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X-ray spectroscopy of clusters of galaxies with XMM

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Abstract. We present some first results on high-resolution X-ray spectra of clusters of galaxies as obtained with the Reflection Grating Spectrometer (RGS) on board of XMM-Newton.

1. Introduction

The visible mass in clusters of galaxies is dominated by hot diffuse gas. Due to the high temperature of the gas it is predominantly visible in the X-ray band. X-ray spectroscopy is the key tool to understand the physics of this gas and its role in the structure and evolution of the cluster. Since the gas is extended, spatially resolved spectroscopy is required. Until recently medium-resolution spectroscopy using Gas Scintillation Proportional Counter (GSPC) or Charge-Coupled Device (CCD) technology was limited to a spatial resolution of a few arcminutes (ASCA and BeppoSAX). Therefore only in a handfull of nearby clusters the core could be resolved spatially. While other instruments aboard the Einstein and Rosat satellites had better spatial resolving power, they either lacked bandwidth or spectral resolving power. High spectral resolution data of clusters have only been obtained for the bright core of the Virgo cluster with the Einstein FPCS detector (Canizares et al. 1979). With XMM-Newton it is now possible to combine high-resolution spectroscopy of moderately extended sources using the Reflection Grating Spectrometer (RGS) with high-sensitivity, medium (CCD-type) spectral resolution imaging with the European Photon Imaging Camera (EPIC) on spatial scales down to a few arcseconds.

2. Cooling flows

Due to the high gas density in the center of most clusters with a dominant central cD galaxy, the cooling time due to X-ray radiation is shorter than the age of the cluster. Accordingly, the temperature will drop in the densest regions. The decreasing temperature causes a drop in pressure that will be compensated by a slow inward gas flow in order to maintain hydrostatic equilibrium. This is the so-called cooling flow. In general it is assumed that the cooling flow is sufficiently strong to keep the cooling gas in pressure equilibrium with the surrounding hot gas. This is the isobaric assumption. A further assumption often made is that at each instant the mass deposition rate $\dot{M}$ is a constant; this assures a stationary cooling flow. Under those assumptions, the time-averaged differential emission measure (DEM) distribution $\mathrm{d}Y/\mathrm{d}T$ of the cooling gas 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 $Y \equiv \int n_{\mathrm{e}} n_{\mathrm{H}} \mathrm{d}V$ 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. Johnstone et al. (1992). 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. 1. This DEM does not extend towards high temperatures, but it has a natural high-temperature cut-off at the temperature of the hot gas, which differs from cluster to cluster. The "true", observed DEM of the cluster also contains in addition to the cooling contribution (1) a sharply peaked component at this cut-off temperature corresponding to the hot non-cooling gas.

In order to test cooling flow models it is immediately evident from Fig. 1 that the most useful ions are the Fe-L shell ions (Fe XVII–XXIV), since they map the most important part of the cooling DEM distribution, spanning almost a decade in temperature. These ions emit most of their strong lines in the 8–17 Å band. This is in the wavelength range for which the XMM-Newton RGS instrument has been optimized. In addition, cooling flow clusters are in general more compact than non-cooling clusters. This yields core radii of the order of a few arcminutes for several of these bright clusters, reducing the spectral resolution of the RGS by no more than typically 0.1–0.3 Å. Therefore the RGS is one of the best instruments to study cooling flows.

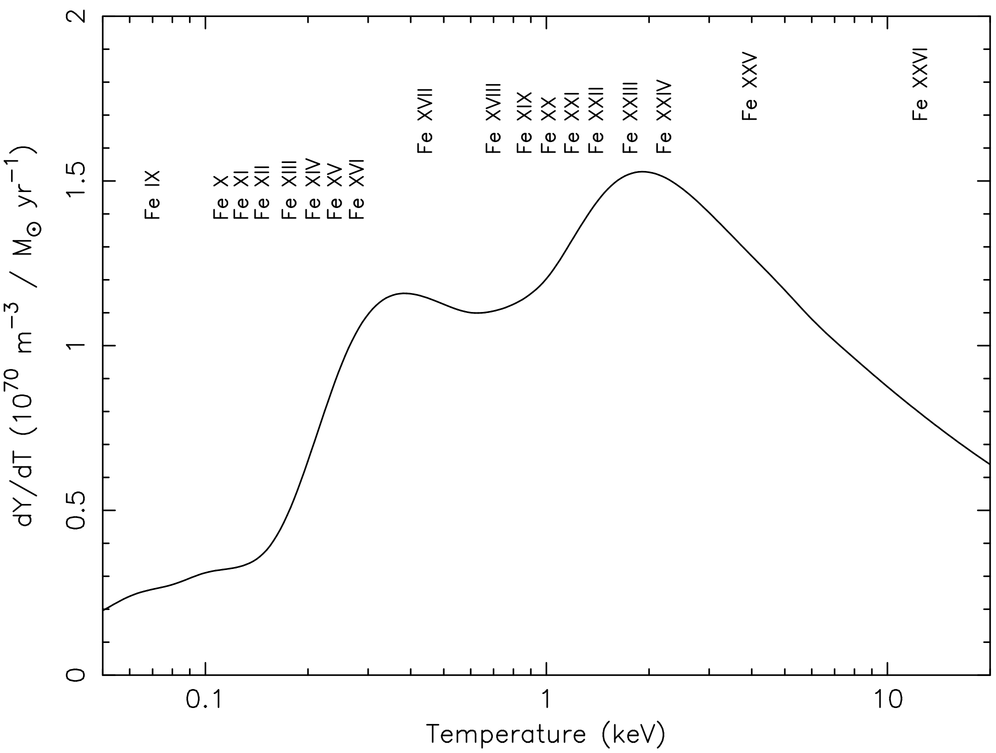

Figure 1. Differential emission measure distribution for isobarically cooling gas, calculated for a plasma with half the solar abundances. The calculation is based upon the SPEX code (Kaastra et al. 1996). For the iron ions the temperatures where the relative concentrations have their maximum value are indicated. Note the distiction between K, L and M-shell ions (Fe XXV–XXVI, XVII–XXIV and IX–XVI, respectively.

3. Initial results

Initial results on three bright clusters of galaxies have been presented by Kaastra et al. (2001) on Sérsic 159-03, Peterson et al. (2001) on A 1835 and Tamura et al. (2001) on A 1795. These clusters span a wide range in initial gas temperatures, ranging from 2.5 keV for Sérsic 159-03, 6 keV for A 1795 up to 8.3 keV for A 1835. The spectra of all these three clusters are qualitatively very similar. An example is shown in Fig. 2. The spectra of all three sources are also shown in this volume by Brinkman (2001). Superimposed upon the spectrum from the hot gas clearly prominent line emission from mainly O VIII, Ne X and Fe XXIII and Fe XXIV is seen. For Sérsic 159-03 this consists both of emission from the hot component (only 2.5 keV) as well as from a cooler component; for the other two clusters it is mainly emission from the cooler component. This line emission from the cool component can be readily understood in terms of the isobaric cooling flow model. However, the same model predicts intense line radiation from Fe XVII

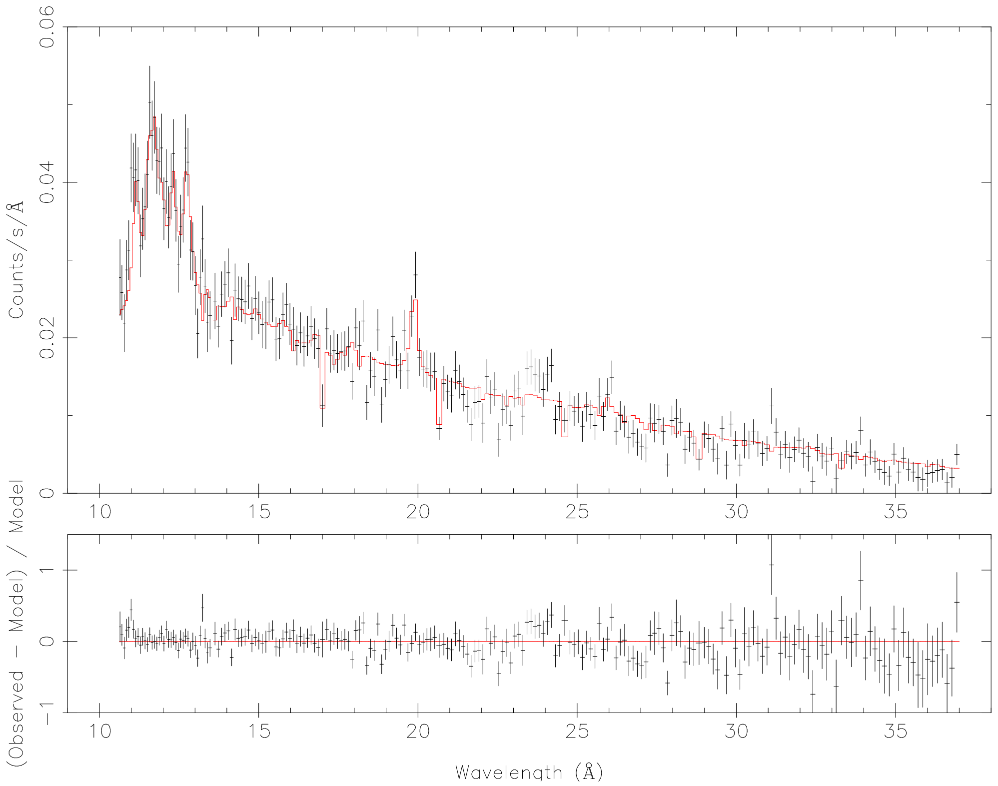

Figure 2. RGS1 spectrum of Sérsic 159−03 with the best fit two component model. Note the O VIII Lyα line at 20.0 Å; the lines between 11.2−12.8 Å are mainly due to Fe XXIV, Fe XXIII and Ne X (from Kaastra et al. 2001).

and neighbouring ions, cf. the peak around 0.4 keV in the DEM shown in Fig. 1. Fe XVII should show prominent lines near 15.01, 16.78, 17.05 and 17.10 Å, with strengths comparable to the O VIII Lymanα line at 19 Å and the Fe XXIV lines between 11−13 Å. These lines are not observed, however, implying that there is at least 5 times less Fe XVII in the cluster than the standard isobaric cooling flow model predicts. In fact, the spectra can only be modelled with the isobaric model, provided that a lower temperature cut-off is introduced. For Sérsic 159-03 this cut-off is near 1.4 keV, for A 1795 around 2.4 keV. This result is confirmed by the lower resolution EPIC instruments, although in the latter case it follows only after spectral model fitting, the spectral resolution of the data is too low to see the individual lines.

Different scenarios have been suggested in order to explain the absence of the expected line emission from the cooling gas, such as re-heating, absorption, heat conduction, etc. For an overview of these possibilities and a discussion on the problems associated with them we refer to the paper by Peterson et al. (2001), but see also Fabian et al. (2001). The rapidly increasing number of clusters studied by the RGS will help to explore this surprising result on the cooling flow model for clusters of galaxies.

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