Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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Thermal structure of cooling clusters

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Abstract. We present spatially resolved X-ray spectra taken with the EPIC cameras of XMM-Newton of a sample of 17 cooling clusters and three non-cooling clusters for comparison. The deprojected spectra are analyzed with a single-temperature model. All cooling clusters show a central decrement of the average temperature, most of them of a factor of ∼2. Three clusters show a weak temperature decrement, while two others have a very strong temperature decrement. We investigate the role of heat conduction by electrons and find that the theoretically predicted conductivity rates are not high enough to balance radiation losses.

1. Introduction

The first high-resolution X-ray spectra of clusters of galaxies taken with the Reflection Grating Spectrometers (RGS) of XMM-Newton showed the presence of cooler gas in the cores of several clusters. However, the amount of cool gas at lower temperatures was much smaller than predicted by the isobaric cooling flow model (Sérsic 159−3, Kaastra et al. 2001; A1835, Peterson et al. 2001; A1795, Tamura et al. 2001a). The lack of relatively cool gas has been confirmed by the RGS spectra of other clusters, like A496, Tamura et al. (2001b) and Virgo, Sakelliou et al. (2001b) and also by Chandra observations. In order to be able to distinguish between the various theoretical models that have been proposed, it is important to measure the temperature structure for each radius. We report on a study of a large sample of clusters and use the spatially resolved XMM-Newton/EPIC spectra to investigate the temperature structure at each radius. We present here only results from single temperature fits and discuss heat conduction on cluster scales. More details are given in Kaastra et al. (2004).

2. Cluster sample and single temperature fits

The data analysis is described extensively by Kaastra et al. (2004). Here we summarize the results. Our sample of clusters consists of 17 cooling clusters (NGC 533, Virgo, A262, A1837, Sérsic 159−3, MKW 9, 2A 0335+096, MKW 3s, A2052, A4059, Hydra A, A496, A3112, A1795, A399, Perseus and A1835) and for comparison 3 non-cooling clusters (A3266, Coma and A754). Temperatures range between 1 and 15 keV, and most clusters have intermediate redshift (0.02–0.07). In our analysis, we assume spherical symmetry and we use deprojected spectra. Data obtained by the MOS and pn detectors were fitted simultaneously. The temperature profiles that we derive from our single temperature fits

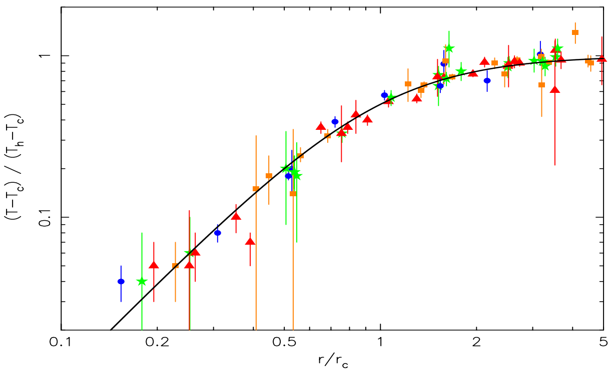

Figure 1. Scaled temperature profiles versus scaled radius. Triangles: clusters cooler than 3 keV; Squares: clusters with temperatures from 3 to 4 keV; Stars: clusters with temperatures from 4 to 6 keV; Circles: clusters with temperatures above 6 keV. The non-cooling clusters Coma, A754 and A3266 have been omitted from the plot. The solid line is the scaling curve Eq. (2.1).

for the cooling parts of the clusters are consistent with:

$$T(r) = T_c + (T_h - T_c)\frac{r^2}{r_c^2 + r^2}. \tag{2.1}$$

In this equation, r_c is a scale parameter for which we find best-fit values between 20 and 100 kpc. The parameter T_c corresponds to the temperature at the center of the cluster, while T_h is the asymptotic temperature at large radii. We find that the relative temperature decrement, given by the ratio $(T_h - T_c)/T_h$ has values between 0.15 and 0.70 for our cluster sample. We show the scaled temperature profiles in Fig. 1. There exist some scaling laws between the parameters of our fit to Eq. (2.1). For instance, there is a correlation between characteristic radius r_c and asymptotic temperature T_h of the form: $r_c \sim T_h^{1.84\pm0.14.}$ However, the virial radius scales proportionally to $T_h^{0.5}$. This implies that $r_c/r_{\rm vir}$ is not constant from cluster to cluster.

3. Heat conduction by electrons

Thermal conduction by electrons might play an important role in cooling clusters. We derive conduction coefficients assuming that heat conduction by electrons balances radiative losses, i.e.: $\int_{\rm V} n^2\Lambda(T)dV = \int_{\rm S}\kappa(\nabla T)dS$, where n, Λ, T and κ are the gas density, cooling function, temperature and thermal conductivity, respectively and V and S are the volume and surface area of the X-ray emitting region. Using data binned into shells, the conductivity coefficients at the boundary of each shell can be computed. The temperature gradient between shells is evaluated by fitting the temperature profile with the function (2.1). Our estimates of the conduction coefficients κ are shown in Fig. 2. The estimated conduction coefficients must be compared to theoretical calculations to see whether heat conduction from the outer regions can totally balance radiative losses. For a highly ionised plasma such as the ICM, the maximum rate is expected to be the Spitzer conductivity $\kappa_{\rm s}$. In the presence of a homogeneous magnetic field, the conductivity is the Spitzer rate only along the field, but severely decreased in the transverse direction. Thermal conduction in a tangled magnetic field has been studied by Chandran & Cowley (1998). They conclude that in cooling flows, thermal conductivity is below the Spitzer level by a factor of order 10^2 to 10^3. Conductivity is less severely decreased if the magnetic field behaves chaotically over a wide range of scales: Narayan & Medvedev (2001) estimate that in this case conductivity is only a factor ∼5 below the Spitzer rate. Therefore,

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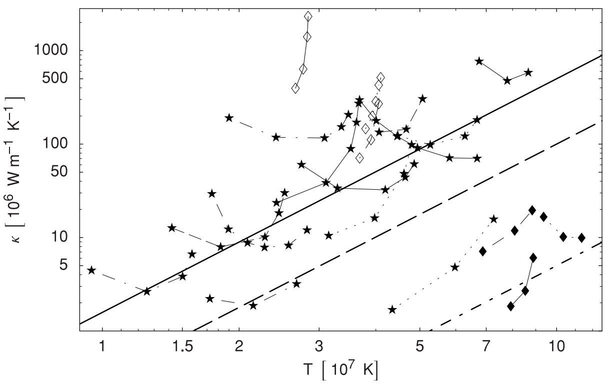

Figure 2. The conduction coefficients κ required for heat conduction to balance radiation losses as a function of temperature. The solid line is the Spitzer conductivity, the dashed lines are one fifth and one hundredth of the Spitzer conductivity, respectively. Filled diamonds: three clusters without cooling flow; Open diamonds: clusters with a shallow temperature profile (MKW 3s, Sérsic 159-3 and Hydra A); Filled stars: remaining clusters. Values for the same cluster are joined by a line and values are given only for bins with cooling times less than ∼30 Gyr.

the Spitzer conductivity κ_s, $\kappa_s/5$ and $\kappa_s/100$ are shown in Fig. 2 for comparison. For the three non cooling clusters we find very low values for the conductivity coefficients: the absence of significant cooling allows even inefficient heat conduction to remove temperature inhomogeneities. The cooling clusters with shallow temperature profile show a very different trend and relatively high conductivity due to the small temperature gradients. Most important, we find conductivities larger than one fifth of the Spitzer rate in almost all the cooling clusters and therefore conclude that heat conduction alone is insufficient to balance radiative losses in cooling clusters.

Although we demonstrated that heat conduction on a global scale cannot maintain the large scale temperature gradients in cooling clusters, heat conduction may still play an important role on smaller spatial scales. In Kaastra et al. (2004) we considered a class of magnetic loop models as a possible mechanism in which heat conduction on smaller scales may occur.

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