XMM-NEWTON RGS OBSERVATIONS OF CLUSTERS OF GALAXIES

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We present the most important achievements made with the Reflection Grating Spectrometer (RGS) of *XMM-Newton* on clusters of galaxies. Thanks to its high spectral resolution, the RGS separates the individual line complexes of different iron ions in the Fe-L complex, thereby allowing for a sensitive determination of the emission measure distribution. The RGS data for a large sample of clusters show that these clusters contain significantly less cooling gas at lower temperatures than expected from the standard isobaric cooling flow model. The emission measure distribution rises steeply with temperature. This is confirmed by spatially resolved EPIC spectra, showing steep emission measure distributions at each radius.

1. Introduction

With the launch of *XMM-Newton* new opportunities for the study of clusters of galaxies have arisen. In particular the combination of the high spectral resolution of the RGS spectrometers and the high sensitivity of the EPIC cameras appears to be extremely useful. As one of the most unexpected results from the first RGS observations of clusters of galaxies [9,3,7] we have found that there is a lack of cool gas in the cores of these clusters, as compared to predictions by the isobaric cooling flow model. In this paper we summarize the progress made so far in the analysis of high resolution RGS spectra of clusters of galaxies.

2. The Fe-L complex

In studying X-ray clusters of galaxies, high resolution X-ray spectroscopy offers excellent diagnostic tools for determining the temperature structure. The temperature of the hottest gas in a cluster can be determined from the curvature of the bremsstrahlung continuum. However when the plasma is not isothermal (like for example in cooling flows), it is not possible in practice to disentangle the different temperature components from the continuum alone. For the hotter gas, the Fe-K complex is temperature sensitive, but more importantly at lower temperatures the emission from the Fe-L complex allows temperature diagnostics over a full decade in temperature (Fig. 1). Also, the line power in the Fe-L complex is in general larger than in the Fe-K complex

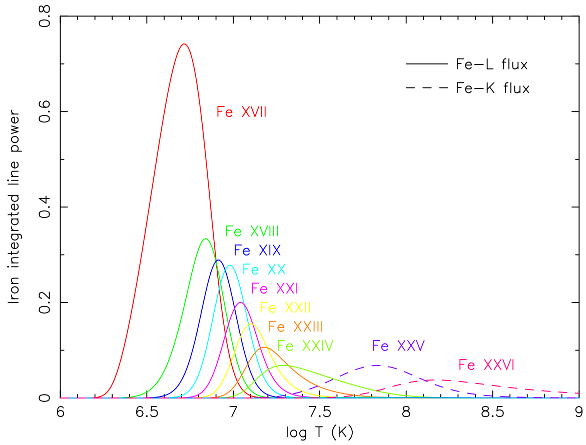

Figure 1. Integrated line power over the Fe-L complex (for Fe XVII–XXIV) or the Fe-K complex (for Fe XXV and XXVI). From [5].

(Fig. 1).

In principle, even with CCD resolution (like the EPIC camera's of *XMM-Newton*) it is possible to derive the temperature structure of clusters. This is evident from Fig. 2, which shows that the average energy of the line emission from iron ions is an increasing function of the ionisation stage, with a spacing between the different ions comparable to the EPIC resolution. Corresponding isothermal spectra are shown in Fig. 3. Although in particular the centroid of the Fe-L complex is a

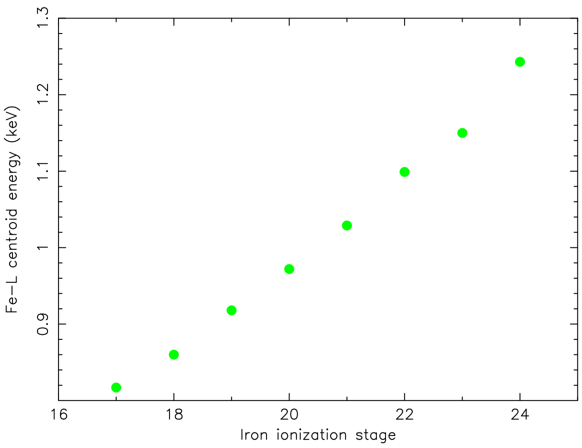

Figure 2. Average energy of the Fe-L emission for different iron ions, taken at the temperature where the emissivity reaches a maximum. From [5].

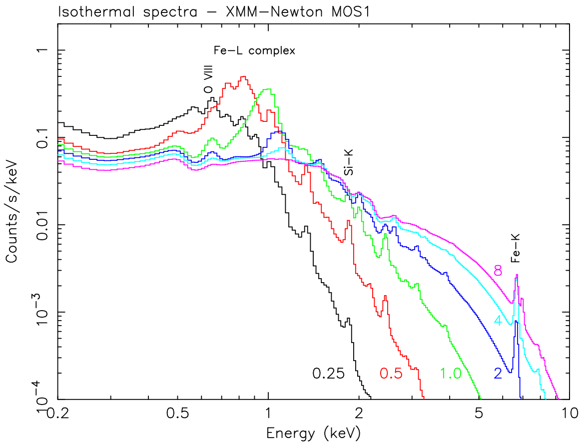

Figure 3. Spectra of isothermal plasmas convolved with the energy resolution of the EPIC camera's of *XMM-Newton*. The curves are labeled according to the temperature (keV).

good temperature indicator, higher spectral resolution is needed in order to interpret the spectra unambiguously. This is due to possible complexities such as contamination by other elements (in particular Mg, Ne and O), resonance scattering, intrinsic absorption or calibration uncertainties. In the past, problems with certain spectral models could always be waived by invoking additional absorption, be it instrumental or in the source. Now, with the RGS data available, individual line diagnostics allows us to determine the physics of the emitting region sharply.

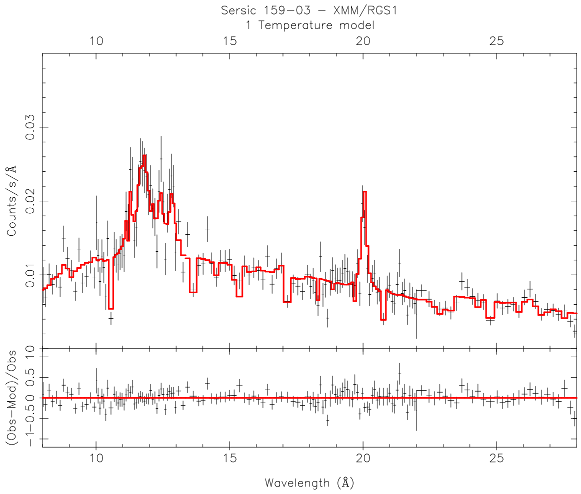

Figure 4. Observed RGS spectrum of the cluster Sérsic 159−03, fitted here with a single temperature model.

We illustrate this in Figs. 4–6. A fit with a single temperature model to the data of the cluster Sérsic 159−03 provides a good fit to the data, although the inclusion of a weaker lower temperature component improves the fit slightly [3]. However if we force the spectrum to be absorbed by a layer of neutral gas with a column density of 10^{25} m^{-2} (Fig. 5), it is not possible to obtain a good fit. Although by adjusting the oxygen abundance the spectrum near the O VIII Lyα line (redshifted to 20 Å) can be matched, this is not possible for the spectral band between 17–24 Å (the band below the neutral oxygen edge of the additional column). Only above the oxygen edge a reasonable but not perfect fit is obtained.

Thus, the RGS data clearly exclude large intrinsic absorption columns of neutral gas. They also exclude large quantities of warm absorbing gas (Fig. 6). In this last simulation, the temper-

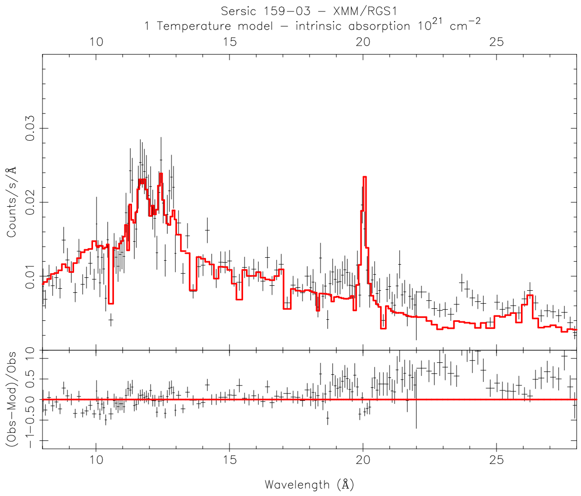

Figure 5. As Fig. 4, but now with neutral gas with a column density of 10^{25} m^{-2} added to the model.

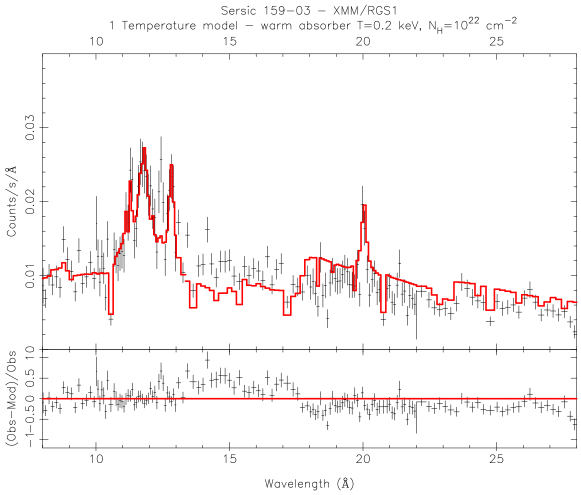

Figure 6. As Fig. 4, but now with warm gas with a column density of 10^{26} m^{-2} added to the model.

ature of the absorbing gas was raised to 0.2 keV and the column density increased to 10^{26} m^{-2}. Also in this case not a good fit is obtained, mostly due to the lack of a clear O VII edge around 17 Å.

3. Isobaric Cooling flows

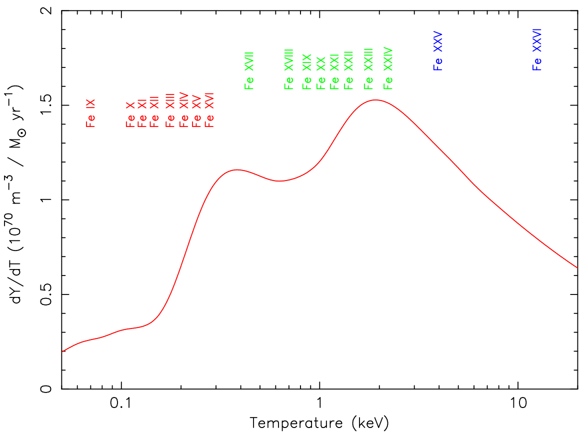

Figure 7. Differential emission measure distribution for isobarically cooling gas, calculated for a plasma with half the solar abundances. The calculation is based upon the SPEX code [4]. For the iron ions the temperatures where the relative concentrations have their maximum value are indicated. Note the distinction between K, L and M-shell ions (Fe XXV−XXVI, XVII−XXIV and IX−XVI, respectively. From [2].

The most popular cooling flow model is the so-called isobaric cooling flow [1]. The cooling gas is assumed to be in pressure equilibrium with its surroundings. It can be shown that for such a cooling flow, the differential emission measure (DEM) distribution $\mathrm{d}Y/\mathrm{d}T$ can be expressed as

$$\mathrm{d}Y/\mathrm{d}T = \frac{5\dot{M}k}{2\mu m_{\mathrm{H}}\Lambda(T)} \tag{1}$$

where Y is the emission measure defined as

$$Y \equiv \int n_{\mathrm{e}} n_{\mathrm{H}} \mathrm{d}V \tag{2}$$

with n_{e} the electron density, n_{H} the hydrogen density and V the emitting volume; μ is the mean molecular weight, m_{H} the mass of the hydrogen atom and $\Lambda(T)$ the cooling function at temperature T. For more details see e.g. [1]. Thus, the amount of gas at each temperature in the cooling flow is expected to be inversely proportional to the cooling function. This DEM distribution is shown in Fig. 7. Based upon this DEM distribution, a significant amount of cooling gas is expected.

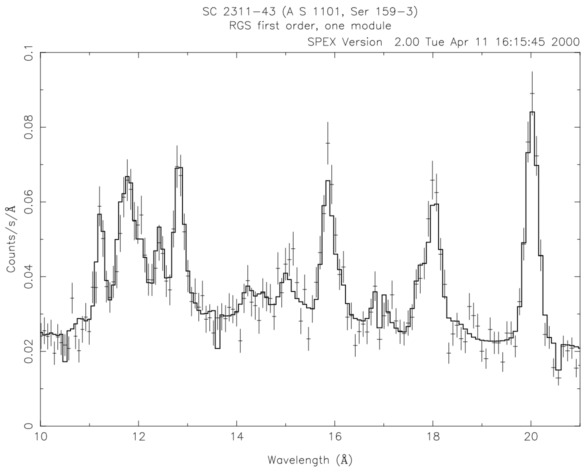

Figure 8. Simulated RGS spectrum of Sérsic 159−03 based upon a cooling flow model.

This model served to predict the spectrum of the cluster Sérsic 159−03, the first cluster to be observed with *XMM-Newton*. The predicted spectrum (Fig. 8) shows strong emission lines from Fe XVII and Fe XVIII, redshifted to the 16–18 Å band, corresponding to strong emission from plasma at a temperature of a few million K. These lines are of comparable strength to the lines from Fe XXIII and Fe XXIV from the hot gas in the 11–13 Å band and the O VIII Lyα line.

However, the observed spectrum looked quite different (Fig. 9). The spectrum shows the expected O VIII line (20 Å), the expected Fe-L emission of Fe XXIII, Fe XXIV as well as Ne X between 11−13 Å, all from kT=2.5 keV gas. But there are almost no Fe XVII or Fe XVIII emission lines. The emission measure of cool gas at kT=0.8 keV is only 2 % of the emission measure of the hot gas [3]. Qualitatively similar results were obtained for the clusters A 1795 [9] and A 1835 [7].

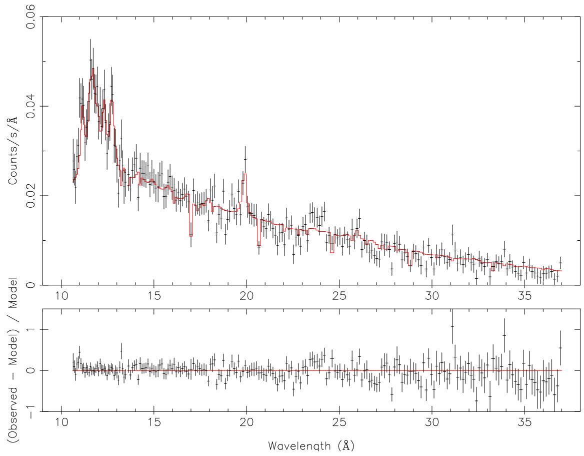

Figure 9. RGS1 spectrum of Sérsic 159−03 with the best fit two component model. Note the O VIII Lyα line at 20.0 Å; the lines between 11.2−12.8 Å are mainly due to Fe XXIV, Fe XXIII and Ne X. From [3].

4. New results on a large sample of clusters

In order to investigate whether the observed deficiencies of cooling gas are specific to the three clusters that were investigated or a more general property of cooling clusters, we studied a sample of 13 cooling clusters with RGS [8] and EPIC [6]. The clusters were selected to have strong lines for a good temperature diagnostics, implying preferentially high flux and low temperature (hot clusters have a strong bremsstrahlung continuum and therefore effectively a high background for the line emission). We also favour clusters with a small angular core radius, since these suffer less from spectral broadening due to the spatial extent of the cluster. This favours compact, intermediate distance clusters. The sample is listed in Table 1.

The RGS spectra of a selected set of clusters as well as the composite spectrum are shown in Fig. 10 and Fig. 11. All spectra show clearly that the isobaric cooling flow model cannot explain the observed RGS spectra. This model over predicts the Fe XVII and Fe XVIII lines in the spectrum. Instead, a cut-off isobaric cooling flow model (with a low temperature cut-off at about 0.3–0.5 times the maximum temperature), or al-

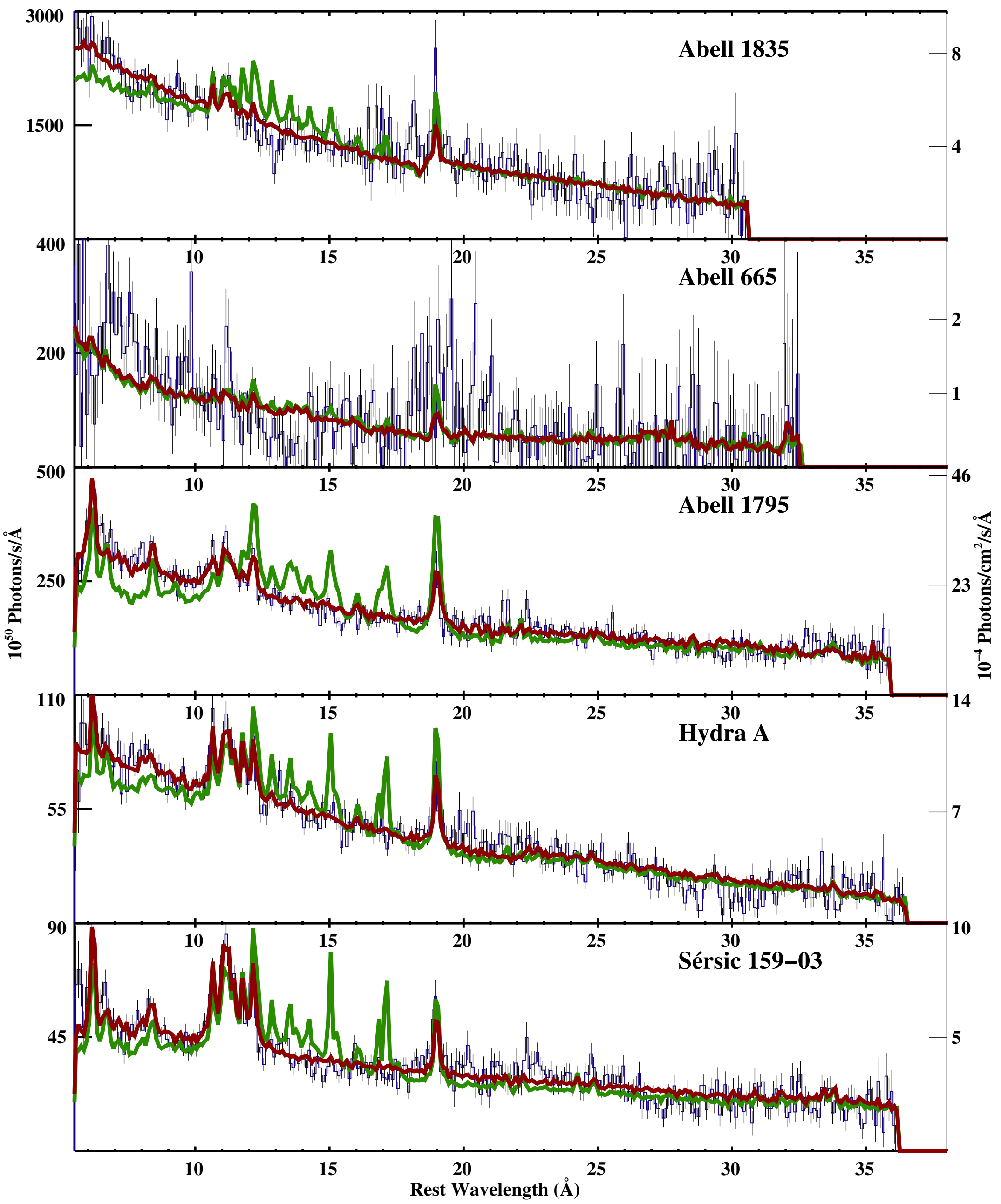

Figure 10. RGS spectra of a few hot clusters. The blue histogram and black data points are the observed spectrum, the green curve is the best fit isobaric cooling flow model, and the red curve an empirical cooling flow spectrum. From [8].

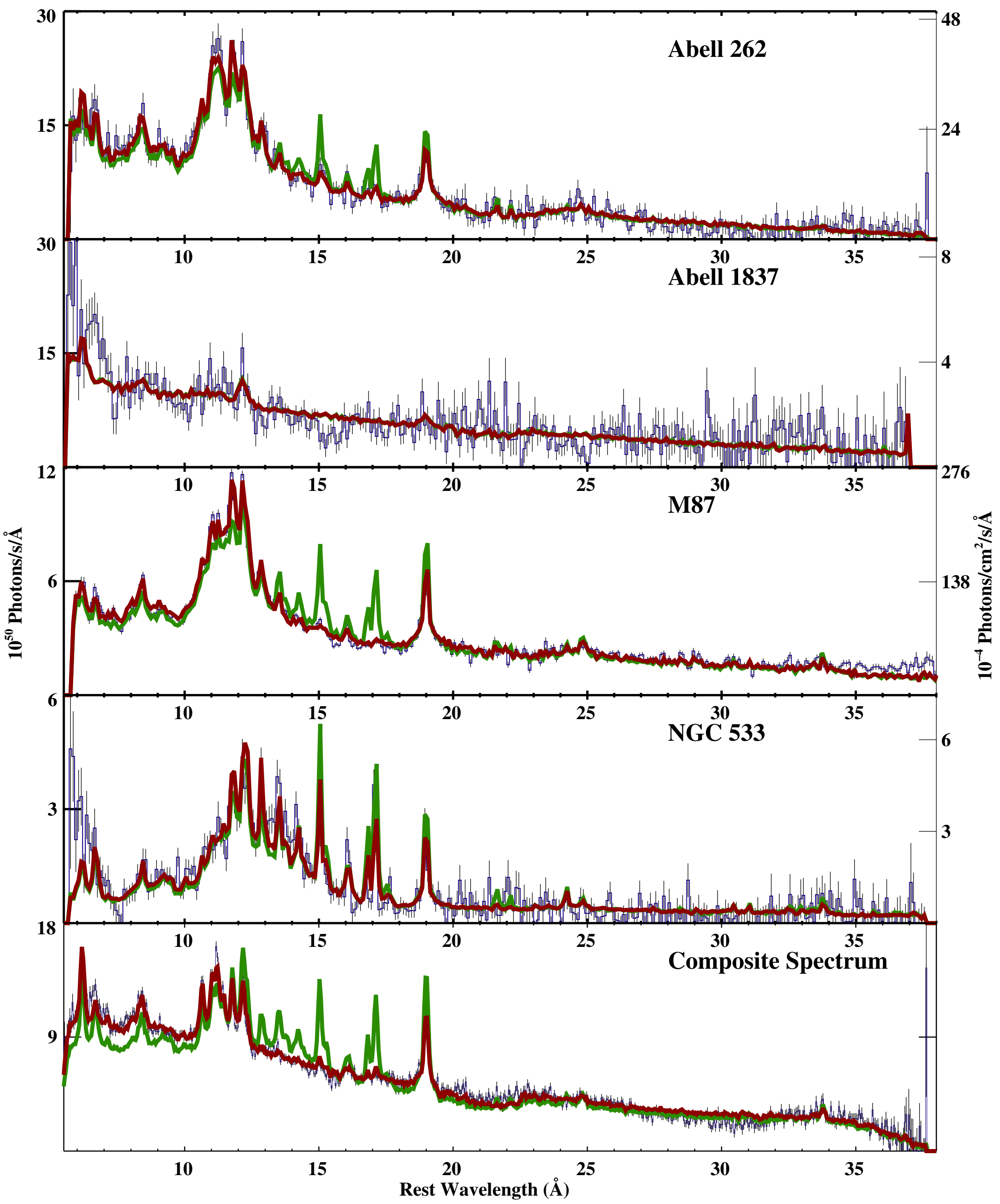

Figure 11. As Fig. 10, but for cooler clusters as well as the composite spectrum (excluding Virgo). From [8].

Table 1
Cluster sample. The unabsorbed 0.1–2.4 keV X-ray flux is given in units of 10^{-15} W m^{-2}.

Cluster	T (keV)	Flux	z
NGC 533	1.3	6	0.0175
A 262	2.2	49	0.0155
Ser 159-03	2.4	24	0.0572
Virgo	2.6	821	0.0027
2A 0335+096	3.0	81	0.0344
A 2052	3.1	47	0.0356
Hydra A	3.4	48	0.0550
MKW 3s	3.5	30	0.0455
A 4059	4.1	31	0.0466
A 1837	4.4	7	0.0707
A 496	4.4	75	0.0322
A 1795	5.8	68	0.0639
A 1835	7.2	15	0.2541

ternatively a continuous DEM distribution with a steep temperature dependence provides an excellent fit to the RGS data [8]. Thus, the deficiency of the standard isobaric cooling flow model is not specific for the first three clusters that were studied with *XMM-Newton*, but is a general property of all cooling clusters.

The DEM distribution of the clusters as derived from the RGS spectra is shown in Fig. 12. It is clear from this figure that the DEM is much steeper than predicted by the isobaric cooling flow model, and that at low temperatures the observed luminosity (and emission measure) is almost an order of magnitude smaller than the prediction. There is no clear dependence on the cluster temperature (Fig. 13), excluding for example models with an inhomogeneous metallicity.

5. Spatially resolved DEMs

For most of our clusters the statistics are not good enough to perform spatially resolved spectroscopy in the cross dispersion direction using the RGS data. For that information we rely on the EPIC data. Fortunately, as the RGS spectra showed, the cluster spectra show no evidence for large amounts of absorbing material in the core region. This makes the analysis of the EPIC data more straightforward. Radial temperature profiles of the clusters are shown in Figs. 14–15. The high sensitivity of *XMM-Newton* allows an accurate determination of the average cluster temperature as a function of radius. The effects of the cooling towards the center are clearly visible in

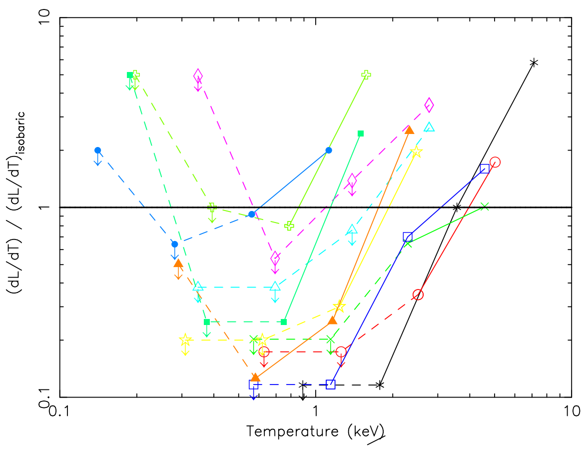

Figure 12. Differential emission measure (DEM) distribution for the sample of clusters. The y-axis gives the DEM divided by the expected DEM for the isobaric cooling flow model. Each cluster has a separate colour and symbol, detections are connected with a solid line, upper limits with a dashed line. Adapted from [8].

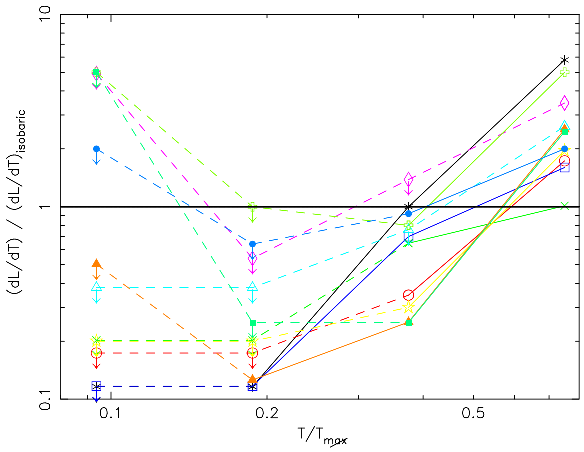

Figure 13. Similar to Fig. 12, but the temperature axis scaled to the maximum temperature of the hot gas. Adapted from [8].

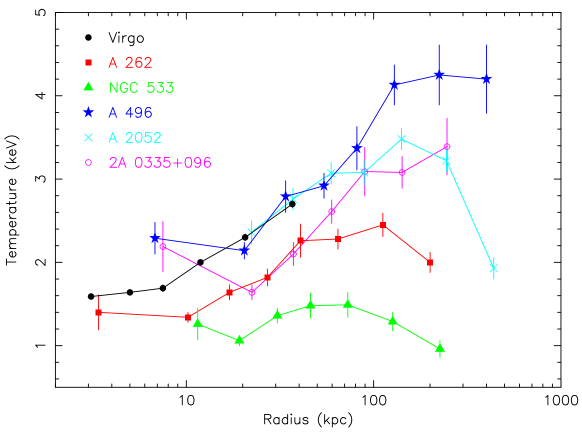

Figure 14. Radial temperature profile as determined from the EPIC spectra. From [5].

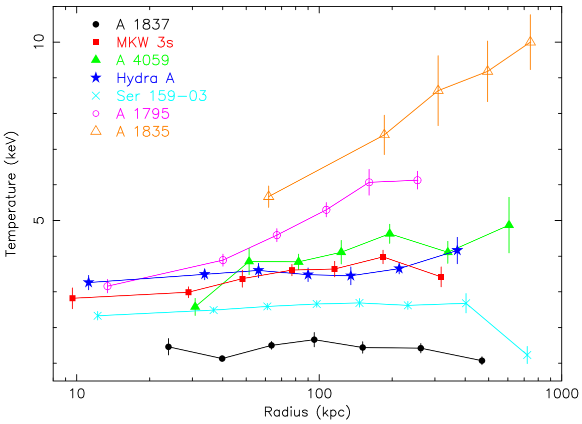

Figure 15. Radial temperature profile as determined from the EPIC spectra. From [5].

these radial profiles.

It is more interesting, however, to study the DEM as a function of radius instead of only the average temperature. We have done this now for our sample [6], and a typical example is shown in Fig. 16. We find in general for our sample that the EPIC spectra in the central region are not consistent with the isobaric cooling flow model. Just as in the RGS data, the DEM is much steeper than predicted by that model. Although the data show in general a decrease of the maximum temperature towards the center, the spectra at each radius are not isothermal but show a significant emission measure at half the maximum temperature.

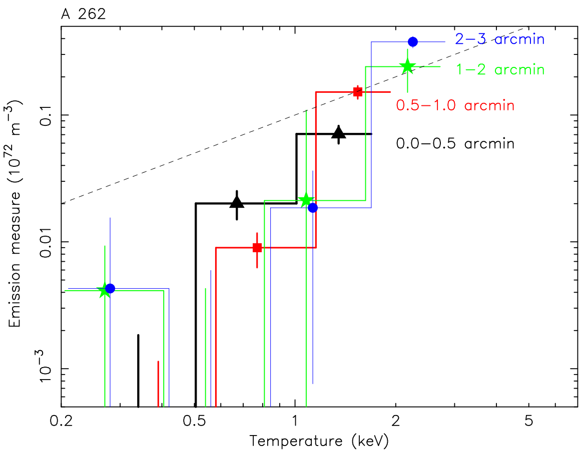

Figure 16. Emission measure distribution (not differential in this plot!) for the innermost four annuli of A 262, as determined from the *XMM-Newton* EPIC spectra. The dashed line approximates the expected slope of the isobaric cooling flow model. The data show that this cluster is neither locally isothermal (there is significant emission at half the maximum temperature), nor is it consistent with the isobaric cooling flow model. Adapted from [6].

A wide range of explanations has been given for the lack of cool gas in these clusters. An incomplete list with some comments is given below. We do not discuss these possibilities in detail, but refer to [8,6] for more details on the failure or success of some of these interpretations when they are compared to the present cluster sample.

- Atomic physics errors: not important here
- Resonance scattering: insufficient optical depth
- Evolution effects (mergers): unlikely for all clusters
- Inhomogeneous metallicity: inconsistent (no $T_{\rm cut}$ ∼1 keV)

- Differential cold absorption: unlikely, no edges observed
- Sporadic heating (AGN): difficult, needs fine-tuning
- Thermal heat conduction: problematic
- Rapid cooling due to mixing with cold gas: why?
- Magnetic reconnection
- Turbulent mixing

6. Abundances

The RGS has given a significant contribution to the study of cooling flows in clusters of galaxies, as we showed in this paper. But also for the study of abundances the RGS is invaluable. The RGS is in particular sensitive to measuring the abundances of O, Ne, Mg, Si and Fe (see Fig. 17). We do not discuss these results in detail in this paper, but refer to [10] for a full analysis. Here we only note that the oxygen abundance can be measured with high precision thanks to the superb energy resolution of the RGS at longer wavelengths.

7. Conclusions

The RGS spectrometers of *XMM-Newton* have opened a new window on clusters. They have provided already a major contribution to the cooling flow problem, and are very important for abundance studies. The archive of *XMM-Newton* is open, and future AOs offer sufficient opportunities to investigate these and other questions in clusters of galaxies.

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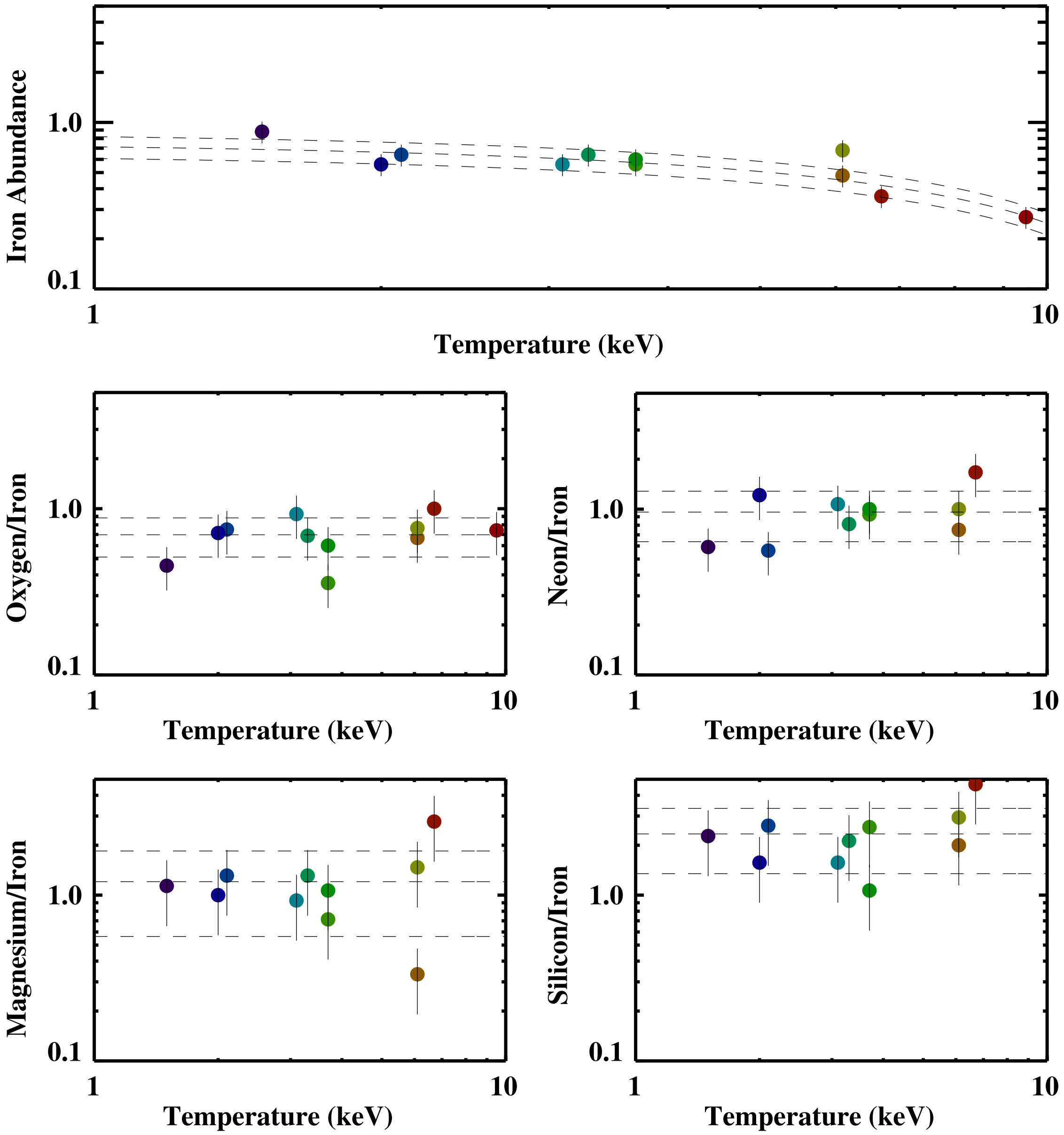

Figure 17. Abundances and abundance ratios plotted as a function of the ambient cluster temperature. The iron abundance tends to increase for lower mass systems. No other obvious trends can be seen. The dashed lines are the average value for the sample and the 1σ ranges. The abundances are derived from fits to the RGS spectra. From [8].