC1275, Molendi 1997; Virgo/M87 Guinazzi & Molendi 1999) spectra of cooling-flow clusters show evidence of a temperature decrement in their cores. From spectral fitting of ASCA data with multi-phase models (see further on for a description of multi-phase models) evidence of intrinsic absorption in the soft energy band, from cold gas with typical column depths of a few \(10^{21}\) cm\(^{-2}\), has been found (e.g. Allen 2000).

Early observations (e.g. Fabian, Nulsen and Canizares 1984) have shown that, although very peaked, the surface brightness profile is not as peaked as it should be if all the cooling gas were to flow to the center. This implies that the mass deposition rate \(\dot{M}\) is not the same at all radii but scales linearly with the radius, \(\dot{M} \propto r\), (e.g. Peres et al. 1998). The above result has been explained in the context of inhomogeneous models (Nulsen 1986, Thomas et al. 1987). In these models the gas is considered to be highly multi-phase, i.e. at each radius different phases, characterized by different temperatures and densities, coexist with one another. The different phases are kept in pressure equilibrium, since the sonic timescale, on which pressure waves propagate, is shorter than the cooling timescale. The phases comove with typical velocities substantially smaller than the sound speed. A chaotic magnetic field, which is supposed to be present in the cores of cooling clusters, may help in threading the phases together. The same magnetic field is invoked to suppress heat conduction which would otherwise rapidly bring the different phases to the same temperature. At temperatures of the order of \(10^6\) K the cooling timescale becomes shorter than the sonic timescale and the gas blobs which reach this temperature fall out of pressure equilibrium with the other phases. The cool blobs decouple from the flow which continues to move inwards.

Cooling-flows are frequent in clusters and must therefore be a persistent rather than an episodic phenomenon in the life of galaxy clusters. The amount of gas expected to cool from the X-ray temperatures throughout the lifetime of a cluster is of the order \(M = 10^{12} M_\odot / (100 M_\odot / yr)\) (Sarazin 1988). This mass, although smaller by orders of magnitude than the total mass of a rich cluster, is by no means small, indeed it is comparable to the mass of the cD galaxy at the center of cooling-flow clusters. Searches longward of the X-ray band at optical (e.g. Donahue & Stocke 1994) infrared (e.g. O’Dea et al. 1994) wavelengths and at 21 cm (e.g. Dwarakanath, van Gorkom, & Owen 1994) have systematically come up with mass estimates of cold gas which are orders of magnitude smaller than the mass which is estimated to be cooling from the X-ray band. This point, plus the lack of direct evidence of the gas motion (X-ray instruments with spectral resolution orders of magnitude better than what we now have are required), have led some to view cooling-flows suspiciously and to look for alternative solutions. Many authors have suggested that the cooling might be balanced by a heating mechanism (e.g. Tucker & Rosner 1983, Binney & Tabor 1995, Ciotti & Ostriker 2001). However no stable heating process yet devised is able to counteract the effects of

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radiative cooling and account for observed X-ray images (e.g. Canizares et al. 1993).

With the coming into operation of the latest generation of X-ray observatories XMM-Newton and Chandra, new light is being shed on cooling-flows. Observations of three clusters: A1835 (Peterson et al. 2001), Sersic 159-03 (Kaastra et al. 2001) and A1795 (Tamura et al. 2001) with the RGS instrument on board XMM-Newton, have brought some unexpected results. The RGS spectra of the above systems all show a remarkable lack of emission lines expected from gas cooling below 1-2 keV. The most obvious interpretation is that gas is cooling down to 2-3 keV but not further. Moreover from the XMM-Newton EPIC observation of M87 (Böhringer et al. 2001) and the Chandra observation of Hydra A (David et al. 2001) evidence has been found against multi-phase gas in the cooling-flows of these two clusters.

In this paper we make use of the unprecedented combination of spectral and spatial resolution and high throughput of the EPIC experiment on-board XMM-Newton to make a systematic comparison between different spectral models for the cooling-flows in A1835, A1795 and M87/Virgo. Our goal is to test if the gas is strongly multi-phase, i.e. characterized by a broad range of temperatures extending down to \( \sim 0.1 \) keV, or not.

2. OBSERVATIONS AND DATA PREPARATION

We use data from three clusters observed in the CAL/PV phase, namely A1835, A1795 and M87/Virgo. Details on the observations, as well as results from the analysis of these clusters, have already been published in the recent A&A special issue. The A1835 results are reported in Peterson et al. (2001), the A1795 results in Tamura et al. (2001) and Arnaud et al. (2001), and the M87 results in Böhringer et al. (2001) and Belsole et al. (2001).

In this paper we do not make use of PN data. From a comparative analysis of PN and MOS spectra of 10 sources observed during the CAL/PV phase (Molendi 2001) we have found that the PN spectra give systematically softer best fitting spectral models than the MOS in the 0.5-1.0 keV range. If the parameters of the model adopted to fit simultaneously the PN and MOS spectra are forced to be the same, with the exception of the column density and the normalization, the best fitting PN column densities are systematically smaller than the MOS column densities. For the 5 out of 10 objects in our sample where no excess absorption is expected, we have found the best fitting column densities derived from the MOS to be always in good agreement with the line of sight galactic values, while the ones estimated from PN data are always substantially smaller. We conclude that, of the two instruments, the MOS has a more reliable calibration at soft energies. Since the soft X-ray emission plays a central role in this paper we have decided to limit our analysis to the MOS data.

We have obtained calibrated event files for the MOS1 and MOS2 cameras for all three observations with SAS5.0. Data were manually screened to remove any remaining bright pixels or hot columns. Periods in which the background is increased by soft-proton flares have been excluded using an intensity filter; we rejected all events accumulated when the count rate exceeds 15 cts/100s in the [10 – 12] keV band. We have accumulated spectra in concentric annular regions centered on the emission peak with bounding radii: 0-0.5 arcmin, 0.5-1 arcmin and 1-2 arcmin for A1835: 0-0.5 arcmin, 0.5-1 arcmin, 1-2 arcmin and 2-3 arcmin for A1795: 0.5-1 arcmin, 1-2 arcmin, 2-3 arcmin, 3-4 arcmin, 4-5 arcmin, 5-7 arcmin and 7-9 arcmin for M87. The 0-0.5 arcmin region of M87 has been excluded as it is highly contaminated by the emission of the nucleus and the jet. For all 3 clusters we have removed point sources. For M87 we have also removed the substructures which are clearly visible from the X-ray image (e.g. Belsole 2001). Spectra have been accumulated for MOS1 and MOS2 independently. The Lockman hole observations have been used for the background. Background spectra have been accumulated from the same detector regions as the source spectra.

The vignetting correction has been applied to the spectra rather than to the effective areas, similarly to what has been done by other authors who have analyzed EPIC data (Arnaud et al. 2001).

Spectral fits were performed in the 0.5-10 keV band for A1835 and A1795 and in the 0.5-4.0 keV band for M87. Data below 0.5 keV were excluded to avoid residual calibration problems in the MOS response matrices at soft energies. Data above 4 keV were excluded from the analysis of M87 because above this energy the spectra show a substantial contamination from hotter gas emitted further out in the cluster, on the same line of sight.

3. SPECTRAL MODELING

All spectral fitting has been performed using version 11.0.1 of the XSPEC package. All spectral models include a multiplicative component accounting for the line of sight galactic absorption, which is fixed to the value derived from radio maps. The adopted numbers are \( 2.3 \times 10^{20} \text{cm}^{-2} \), \( 1.2 \times 10^{20} \text{cm}^{-2} \) and \( 1.8 \times 10^{20} \text{cm}^{-2} \) for A1835, A1795 and M87, respectively. The values for A1835 and A1795 come from the maps of Dickey & Lockman (1990) while the one for M87 is from a detailed study of the core of the Virgo cluster from Lief et al. (1996). We note that the absorbing column depth towards the field which has been used for background, i.e. the Lockman hole, is smaller, \( N_H \sim 6 \times 10^{19} \text{cm}^{-2} \), than that found on the line of sight of the 3 clusters we are considering. In principle, this could lead to an underestimation of the background at soft energies and to a background subtracted source spectrum that is softer than the real one. However, for A1835, where the \( N_H \) difference is largest, it will lead to a background variation of less than 15% at 0.5 keV and of only a few percent at 1 keV. The effect on the source spectra, which at energies between 0.5 and 1.0 keV, are always at least 20 times more intense than the background spectra, will therefore be contained to less than 0.75% at all energies and for all spectra. Moreover, in the case of M87 and A1795, where the \( N_H \) difference leads to a background variation of less than 10% at 0.5 keV, the effect on the source spectra will be smaller than 0.5% at all energies and for all spectra.

We have compared our data with three different spectral models. Model A is a single temperature model (mekal model in XSPEC), this model has 3 free parameters: the
temperature \( T \), the metal abundance \( Z \), which is expressed in solar units, and the normalization. Model B includes a single temperature component plus an isobaric multi-phase component multiplied by an absorber located at the source ( mekal + zwabs*mkcflow in XSPEC), this model has 5 free parameters: the temperature \( T \), the abundance \( Z \) and the normalization of the single-phase component plus the normalization of the multi-phase component, which is expressed in units of the mass deposition rate, \( M \), and the column density of the intrinsic absorber, \( N_H \). The other parameters of the multi-phase component are not free: the minimum temperature, \( T_{\text{min}} \), is fixed at a value of 100 eV, the maximum temperature, \( T_{\text{max}} \), and the metal abundance, \( Z_{\text{mkcflow}} \), are linked respectively to the temperature, \( T \), and the metal abundance, \( Z \), of the single-phase component. Model B is commonly adopted to fit spectra from multi-phase cooling-flows (e.g. Allen 2000). This model was originally written to fit spectra from the entire cooling-flow region. Since we are applying it to annular regions the normalization cannot be interpreted as the mass deposition rate for the whole cooling-flow. However, the important point is that such a spectral component has the spectral shape expected form a multi-phase gas where the different phases are in pressure equilibrium with each other. Model C includes a single temperature component plus an isobaric multi-phase component (mekal + mkcflow in XSPEC). As for model B this model has 5 free parameters: the temperature \( T \), the abundance \( Z \) and the normalization of the single-phase component plus the minimum temperature, \( T_{\text{min}} \), and the normalization of the multi-phase component, \( M \). The other parameters of the multi-phase component are not free: the maximum temperature, \( T_{\text{max}} \) and the metal abundance, \( Z_{\text{mkcflow}} \), are linked respectively to the temperature, \( T \), and the metal abundance, \( Z \), of the single-phase component. This model is similar to the one adopted to fit the RGS data of A1835 (Peterson et al. 2001). It may be regarded as a "fake multi-phase" in the following sense. From ASCA (e.g. Virgo/M87 Matsumoto et al. 1996; Centaurus, Fukazawa et al. 1994) and BeppoSAX (e.g. Perseus/NGC1275 Molendi 1997; Virgo/M87 Guainazzi & Molendi 1999) and more recently Chandra (e.g. Hydra A, David et al. 2001) and XMM-Newton (e.g. A1835, Peterson et al. 2001) observations we know that clusters feature a temperature decrement within the cooling-flow region. Suppose now that the gas in cooling-flow clusters is not multi-phase but single-phase, than the spectra accumulated from annuli where the temperature gradient is large will appear as multi-phase not because the gas is truly multi-phase but because the observed spectrum comes from spatially distinct regions characterized by different temperatures. Model C should give a better fit to the data than model B if the gas is single-phase, because in this case the spectrum from a given annular region should be better described by a model with a minimum and a maximum temperature, which describe the minimum and maximum single temperatures within the given annular region, rather than from a model with a maximum temperature and a multi-phase component with practically no minimum temperature.

In the case of M87 which, having a low temperature of 1-2 keV, features very prominent emission lines of various elements, we have allowed for independent fitting of individual metals abundances. This has been achieved by substituting the mekal and mkcflow components with vmekal and vncflow respectively. Individual element abundances for the vncflow component, in models B and C, have been linked to the same elements abundances in the vmekal component.

On the basis of the above discussion it is relatively straightforward to make predictions as to what we should expect to find when comparing spectral fits obtained with models A, B and C. If the medium is truly multi-phase, models B and C should give better fits than model A everywhere within the cooling-flow region. Model B should give better results than model C. If the medium is single-phase then: for regions characterized by a narrow temperature distribution (i.e. at relatively large radii), models B and C should not provide substantial improvements with respect to model A, for regions characterized by a broad temperature distribution (i.e. in the innermost radial bins) models B and C should provide substantial improvements with respect to model A. Model C should give better fits than model B.

### 3.1. Results

In the bottom panels of Figures 1, 2 and 3 we plot the temperature profiles for A1837, A1795 and M87 respectively, as obtained from model A and, for those bins where model C provides a significantly better fit than model A, the minimum and maximum temperatures obtained from model C. In the top panels of the same figures we plot the \( \Delta \chi^2 \) between models A and B (filled circles) and models A and C (open circles) as a function of radius. The horizontal lines indicate the \( \Delta \chi^2 \) values for which the statistical improvement of the model B or C fit with respect to model A are significant at the 99% level according to the F-test. Whenever a datapoint lies above this line the improvement is significant at more than the 99% level. The vertical line indicates the cooling radius (i.e. the radius at which the cooling time equals the Hubble time) as determined from deprojection analysis of ROSAT images by Peres et al. (1998) for A1795 and by Allen (2000) for A1835. For M87 all bins are within the cooling radius \( r_c = 20 \) arcmin, Peres et al. 1998.

In the case of A1835 (Figure 1), the outermost radial bin that we consider is completely outside the cooling region, thus the fact that neither model B nor model C provide a significant improvement with respect to model A is not at all surprising, as there is a general consensus that the gas outside the cooling region is single-phase. Indeed we have included in our analysis of A1835 and A1795 a radial bin outside the cooling region to use it as a sort of control point to verify that our statistical test is capable of confirming that the gas is single-phase outside the cooling radius. The middle bin in Figure 1 is partially in the cooling region and partially outside so the fact that the improvement is not significant is not particularly compelling. In the innermost bin we find that both models B and C give substantially smaller \( \chi^2 \) than model A. In the case of model B the improvement is significant at slightly less than the 99% level while for model C it is significant at much more than the 99% level. The rather large \( \Delta \chi^2 \) between model B and model C is telling us that the spectrum for this region is better fitted by an emission model characterized by a min-
imum temperature of 2.9±0.7 keV (nicely consistent with the one derived by Peterson et al. 2001 from the analysis of the RGS spectrum), than by a model characterized by a temperature distribution extending down to 0.1 keV where most of the softer emission, which is coming from the cooler phases, is hidden by an intrinsic absorber.

In the case of A1795 (Figure 2), as for A1835, the outermost bin is almost completely outside the cooling region, the $\Delta \chi^2$ for both model B and C with respect to model A is zero, meaning that the multi-phase component is rejected by the fitting procedure by pushing its normalization to zero. The bin with bounding radii 1 and 2 arcmin is completely inside the cooling region and for both model B and C the improvement with respect to model A is negligible. This is an important result as it is telling us that the spectrum from a region within the cooling radius, where the temperature profile is not very different from the temperature outside the cooling-flow, does not show any evidence of being produced by a multi-phase gas. The next bin shows a qualitatively similar result, the $\Delta \chi^2$ for both models B and C are not statistically significant at the 99% level. Finally in the innermost bin, where, because of projection effects, the spanned temperature range is largest, both models B and C show a significant improvement with respect to model A, but as for the innermost bin of A1835 the fit for model C is substantially better than the fit with model B. The minimum temperature derived from model C is 1.9±0.5 keV, which is consistent with what has been found by Tamura et al. (2001) from the analysis of the RGS data. Note also how the $\Delta \chi^2$ values increase continuously with decreasing radius, as is expected if the gas is single-phase and the multi-phasenessness comes from putting together distinct regions with different temperatures and from the fact that, because of projection effects, the spanned temperature range is larger at smaller radii.

M87 (Figure 3) is the nearest system we have investigated, indeed it is so near that the whole field of view is contained within the cooling radius. The temperature profile for this object (see Böhringer et al. 2001 and Figure 3) shows a small gradient for radii larger than ~ 2 arcmin and a rapid decrease for smaller radii. The comparison of $\Delta \chi^2$ in this cluster, which in some sense is the most important, as it is the one where we can best separate different emitting regions, points very clearly in favor of the single-phase hypothesis. For the outermost bin (bounding radii 7-9 arcmin) neither model B nor model C provides a substantially better fit than model A, indeed in the case of model B the multi-phase component is rejected by the fitting procedure itself by pushing its normalization to zero. Note that this regions is well within the cooling radius of M87 (~ 20 arcmin). For all spectra at radii larger than 2 arcmin and smaller than 7 arcmin, model B does not give a better fit than the single-phase model, while model C does. From the bottom panel of figure 3 it is clear that the temperature range spanned by model C is always narrow, thus the comparison between models A, B and C is telling us that a model containing a multi-phase component characterized by a narrow temperature range gives a better description of the data than a single temperature model, while a model containing a multi-phase component characterized by a broad temperature distribution does not. At radii smaller than 2 arcmin, where the temperature profile suddenly steepens the $\Delta \chi^2$ shoot up. In the innermost two bins the implied statistical significance for both models is well over the 99% level and, as for the innermost bin of A1795 and A1835, model C gives a much better fit than model B.

To better understand why model C performs so much better than model B we have made a detailed comparison between the best fitting model B and C spectra for the innermost region of M87. Requiring temperatures In Figure 4 we show the observed spectrum with the best fitting multi-phase components for models B and C convolved with the EPIC instrumental response. The two components are similar above 2 keV, where the effect of the intrinsic absorption (model B), or of a cutoff temperature (model C) is modest. At smaller energies the difference becomes more evident. In the region around 0.9 keV, where the Fe-L complex is dominant, the two spectra are very different, the model B component features a peak at 1 keV followed by a broad shoulder extending down to about 0.7 keV, this is due primarily to Fe-L lines from low ionization states requiring temperatures smaller than about 1 keV; the model C component, as the model B component, presents a peak around 1 keV, but the decrease towards smaller energies is much more rapid because the low ionization lines produced by gas at temperatures smaller than 1 keV are absent. The $\Delta \chi^2$ between the best fits with model B and C over the entire spectral range considered is 113, with most of it, $\Delta \chi^2 = 90$, coming from the energy range 0.7-1.2 keV, where the multi-phase components differ as explained above. In Figure 5 we show the residuals of the best fits with model B and C, in this energy range. As can be seen model C is capable of reproducing the observed spectrum rather well, while model B is clearly in defect of the data between 0.9 and 1.0 keV and in excess between 0.7 and 0.9 keV, indicating that the multi-phase component in model B is characterized by an Fe-L shell quasi-continuum emission that it is too broad to correctly reproduce the data. More specifically, there is too much emission from low ionization lines predominantly emitted from gas with temperature smaller than ~ 1 keV and too little emission from higher ionization lines mostly coming from gas with temperatures larger than ~ 1 keV. Thus the key feature allowing us to discriminate between models B (dashed line) and C (solid line), in the case of M87, is the shape of the Fe-L shell blend.

The results of our spectral model comparison may be summarized as follows: for the outer regions, which are characterized by a narrow temperature distribution, neither model B nor model C provide an improvement with respect to model A (with the exception of the regions between 2 and 7 arcmin in M87 where, due to the high statistical quality of the data, the fitting procedure can discriminate between a single temperature spectrum and a multi temperature spectrum characterized by a narrow temperature range); for the inner regions, which are characterized by a broad temperature distribution, models B and C provide an improvement with respect to model A and model C always gives better fits than model B. These results all point in the same direction, namely that the gas in cooling-flows does not show the broad temperature distribution expected from standard multi-phase models.
The presence of a moderate temperature range, such as the one measured in the M87 spectra (see Fig. 3) could result either from a moderately multi-phase gas or alternatively from a single phase gas characterized by an azimuthal temperature gradient.

3.2. The intrinsic $N_H$

In Figure 6 we plot the intrinsic $N_H$ profiles for A1835 (top panel), A1795 (middle panel) and M87 (bottom panel) as derived from model B. If the physical scenario underlying model B were correct the intrinsic $N_H$ distribution should be characterized by a clear decrease with increasing radius for any realistic distribution of the intrinsic absorber, as the innermost emitting regions are viewed through all other regions and should therefore present the largest absorption. The intrinsic $N_H$ distributions for all our clusters show no such trend. The case of M87, where we have 7 bins and the errors are small, is particularly illuminating.

If we accept that model B does not provide a realistic description of the data, then the large absorption column depths inferred by previous analysis of cooling-flow spectra (Allen 2000 and references therein) and from fits with model B presented in this paper, must be considered as an artifact. Indeed if the gas is not strongly multi-phase, spectra for regions where the spanned temperature range is large can be fitted with a multi-phase model only if the soft emission predicted by the standard multi-phase model, which is not present in the observed spectra, is somehow hidden. This can of course be achieved by introducing an absorption component. The good combination of spectral resolution, large spectral band and good spatial resolution of the EPIC cameras is allowing us, for the first time, to clearly discriminate between an absorbed, truly multi-phase spectrum (model B), and a "fake" multi-phase spectrum characterized by a temperature range (model C).

We remark that model C, while certainly doing a better job than model B, does not provide the most appropriate description of the spectrum. A model in which the projection effects, which contribute to the multi-phase appearance of the gas are explicitly accounted for would certainly give a better description allowing the study of the temperature structure of the ICM. We defer the analysis of our data with such a model to future work.

3.3. Mass Deposition Rates

Our analysis shows that in the outer rings of all 3 clusters the spectrum is consistent with being single-phase, whereas inside 1 arcmin, 2 arcmin and 6 arcmin for A1835, A1795 and M87 respectively, model C provides a substantially better fit than model A. Model C also provides a better fit than model B, implying that the spectral shape in the soft band is always better modeled by a minimum temperature than by an intrinsic absorber. The minimum temperature is always larger than about 1 keV and, in the case of A1835 and A1795, it is consistent with that derived from the analysis of ROSAT PSPC images (Allen 2000); for A1795 we find $M = 27.6 \pm 6.2 M_\odot /yr$ against $450 \pm 50 M_\odot /yr$ (Peres et al. 1998), and in the case of M87 $M < 0.5 M_\odot /yr$ to be compared with 40 $\pm 5 M_\odot /yr$ (Peres et al. 1998).

4. DISCUSSION

In a recent paper Fabian et al. (2001) proposed three possible ways of reconciling the absence of emission lines in the RGS spectra of cooling-flow clusters with the presence of gas with temperatures smaller than 1-2 keV. In the following we discuss each of these possibilities in the light of our results on the EPIC data.

The first solution outlined by Fabian et al. (2001) is to hide the emission lines behind a patchy intrinsic absorber, possibly more concentrated towards the center of the cluster. From Figure 6 and the related discussion we have evidence that if such an absorber exists it probably operates on scales smaller than the ones we can investigate with EPIC. If that is the case then mass deposition will occur only in the innermost regions and not throughout the entire cooling-flow region.

Another possibility considered in Fabian et al. (2001) would be for the gas to be highly bimodal in its metal distribution with say 10% of the gas having a metallicity of 3 in solar units, and the remaining 90% having no metals at all. At temperatures below about 2 keV, when line cooling becomes important, the metal rich gas would cool at a much faster rate than the metal poor gas and lines from metals at temperature below about 2 keV would not be observed. We have tested this possibility by allowing the metallicity of the multi-phase component in model B to vary independently from the metallicity of the single-phase component. In none of our fits do we find the best fitting value of the metallicity of the multi-phase component to be significantly smaller than the one of the single-phase component, implying that the multi-phase gas is not metal poorer than the ambient gas. If this mechanism is operating, it must be doing so on scales smaller than the ones we have investigated and mass deposition should be confined to such scales.

The third possibility indicated by Fabian et al. (2001) is that the X-ray emitting gas may be cooling very rapidly by mixing with gas at 10$^7$ K, which is known to be present within about 50-70 kpc of the center of some cooling-flow clusters. However, as pointed out by Crawford et al. (1999), line emitting gas at about 10$^7$ K is not always found in the core of cooling-flow clusters, and in most clusters it extends to radii smaller than the cooling radius. In
all the gas flowed to the center of the cluster. Perhaps the most obvious way out of this dilemma is to assume that a heating mechanism is counteracting the radiative cooling. Over the past 15 years many different heating mechanisms have been proposed (e.g. Tucker & Rosner 1983, Binney & Tabor 1995, Ciotti & Ostriker 2001). However no stable heating process yet devised is able to counteract the effects of radiative cooling and account for observed X-ray images (Canizares et al. 1993). This has in turn led some workers to consider sporadic heating mechanisms. Several heating mechanisms of this kind have been presented in the past. Recently Soker et al. (2001), motivated by the analysis of Hydra A with Chandra data (David et al. 2000), have proposed heating by sporadic outbursts of the central radio source. The fact that A1835 and Sersic 159-03 do not have strong radio sources, in our view, argues against such a mechanism. Indeed we should look for a heating mechanism that can operate in all cooling clusters.

Before XMM-Newton and Chandra the lack of a stable heating process that could counteract the effects of radiative cooling and account for observed X-ray images was considered as a crucial point in favor of multi-phase models. Now that the new results emerging from the analysis of XMM-Newton and Chandra data question the standard cooling-flow picture, the hunt for a self consistent heating mechanism is again open.

Last, but perhaps not least, the term ”cooling-flow” cluster is most likely no longer appropriate, as it describes a phenomenon of smaller entity and impact than previously thought. We propose to substitute it with that of ”cool-core” cluster. The latter definition is less ambitious than the first, as it reflects only an observational fact rather than an inferred physical property, the flow, but has the undeniable advantage of being firmer.

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REFERENCES

Allen, S. W. 2000, MNRAS, 315 269
Arnaud, M., Neumann, D. M., Aghanim, N., Gastaud, R., Majerowicz, S., & Hughes, J. P. 2001, A&A, 365, L80
Belsole, E., Saavedra, J. L., Brighenti, H., Worrall, D. M.: Matsushita, K., Mushotzky, R. F., Sakelliou, I., Molendi, S., Ehle, M., Kennea, J., & Stewart, G. 2001, A&A, 365, L188
Binney, J., & Tabor, G. 1995, MNRAS, 276, 663
Böhringer, H., Belsole, E., Kennea, J., Matsushita, K., Molendi, S., Worrall, D. M., Mushotzky, R. F., Ehle, M., Guainazzi, M., Sakelliou, I., Stewart, G., Vestrand, W. T., Dos Santos, S. 2001, A&A, 365, L181
Canizares, C. R., Markert, T. H., Markoff, S., & Hughes, J. P. 1993, ApJ, 405, L17
Ciotti, L., & Ostriker, J.P. 2001, ApJ in press (astro-ph/9912064)
Crawford C.S., Allen, S.W., Ebeling H., Edge A.C. & Fabian A. C., 1999, MNRAS, 306, 857
David, L.P., Nulsen, P.E.J., McNamara, B.R., Forman W., Jones C., Ponnam, Robertson B., & Wise M. 2001, in press (astro-ph/0010224)
Dickey, J. M., & Lockman, F. J. 1990, ARA&A, 28, 215
Donahue, M., & Stocke, J. T. 1994, ApJ, 422, 459
Dwarakanath, K. S., van Gorkom, J. H., & Owen, F. N. 1994, ApJ, 432, 469
Fabian, A.C., Nulsen, P. E. J., Canizares, C. R. 1984 Nature, 310, 734

Fabian, A.C., Mushotzky R.F., Nulsen P.E.J., & Peterson J.R. 2001, MNRAS, 321, L20
Fukazawa Y., Ohashi, T., Fabian, A.C., Canizares, C. 1994, Ikebe, Y., Makishima, K, Mushotzky, R., & Yamashita, K. PASJL, 46, 55
Guainazzi, M., & Molendi S. 1999, A&A, 351, L19
Hu, E. M., Cowie, L. L., Wang, Z. 1985, ApJS, 59, 447
Kaastra, J. S., Ferrigno, C., Tamura, T., Paerels, F. S. B., Peterson, J. R., & Mittaz, J. P. D. 20001, A&A, 365, L99
Lieu, R., Mittaz, J. P. D., Bowyer, S., Lockman, F.J., Hwang, C.-Y.; Schmitt, J.H.M.M 1996, ApJ, 458, L5
Matsumoto H., Koyama, K., Awaki, H., Tomida, H., Tsuru, T., Mushotzky, R. & Hatsukade, I. 1996, PASJ, 48, 201
Molendi, S. 2001, Report on MOS PN cross-calibration to be presented at the Leicester EPIC calibration meeting to be held in June 2001
Molendi, S. 1998, Nuclear Physics, 69/1-3, 563
Nulsen P. E. J. 1986, MNRAS, 221, 377
O'Dea, C. P., Baum, S. A., Maloney, P. R., Tacconi, L. J., & Sparks, W. B. 1994 ApJ, 422, 467
Peres, C. B., Fabian, A. C., Edge, A. C., Allen, S. W., Johnstone, R. M., & White, D. A. 1998, MNRAS, 298, 416
Peterson, J. R., Paerels, F. B. S., Kaastra, J. S., Arnaud, M., Reiprich, T. H., Fabian, A. C., Mushotzky, R. F., Jernigan, J. G., Sakelliou, I. 2001, A&A 365, L104

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Sarazin, C. L. 1988, X-ray emission from clusters of galaxies (Cambridge: Cambridge University Press)

Tamura, T., Kaastra, J. S., Peterson, J. R., Paerels, F. B. S., Mittaz, J. P. D., Trudolyubov, S. P., Stewart, G., Fabian, A. C., Mushotzky, R. F., Lumb, D. H.; Ikebe, Y. 2001, A&A 365, L87

Soker, N., White, R.E., David, L.P., & McNamara, B.R. 2001, ApJ submitted (astro-ph/0009173)

Tamura, T., Kaastra, J. S., Peterson, J. R., Paerels, F. B. S., Mittaz, J. P. D., Trudolyubov, S. P., Stewart, G., Fabian, A. C., Mushotzky, R. F., Lumb, D. H.; Ikebe, Y. 2001, A&A, 365, L8

Thomas, P., A 1987, MNRAS, 228, 973

Tucker, W.H., & Rosner R. 1983, ApJ, 267, 547
Fig. 1.— **Top Panel**: $\Delta \chi^2$ between models A and B (filled circles) and models A and C (open circles) as a function of radius. The horizontal lines indicate the $\Delta \chi^2$ values for which the statistical improvement of the model B (C) fit with respect to model A are significant at the 99% level according to the F-test. The vertical line indicates the cooling radius (i.e. the radius at which the cooling time equals the Hubble time). **Bottom Panel**: Temperature profile for A1837 as obtained from model A, filled circles. For bins where model C gives a better fit than model A we also show the maximum and minimum temperatures from model C, which are indicated as empty and full triangles respectively. Uncertainties are at the 68% level for one interesting parameter ($\Delta \chi^2 = 1$).

Fig. 2.— Same as Fig. 1, for A1795.
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Fig. 3.— Same as Fig. 1, for M87. Note that the $\Delta \chi^2$ value obtained by comparing model A to model B in the outermost bin, which is 0, is not shown in the plot.

Fig. 4.— M87 spectrum for the annulus with bounding radii 0.5-1.0 arcmin. The filled circles are the datapoints, the dashed and solid lines represent respectively the best fitting multi-phase components for models B and C convolved with the EPIC instrumental response.
Fig. 5.— Residuals in the form of a ratio of the data over the model for the M87 spectrum shown in Figure 5. The filled and open circles are respectively the residuals for models B and C.

Fig. 6.— Radial intrinsic absorption profiles as obtained with model B, for A1835 (top panel), A1795 (middle panel) and M87 (bottom panel). Spectral fits beyond 2 arcmin for A1835 and A1795 all have $N_H$ confidence intervals ranging from 0 to at least $10^{22}$ cm$^{-2}$.