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The Birmingham–CfA cluster scaling project – III. Entropy and similarity in galaxy systems

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ABSTRACT

We examine profiles and scaling properties of the entropy of the intergalactic gas in a sample of 66 virialized systems, ranging in mass from single elliptical galaxies to rich clusters, for which we have resolved X-ray temperature profiles. Some of the properties we derive appear to be inconsistent with any of the models put forward to explain the breaking of self-similarity in the baryon content of clusters. In particular, the entropy profiles, scaled to the virial radius, are broadly similar in form across the sample, apart from a normalization factor that differs from simple self-similar scaling with temperature. Low-mass systems do not show the large isentropic cores predicted by preheating models, and the high entropy excesses reported at large radii in groups by Finoguenov et al. are confirmed, and found to extend even to moderately-rich clusters. We discuss the implications of these results for the evolutionary history of hot gas in clusters, and suggest that preheating may affect the entropy of intracluster gas primarily by reducing the density of material accreting into groups and clusters along cosmic filaments.

Key words: galaxies: clusters: general – intergalactic medium – X-rays: galaxies: clusters.

1 INTRODUCTION

In the widely accepted standard model for cosmic structure formation, the Universe evolves hierarchically as primordial density fluctuations are amplified by gravity, collapse and merge to form progressively larger systems. This hierarchical development leads to the prediction of self-similar scalings between systems of different masses and at different epochs. These scalings are also seen in cosmological simulations involving only gravitationally driven evolution, including compression and shock heating of baryonic matter. Such simulations (see, for example, Navarro, Frenk & White 1995; Frenk et al. 1999) result in haloes in which the density profiles of both dark matter and baryonic material, when radially scaled to the virial radius (which we define here to be the radius R_{200}, within which the mean density of a system is 200 times the critical density of the Universe) are almost identical in virialized systems covering a wide range of masses, from individual galaxies to rich clusters.

Given self-similar scalings of gas temperature and density, scaled X-ray surface brightness profiles are also expected to be similar. Furthermore, a simple scaling is expected between X-ray luminosity L_X and temperature T. Assuming that the emission is dominated by bremsstrahlung, $L_X \propto M_{\rm gas}^2 R^{-3} T^{1/2}$, or $L_X \propto f_{\rm gas}^2 T^2$, where $M_{\rm gas}$ is the gas mass within radius R, and $f_{\rm gas} = M_{\rm gas}/M$ is the gas mass fraction. X-ray properties of clusters deviate substantially from this simple scaling, and the observed L_X–T relation (White, Jones & Forman 1997; Markevitch 1998) is considerably steeper than T^2 in the cluster regime, and steepens further (Helsdon & Ponman 2000) in galaxy groups. Ponman, Cannon & Navarro (1999) showed that the latter effect is due to the suppression of L_X in galaxy groups, arising from a reduction in gas density in the inner regions of poor systems, relative to richer clusters.

It is instructive to view this in terms of the entropy of the intergalactic medium (IGM), which in the self-similar case should increase in a very simple scaling with the mean temperature of virialized systems. In practice, it is found (Ponman et al. 1999; Lloyd-Davies, Ponman & Canon 2000) that an excess in the entropy, above the self-similar prediction, is apparent in the inner regions of poor clusters and groups, outside the dense central regions in which cooling is expected to radiate away entropy within the age of the Universe. This effect has been referred to as the 'entropy floor', with the implication that additional physical processes, beyond gravity and resulting compression and shock heating, have acted to set a lower limit to the entropy that the gas in collapsed haloes can have.

A great deal of theoretical work has been devoted to explaining this phenomenon over the past few years. As we will discuss in some detail later, the explanations proposed fall into three main classes: the gas has been heated either at an early epoch, before clusters were assembled (Evrard & Henry 1991; Kaiser 1991; Cavaliere, Menci & Tozzi 1997; Balogh, Babul & Patton 1999; Valageas &

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Silk 1999; Tozzi & Norman 2001), or it has been heated *in situ* by star formation and/or energy input from active galactic nuclei (AGNs) (Bower 1997; Loewenstein 2000; Voit & Bryan 2001; Nath & Roychowdhury 2002). Alternatively, some authors have argued (Knight & Ponman 1997; Bryan 2000; Pearce et al. 2000; Muanwong et al. 2001; Wu & Xue 2002a; Davé, Katz & Weinberg 2002) that cooling alone will remove low-entropy gas from the centres of haloes, producing a very similar effect to non-gravitional heating.

In the present paper we aim to confront these models with the observed properties of the hot gas in a large sample of galaxy systems, spanning a wide range in total mass. In the fullness of time, high-quality X-ray observations of the density and temperature structure of the IGM will be available from *XMM-Newton* and *Chandra*. However, at present, such observations are sparse, and it is essential to have a broadly representative and wide-ranging sample of virialized systems in order to study scaling properties. The value of this in the context of similarity-breaking in clusters has already been shown by a number of earlier studies.

In the present paper and in two companion papers (Sanderson et al. 2003 – Paper I – and Sanderson & Ponman 2003 – Paper II), we examine scaling properties derived from the largest sample of virialized systems with resolved X-ray temperature profiles yet assembled. Following a brief description of the sample and our analysis in Section 2 (details are given in Paper I), we present the profiles and scaling properties for the entropy and temperature across our sample in Sections 3 and 4. These results are used in Section 5, along with relevant results from Papers I and II, to test the various models proposed to account for the entropy floor, and finally in Section 6 we draw our conclusions from this study, and propose a new model to explain the behaviour of the entropy of intracluster gas.

2 SAMPLE AND ANALYSIS

Our sample comprises 66 virialized systems, from rich clusters of galaxies, through groups and down to the level of individual galaxy-sized haloes. In Sanderson et al.(2003, hereafter Paper I), we reported a detailed study of the three-dimensional X-ray properties of this sample, based on data from the *ROSAT* and *ASCA* observatories, which we assembled from the work of three separate investigators (Markevitch 1996; Markevitch & Vikhlinin 1997; Markevitch 1998; Markevitch et al. 1998, 1999; Finoguenov & Ponman 1999; Finoguenov, David & Ponman 2000; Finoguenov & Jones 2000; Lloyd-Davies et al. 2000; Finoguenov, Arnaud & David 2001), combined with a number of cool groups analysed specially to provide better coverage of the crucial low end of the mass range. To each system we fitted analytical functions describing the gas density and temperature variation with radius outside any central cooling region, which was excised or fitted separately. This approach allows us to put the X-ray data from the three earlier studies on a unified footing, and gives us the freedom to extrapolate the gas properties to arbitrary radius. We used a beta model to parametrize the density and specified the temperature variation with either a linear ramp or a polytropic IGM. We have used these data to determine the gravitating mass profile and thus to calculate radii of overdensity in a self-consistent manner. Similarly, we have derived mean temperatures for each system, by averaging the gas temperature within $0.3R_{200}$, weighted by its luminosity (Paper I).

3 ENTROPY AND TEMPERATURE DISTRIBUTIONS

For convenience, we define 'entropy' in the present paper as

$$S = T\big/n_e^{2/3}\ \mathrm{keV\ cm^2}, \qquad (1)$$

which relates directly to observations. This has been referred to by a number of authors as the 'adiabat', since (apart from a constant relating to mean particle mass) it is the coefficient relating pressure and density in the adiabatic relationship $P = K\rho^{\gamma}$. Hence S is conserved in any adiabatic process. Note that the true thermodynamic entropy is related to our definition via a logarithm and additive constant.

In Fig. 1 we overlay the scaled entropy profiles for all 66 systems in our sample. Under the assumption that all these systems form at the same redshift, their mean mass densities should be identical. Hence in the simple self-similar case, where all have similar profiles and identical gas fractions, S will simply scale with mean system temperature T. We apply this scaling, and scale the radial coordinate to R_{200} for each system, derived from our fitted models (Paper I). It can be seen that the entropy profiles of the cooler systems, scaled in this way, tend to be significantly higher than those of richer clusters. To see this more clearly, in the right panel of Fig. 1 we show the profiles grouped into bands of mean system temperature. In this grouped plot we have excluded the two galaxies in our sample, whose profiles may be dominated by stellar wind losses rather than by the processes operating in groups and clusters.

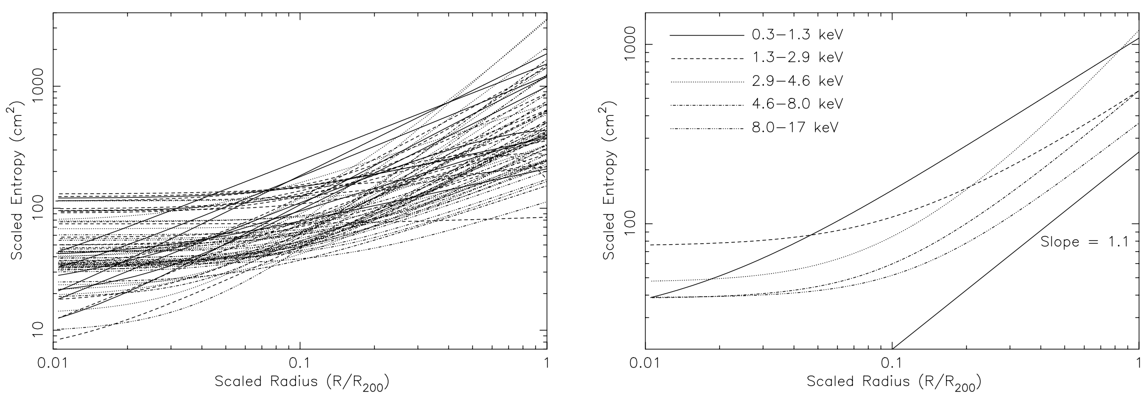

Figure 1. Entropy profiles for each system in our sample (left panel) derived from our fitted models, each scaled by $1/T$. The line style of each profile denotes the mean temperature of the system, as described below. In the right panel, these profiles (excluding the two galaxies, as discussed in the text) have been grouped into temperature bands: 0.3–1.3 keV (solid), 1.3–2.9 keV (dashed), 2.9–4.6 keV (dotted), 4.6–8 keV (dot–dashed) and 8–17 keV (triple-dot–dashed). The bottom line shows the slope of 1.1 expected from shock heating. Its normalization is arbitrary.

It can be seen that there is a strong tendency for the scaled entropy to be higher, at a given scaled radius, in cooler systems. Simulations and analytical models of cluster formation involving only gravity and shock heating, produce entropy profiles with logarithmic slopes of approximately 1.1 (Tozzi & Norman 2001), which agrees rather well with the slope of our profiles outside $0.1R_{200}$. The mean profile in the 2.9–4.6 keV band is significantly affected by two systems, visible in the left-hand panel, that have strongly rising profiles. One of these is AWM7, for which the temperature profile is subject to especially large systematic uncertainties, as a result of the strong cooling flow, as discussed in Paper I. The temperature model adopted, from the analysis of Lloyd-Davies et al. (2000), rises strongly with radius. As a result, the slope of $S(r)$ in this band is almost certainly overestimated in the figure.

One possibility that we can discard right away is that the observed scaling results from systematic differences in the formation epochs of low- and high-mass systems. In hierarchical models, low-mass systems are expected to form, on average, earlier than high-mass ones. Hence they should tend to have higher mean densities, and therefore *lower* gas entropy – the opposite of what we observe. It is true that, owing to the usual selection effects, the rarer and more luminous massive systems in our sample tend to be at higher redshifts than the groups. Hence if, contrary to expectations, all systems virialized at the redshift we observe them, then the more massive systems would be more dense, and have lower entropies. However, this effect is considerably smaller than the trend we observe. The highest-redshift clusters in our sample are at $z \sim 0.2$; hence their mean densities, scaling as $(1 + z_{\rm f})^3$, could be 70 per cent higher than the lowest-redshift systems, and their entropies (scaling as $n^{2/3}$) consequently lower by a factor of 1.44. All but four members of our sample lie at $z < 0.1$, and hence would have entropies changed by less than 20 per cent as a result of such a redshift-dependent density scaling. In contrast, Fig. 1 shows that the scaled entropy actually differs by a factor three between the high- and low-temperature bins for our sample.

At small radii, our fitted models exclude the effects of cooled gas, since any central cooling region is excised, or represented by a separate component in our analysis (Section 2). This central cooling region is present in 54 of our 66 systems (see table 1 in Paper I), and in these cases its radius ($r_{\rm cool}$) ranges from $0.03R_{200}$ to $0.2R_{200}$, with a median value of $r_{\rm cool} = 0.06R_{200}$. Apart from the coolest systems, our entropy profiles generally flatten inside $0.1R_{200}$. This effect is also seen in many cosmological simulations (Frenk et al. 1999) even in the absence of non-gravitational heating and cooling processes, and appears to result from the introduction of a core into the gas density distribution, due to transfer of energy between baryonic and dark matter during merger events (Eke, Navarro & Frenk 1998). Preheating models generally predict large isentropic central regions in low-mass systems, which are not seen in our data. We will return to this point in Section 5 below.

The preheating model of Dos Santos & Doré (2002) predicts that entropy should scale according to $(1 + T/T_0)$, rather than T, where T_0 is a constant related to the degree of preheating, which they estimate as $T_0 = 2$ keV, to provide a best fit to the entropy-floor data of Lloyd-Davies et al. (2000). In Fig. 2, we show the effect of this scaling on our temperature-grouped entropy profiles. This scaling does indeed bring the profiles into good agreement, apart from the fact that our coolest systems show little sign of any central entropy core. Note from the left-hand panel in Fig. 1 that this is a general feature of almost all the entropy profiles for cool systems, rather than a result of averaging together systems with cores and others with strongly dropping central entropies.

It is also instructive to compare temperature profiles across the range of masses in our sample. We use the virial radii and masses calculated from our fitted models to compute the virial temperature

$$T_{200} = \frac{GM\mu m_{\rm p}}{2R_{200}}, \tag{2}$$

expressed in keV. This is used to normalize each temperature profile, and the scaled profiles are grouped in temperature bands, to reduce the large scatter and make trends more obvious. The result is shown in Fig. 3. As with the grouped entropy plots, we have excluded the two galaxies from these profiles. We have also omitted AWM7 from the 2.9–4.6 keV band, since its highly uncertain (see discussion

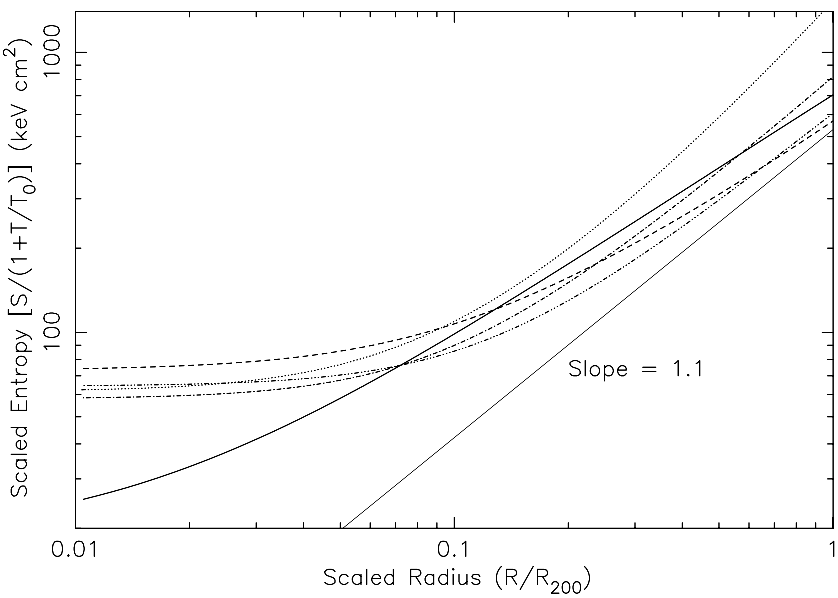

Figure 2. The variation of gas entropy [scaled by $(1 + T/T_0)^{-1}$] with scaled radius, grouped by system temperature. The solid line represents the coolest systems (excluding the two galaxies) (0.3–1.3 keV), increasing in temperature through dashed (1.3–2.9 keV), dotted (2.9–4.6 keV), dot–dashed (4.6–8 keV) and finally triple-dot–dashed (8–17 keV). The lower solid line (with arbitrary normalization) indicates the slope of 1.1 expected from shock heating.

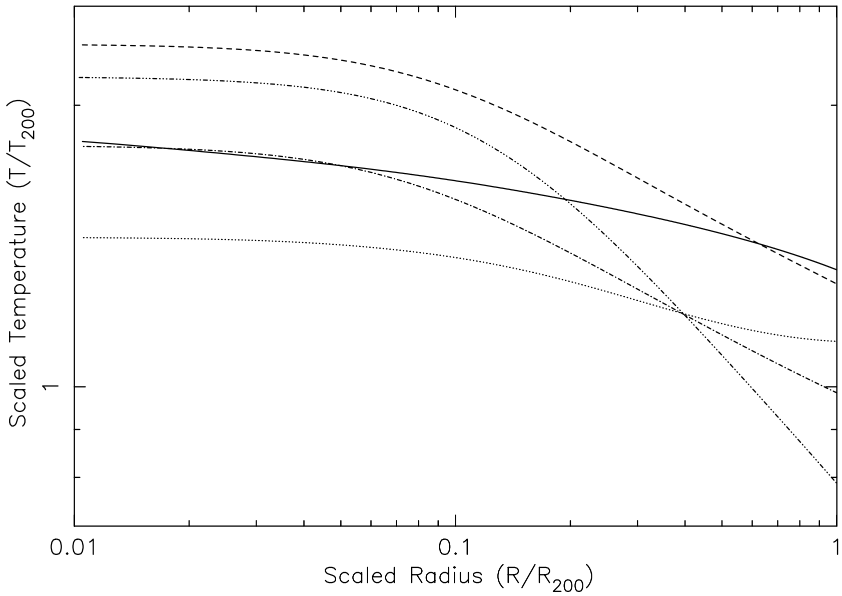

Figure 3. The variation of gas temperature (scaled by T_{200}) with scaled radius, grouped by system temperature. The solid line represents the coolest systems (excluding the two galaxies) (0.3–1.3 keV), increasing in temperature through dashed (1.3–2.9 keV), dotted (2.9–4.6 keV, excluding AWM 7), dot–dashed (4.6–8 keV) and finally triple-dot–dashed (8–17 keV).

above) and strongly rising $T(r)$ profile distorts the mean profile for the whole band.

Raising the entropy of the IGM results in increased temperatures as well as lower densities, and, for a given level of entropy increase, this effect will be most prominent in low-mass systems, where the 'natural' shock-generated entropy is lower. As can be seen, our observations do indeed show such an effect at large radii – at R_{200} the scaled temperatures are ordered in precisely this way. However, at smaller radii this is not the case, and, in particular, the coolest systems display very flat temperature profiles whilst the most massive clusters show the largest rise in temperature between R_{200} and the centre. This behaviour is not what is predicted by most models, as we will discuss later.

4 SCALING PROPERTIES

The claim of the discovery of an entropy floor in galaxy systems (Ponman et al. 1999) was based on the measurement of gas entropy at a scaled radius of $0.1R_{200}$ in systems spanning a wide temperature range. This radius was chosen to lie close to the centre, where shock-generated entropy should be a minimum, hence maximizing the sensitivity to any additional entropy whilst lying outside the region where the cooling time is less than the age of the Universe, and hence the entropy may be reduced. This initial study was improved by Lloyd-Davies et al. (2000), who avoided the isothermal assumption made by Ponman et al. and derived an entropy-floor value of $139\,h_{50}^{-1/3}$ keV cm^2 from a sample of 20 systems, which is essentially a subset of the present work.

In Fig. 4, we show the corresponding plot from our much larger sample. With the benefit of this increase in sample size, the trend looks rather different from its appearance in Lloyd-Davies et al. (2000), where a dearth of systems in the 1.5–3.5 keV band led to the interpretation of a relation that followed the self-similar line down from hot systems, flattening towards a floor value of $139\,h_{50}^{-1/3}$ keV cm^2 corresponding to our value of H_0, to $124\,h_{70}^{-1/3}$ keV cm^2. However, it appears from our data that the behaviour is rather that of a slope in $S(T)$ that is significantly shallower than the self-similar relation $S \propto T$ throughout. Using unweighted orthogonal regression (Isobe et al. 1990), we obtain a relation $S(0.1R_{200}) \propto T^{0.65\pm0.05}$, which is marked in Fig. 4. The Lloyd-Davies et al. floor value lies at the bottom of this trend, but it is not clear whether it sets a lower limit to the entropy in galaxy groups, since no groups with $T \lesssim 0.6$ keV have been bright enough for detailed study to date. The two galaxies in our sample do clearly have entropies that lie below the floor level; however, much or all of the hot gas in these systems may have its origin in stellar mass loss, rather than retained primordial material (O'Sullivan, Forbes & Ponman 2001), so it may well be fortuitous that they fall close to the trend set by the groups and clusters.

Grouping the points into temperature bins (Fig. 5) makes the unbroken nature of the trend very clear. An unweighted orthogonal fit to these grouped points gives a logarithmic slope of 0.57 ± 0.04, slightly flatter than that derived from Fig. 4. Note that these results suggest the presence of excess entropy of $\sim$100 keV cm^2 in *all* temperature bands, relative to the hottest systems. Fig. 5 also compares the effect on the relation of calculating R_{200} from a measurement of the mass profile, compared with assuming a scaling $R_{200} \propto T^{1/2}$, as was done (employing the formula derived from simulations by Navarro et al. 1995) by Ponman et al. (1999) and Lloyd-Davies et al. (2000). As discussed in Paper I, the Navarro et al. formula agrees reasonably well with our measurements in rich clusters, but in cool systems the upward bias in temperature, relative to simulations such as those of Navarro et al. (1995), which include only gravitational physics, causes the $R_{200} \propto T^{1/2}$ scaling to overestimate R_{200}, leading in turn to an upward bias in the entropy (since S rises with radius). This may have contributed, in previous studies, to the appearance of flattening in the $S(T)$ relation towards low T.

Whilst measurements close to the cluster centre provide the most sensitive probe of excess entropy, detection of additional entropy at large radii is especially interesting, since many preheating models predict that the rise in entropy is essentially restricted to those central regions where shock-generated entropy is less than the floor value set by preheating. Finoguenov et al. (2002) were the first to find evidence for excess entropy at a much larger radius, R_{500},

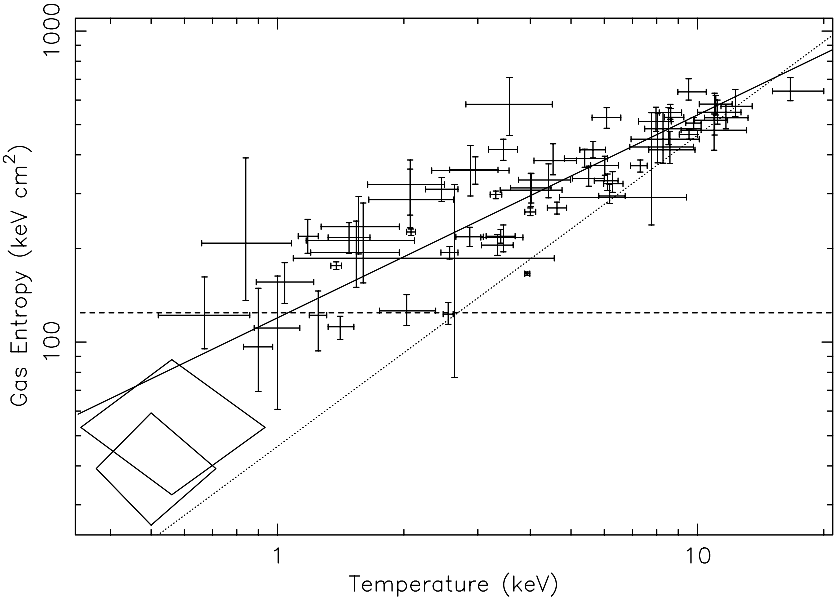

Figure 4. Gas entropy at $0.1R_{200}$ as a function of system temperature. The diamonds represent the two galaxies. The solid line is the best fit to the barred points. The dotted line has a self-similar slope of 1 and is normalized to the mean of the hottest eight clusters. The dashed line is the entropy floor of 124 $h_{70}^{-1/3}$ keV cm^2 from Lloyd-Davies et al. (2000).

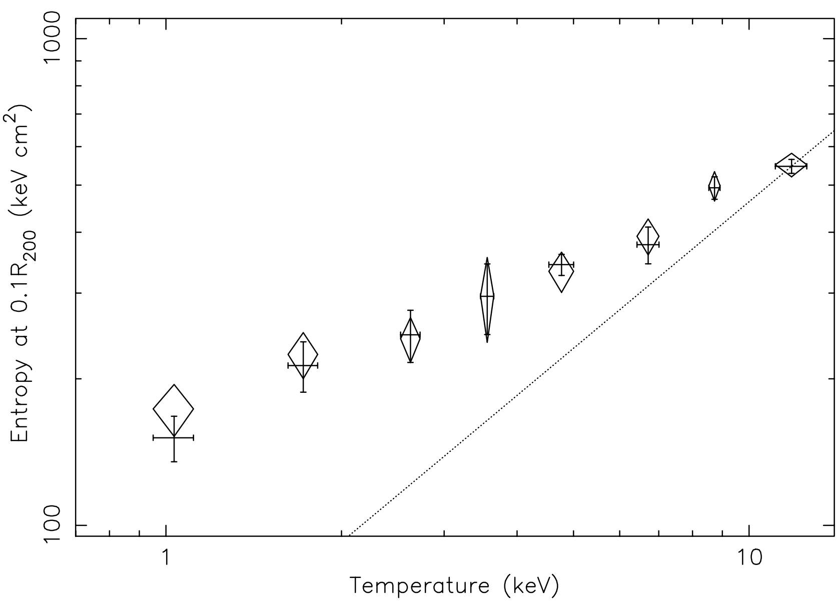

Figure 5. Gas entropy at $0.1R_{200}$ as a function of system temperature, excluding the two galaxies and grouped to a minimum of 8 points per bin. Barred crosses are based our measured values of R_{200}, whilst diamonds result from calculation of R_{200} from mean system temperature using the $T^{1/2}$ scaling of Navarro et al. (1995). The dotted line shows the self-similar slope of 1, normalized to the 8 hottest clusters.

corresponding (Paper II) to $\sim\frac{2}{3}R_{200}$. They argued that the high excess entropy observed at large radii in groups and poor clusters indicates that their IGM is dominated throughout by the effects of preheating, with shocks playing little or no role. We aim, in this paper, to check this result with our larger sample.

Our data, shown in Fig. 6, confirm the existence of substantial excess entropy at R_{500}, above a self-similar extrapolation from the values seen in rich clusters (dotted line). The trend is more clearly seen in temperature-grouped data shown in the right-hand panel, and the logarithmic slope of $S(T)$ is similar to that seen at $0.1R_{200}$. The departure from self-similar entropy values is apparent not only in the coolest systems, but also in quite rich clusters. In fact, the largest absolute values of excess entropy ($\sim$1000 keV cm^2) are seen in clusters with $T \sim 3$–4 keV.

For direct comparison with Finoguenov et al. (2002), we show in Fig. 7 the entropy at R_{500} scaled by $M_{500}^{-2/3}$, and grouped into mass bins to suppress fluctuations. For a set of self-similar systems, virialising at the same epoch (and hence having the same mean density), this scaling should renormalize the entropy to a constant value, independent of system temperature (since $S \propto T \propto M^{2/3}$). Clearly real clusters do not follow this self-similar law. Whilst our plot is broadly consistent in shape with fig. 3 of Finoguenov et al. (2002), our larger sample again reveals important additional features. Finoguenov et al. (2002) concluded that excess entropy was

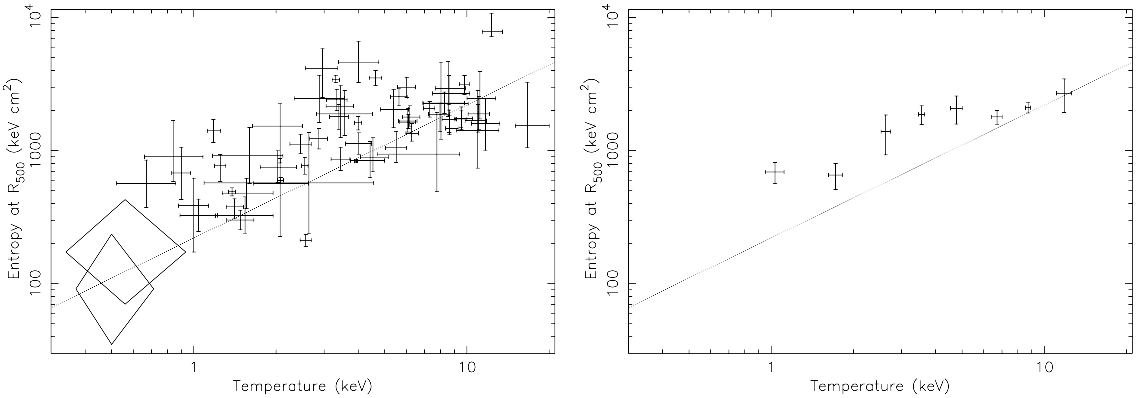

Figure 6. Entropy at R_{500} as a function of system temperature for each of the 66 systems, with the galaxies marked as diamonds (left panel) and grouped to a minimum of 8 points per bin, excluding the galaxies (right panel). The dotted line shows the self-similar slope of 1, normalized to the eight hottest clusters.

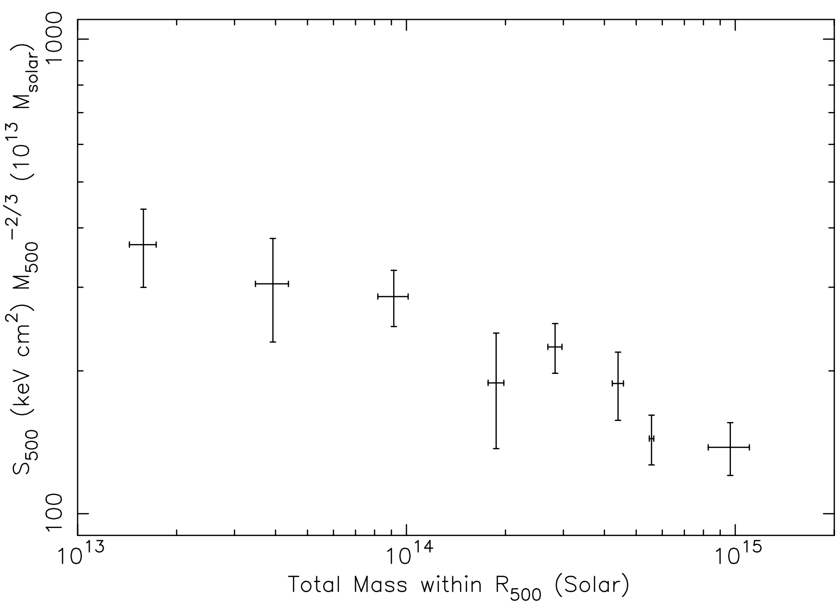

Figure 7. Gas entropy at R_{500}, normalized by $M_{500}^{2/3}$, as a function of the total mass within R_{500} (excluding the two galaxies) and grouped to a minimum of 8 points per bin.

only present in systems with $M_{500} \lesssim 10^{14}\, h_{50}^{-1}$ M$_\odot$ (7×10^{13} M$_\odot$ for our choice of H_0), whereas it is clear from our data that a trend in scaled entropy is present across the full mass range of clusters and groups.

Finoguenov et al. (2002) also examined the entropy at a fixed value of enclosed gravitating mass ($3 \times 10^{13}\, h_{50}^{-1}$ M$_\odot$ over their sample of systems. The infall velocity of gas into an accretion shock should be similar to the free fall velocity at the shock radius, which depends upon the enclosed mass and mean density of the Universe at the epoch in question. In clusters, an enclosed mass of 3×10^{13} h_{50}^{-1} M$_\odot$ lies deep within the system, whilst in small groups it can lie close to R_{200}. Since cluster cores are generally assembled at higher redshifts than the outskirts of groups, one expects the gas density in the shell under consideration to be higher, and the entropy generated by the thermalized kinetic energy is therefore lower, by a factor $(1 + z_{\rm f})$, where $z_{\rm f}$ is the redshift at which the shell was accreted. In practice, Finoguenov et al. (2002) found the entropy of this shell to be bimodal across their sample, with a typical value of ∼300 keV cm^2 for systems with $T \lesssim 3$ keV, and with considerably lower values (scattered over the range 100–300 keV cm^2) in hotter systems. Such a distribution cannot be accounted for on the basis of a $1 + z_{\rm f}$ scaling, and Finoguenov et al. suggested instead that the entropy in cool systems is set by preheating, taking place at $z \sim 3$, after many cluster cores had already collapsed.

The corresponding plot for our sample, which is almost double the size of that of Finoguenov et al., is shown in Fig. 8. For direct comparison, we have derived entropies at an enclosed mass of $2.14 \times 10^{13}\, h_{70}^{-1}$ M$_\odot$, allowing for our different choice of Hubble constant. Note that in some of the most massive systems, the radius enclosing $2.14 \times 10^{13}\, h_{70}^{-1}$ M$_\odot$ lies (just) within the cooling region, and hence our derived entropy value is effectively extrapolated, using the model for the non-cooling component (see Section 3). This affects six of the clusters that contribute to the highest temperature bin in the right-hand panel of Fig. 8, and a handful of cooler clusters. Our results look significantly different from those of Finoguenov et al. (2002). The entropy appears to be non-monotonic, with a minimum value in systems with $T \sim 3$–4 keV. From a purely phenomenological perspective, this non-monotonic behaviour can be understood in terms of mass profiles that take the NFW form (Navarro, Frenk & White 1997)

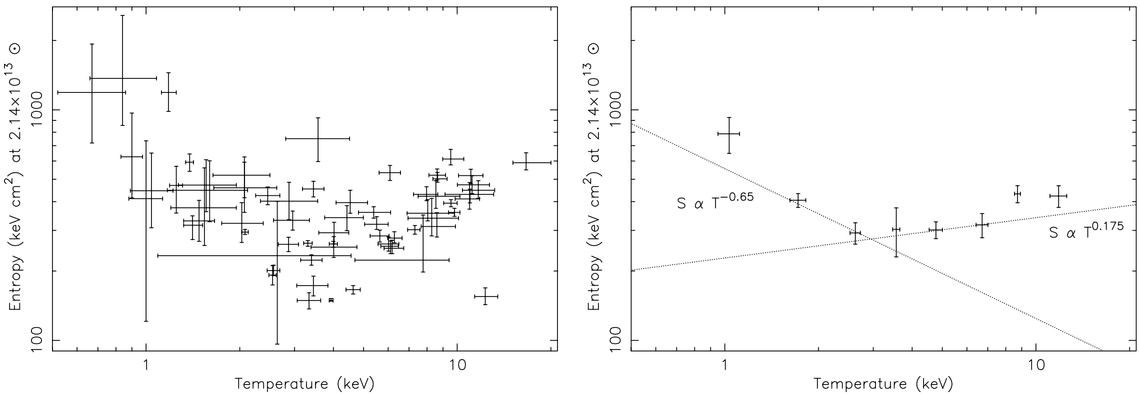

Figure 8. Left: entropy at the radius enclosing a mass of $3 \times 10^{13}\ h_{50}^{-1}\ \mathrm{M}_{\odot}$ as a function of system temperature (excluding the two galaxies). Right: the same data grouped into bins containing eight points or more, with simple limiting trends, discussed in the text, marked for comparison.

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}, \tag{3}$$

combined with entropy profiles that rise as $S \propto r^{1.1}$, outside some flatter central core. In groups, the mass shell under consideration here lies well outside r_s, where enclosed mass grows roughly linearly with radius,

$$M(< r) \sim CrT_{200}^{3/2}, \tag{4}$$

so that the radius at which an enclosed mass of $2.14 \times 10^{13}\ h_{70}^{-1}\ \mathrm{M}_{\odot}$ is achieved scales as

$$r_* \propto T_{200}^{-3/2}. \tag{5}$$

Since the entropy at this radius scales as

$$S(r_*) \propto T_{200} r_*^{1.1}, \tag{6}$$

we expect

$$S(r_*) \propto T_{200}^{-0.65}, \tag{7}$$

which gives a reasonable match to the slope at $T < 3$ keV, as shown in the right-hand panel of Fig. 8.

In more massive systems ($M_{200} > 2 \times 10^{14}\ h_{70}^{-1}\ \mathrm{M}_{\odot}$, $T > 3$ keV), the mass shell we are studying moves inside the scale radius r_s, so that the enclosed mass grows as r^2. An analysis similar to that above then results in

$$S(r_*) \propto T_{200}^{0.175}, \tag{8}$$

provided that $S(r) \propto r^{1.1}$ at these small radii. However, we saw in Fig. 1 that, for all but the coolest systems, $S(r)$ flattens within the cluster core, in which case the positive slope of the $S(r_*)$–T relation will be steeper than 0.175, as is observed.

The above arguments seem able to explain the general form of the relation in Fig. 8, using just the shape of the NFW profile, coupled with entropy profiles similar to those seen in simulations incorporating only gravity and shock heating. We therefore conclude that there may be no need to invoke modification of the entropy profiles by preheating to explain this particular result, despite the initially surprising, non-monotonic trend.

5 DISCUSSION

A substantial amount of theoretical and computational effort has been directed towards the problem of similarity-breaking in groups and clusters, especially over the past four years. We now compare the various models with the results above and with additional information from this paper's companion papers (Papers I and II) to see how they fare.

5.1 Cooling models

A number of authors (Bryan 2000; Pearce et al. 2000; Muanwong et al. 2001; Wu & Xue 2002b; Davé et al. 2002) have suggested that it may be unnecessary to invoke additional heating to explain the entropy floor, since cooling will remove low-entropy gas from clusters. The counterintuitive fact that cooling can have similar effects to heating in this regard was first noted by Knight & Ponman (1997), who found, on the basis of 1D hydrodynamical simulations of cluster growth, that cooling acted to flatten the gas density profiles, especially in low-mass systems, and to steepen the L–T relation, but not sufficiently to match observations. More sophisticated 3D simulations of cluster evolution by Muanwong et al. (2001) and Davé et al. (2002) have shown that larger effects can be produced, depending upon the spatial resolution of the simulations. Davé et al. showed that their simulations converged in this respect, although their cooling function did not incorporate emission from metal lines, which becomes very significant at $T < 2$ keV.

Cooling achieves its effect of breaking the similarity between low- and high-mass clusters, due to the fact that at a given gas density, the cooling time is shorter at lower temperatures. Hence a larger fraction of the hot baryons cool in groups, compared with richer clusters (Bryan 2000). Davé et al. (2002) showed that this is able to reproduce the cluster–group L–T relation quite well, except that the predicted steepening in the relation falls at a slightly lower temperature than that observed. They also compared the predicted gas entropies at $0.1R_{200}$ with the results of Ponman et al. (1999) at $T < 4$ keV, and found reasonable consistency. However, agreement with the results from the present study (Figs 4 and 5), which is superior to that of Ponman et al. (1999) in terms of sample size and allowance for non-isothermality, is much less good. Davé et al. found that $S(0.1R_{200})$ is raised in low-temperature systems, but converges with the self-similar trend through hot clusters for systems with $T > 3$ keV. In contrast, our results show a relation that is flatter than the self-similar line across the full temperature range. Bryan (2000) and Wu & Xue (2002b) produced results in better agreement with our observations, but their analytical model is based on an assumed variation in star formation efficiency with system mass that is much stronger than that which we derive from the subsample of our systems for which we have optical luminosities (Paper II).

However, the most fundamental problem faced by cooling-only models, as many of their proponents have acknowledged, is that cosmological simulations without some form of effective 'feedback' of energy into the baryonic component as stars form, have a serious 'overcooling' problem, which has been recognized for many years. At high redshift, the Universe is dense, and a large fraction of the baryons cool and form stars within small collapsed haloes. For example, Davé et al. (2002) found that in the largest systems in their simulation (with $T \sim 4$ keV) almost half the baryons have cooled out of the hot phase, whilst in small groups over 80 per cent of the gas has cooled. Unless this cooled gas does not form stars, the very high star-formation efficiencies implied are far above those observed in clusters (cf. the discussion in Paper II) or inferred globally from the K-band luminosity function of galaxies (Balogh et al. 2001). Furthermore, recent X-ray spectral observations from *XMM-Newton* and *Chandra* have made it clear that our understanding of cooling gas in the local Universe, on scales ranging from clusters to elliptical galaxies, is deficient (see, for example, Fabian et al. 2001). It seems likely that cooling rates have been seriously overestimated, for reasons which are still under very active debate, but may be related to the effects of feedback from AGNs, which probably exist at the centres of all cooling flows.

5.2 Preheating models

Since less energy is required to raise the entropy of gas by a given amount when its density is lower, it is energetically favourable to 'preheat' gas before it is concentrated into a cluster or group potential. A comparison of the excess entropy required, with that potentially available from supernova explosions associated with star formation (see, for example, Valageas & Silk 1999) shows that a high efficiency of heating of the intergalactic gas is required even in the most favourable circumstances – i.e. only a modest fraction of the supernova energy must be radiated away. However, such high efficiencies have been inferred on the basis of observations and modelling in the case of starburst winds (Strickland & Stevens 2000), and so are not necessarily unreasonable during the epoch of galaxy formation.

A large reservoir of energy at high redshift is potentially available from the formation of massive black holes in galaxies (Valageas & Silk 1999; Wu, Fabian & Nulsen 2000), although it is at present unclear how much of this energy can be coupled into heating of the IGM. Radiative heating from AGNs cannot achieve the required high entropies, but quasar outflows may do so, although the physics and demographics involved are still subject to considerable uncertainties (Nath & Roychowdhury 2002).

Finally, cosmological simulations suggest that a large fraction of the baryon content of the Universe is currently in the form of what has been dubbed the 'warm-hot intergalactic medium', with an entropy of the order of 300 keV cm^2 (Cen & Ostriker 1999; Davé et al. 2001). Davé et al. (2001) showed that this high-entropy gas is primarily heated, not by star-formation, but by the effects of shocks generated during the collapse of gas into filaments. It seems unlikely, however, that this mechanism can account for the excess entropy seen in the inner regions of groups and clusters, since the entropy of the IGM generated in this way declines steeply with redshift (Valageas, Schaeffer & Silk 2002), such that it should be well below the observed floor value, at the epoch when the gas in cluster cores was accreted. This is confirmed by the recent simulations of Borgani et al. (2002), for example, which found baryon distributions in clusters that are essentially self-similar, in the absence of non-gravitational heating processes.

Pioneering efforts to explore the effects of preheating through simulations or analytical treatments (Metzler & Evrard 1994; Navarro et al. 1995; Cavaliere et al. 1997) have been largely superseded by more recent work, and we concentrate here on the latter. Considerable insight can be gained by analytical models in which preheated gas is accreted into clusters. The model of Babul, Balogh and coworkers has reached its most advanced stage of development in Babul et al. (2002). This model assumes Bondi accretion (Bondi 1952) of preheated gas into a potential well represented by a (fixed) NFW profile. This accretion is taken to be isentropic in low-mass systems, with the introduction of a shock-heated regime, motivated by the entropy profiles seen in numerical simulations, for systems above some critical mass. The level of preheating is tuned to achieve a good match to the L–T relation across a wide temperature range (0.3–15 keV). Unfortunately, the entropy level required to achieve this (330 keV cm^2), is well above that actually observed in the inner regions of groups. Moreover, the model predicts large isentropic cores in cool systems. The IGM in groups with $M_{200} < 8 \times 10^{13}$ M$_\odot$ (corresponding to $\sim$2 keV, from our M–T relation in Paper I) is *entirely* isentropic in these models, in strong conflict with our results (Fig. 1).

Tozzi & Norman (2001) and Dos Santos & Doré (2002) have attempted to evaluate the effects of shock heating on the preheated accreting gas. Dos Santos & Doré concentrated on the scaling properties of the gas entropy immediately inside the accretion shock. They found that this is expected to scale with mean system temperature according to $(1 + T/T_0)$, where T_0 is an adjustable parameter related to the initial adiabat on which the preheated gas lies. By choosing the preheating entropy to be 120 keV cm^2, corresponding to $T_0 = 2$ keV, they obtain a good match to the $S(0.1R_{200})$–T plot of Lloyd-Davies et al. (2000), though their curve is rather too concave in comparison with the trend seen in Fig. 5. In order to calculate the expected L–T relation from their model, Dos Santos & Doré made two key additional assumptions: the IGM was assumed to be isothermal, and entropy profiles, $S(r/R_{200})$, were assumed to have the same shape in all systems. Their resulting L–T model steepens rather too gently to match the group data (which show a very steep slope – see, for example, $L \propto T^{4.3}$ from Helsdon & Ponman 2000) entirely satisfactorily. The isothermal assumption is in conflict with our data (Fig. 3) and with the results of cosmological simulations, which generally show a decline in temperature by about a factor three from the inner regions to the virial radius (Frenk et al. 1999). A picture involving self-similar entropy profiles, with a scale factor given by $(1 + T/T_0)$, is in remarkably good agreement with our results, as shown in Fig 2. However, it should be noted that the Dos Santos & Doré (2002) model predicts only the way in which entropy should scale just inside the shock – the self-similarity in the radial distribution of entropy inside the shock is an *assumption*, rather than an output of their model.

A more comprehensive treatment was provided by Tozzi & Norman (2001), who calculated entropy profiles based on solving the shock jump conditions over typical accretion histories, for systems spanning a range of final mass. They found that shock heating generates entropy profiles with a characteristic logarithmic slope $S \propto r^{1.1}$, outside a central isentropic core, which, for a given preheating level, occupies a larger fraction of R_{200} in lower-mass systems. The slope of 1.1 agrees well with our results (Fig. 1), and with numerical simulations (see, for example, Borgani et al. 2001). However, as can be seen from Fig. 1, we do not see the larger isentropic cores in $S(r/R_{200})$, which appear to be a feature of all preheating models.

Nath & Roychowdhury (2002) explored the energetics and evolutionary history of preheating the IGM through outflows from radio-loud, and broad-absorption-line quasars. Their conclusion is that AGNs could provide the energy input required to account for the entropy floor. However, in the context of our results, their most interesting result is that the specific energy injected by AGNs into the gas is expected to be higher in low-mass systems, for two reasons: the incidence of powerful AGNs is expected to be higher in smaller clusters, and the fraction of their power expended in *PdV* work is larger in smaller systems. This appears to be contrary to our entropy-scaling results, shown in Figs 5 and 6, which show that at small radii the excess entropy is similar ($\sim$100 keV cm^2) across a wide range of system masses, whilst at larger radii it is actually highest in moderately rich ($T \sim$ 3–4 keV) clusters.

5.3 Star formation models

A natural development of cooling models, which can help to address the overcooling problem, is the incorporation of feedback due to star formation. In numerical studies, the successful implementation of such a scheme is extremely challenging, and has been the Holy Grail of those engaged in simulations of galaxy formation for some years. Voit & Bryan (2001) introduced an interesting perspective on this issue, in the context of similarity breaking in clusters, by noting that it makes very little difference quite how effective feedback is in heating the IGM, since any gas within virialized systems that has low entropy will have a short cooling time, and so will be removed from its location near the centre of a dark halo either by dropping out of the hot phase, or by being heated by star formation in its vicinity, such that it escapes to large radii. In particular, they noted that the entropy of gas with a cooling time equal to the age of the Universe is $\sim$100 keV cm^2, in striking agreement with the entropy floor reported in groups and clusters. Since the cooling time scales as $T^{1/2}/n$ in systems with $T > 2$ keV, where bremsstrahlung dominates cooling, whilst $S = T/n^{2/3}$, it follows that a given cooling time is achieved in gas with an entropy that scales as

$$S_{\rm cool} \propto (t_{\rm cool} T)^{2/3}, \tag{9}$$

so that the entropy floor generated in this way is expected to be higher in hotter systems (Voit & Bryan 2001). This feature may help to explain the flat trend in entropy with temperature apparent in Fig. 5 – note the similarity between the dependence of $S_{\rm cool}$ on T and the slope seen in Figs 4 , 5 and 6.

This approach was developed further by Voit et al. (2002), who constructed models in which the entropy distribution is either truncated below some critical entropy (corresponding to gas cooling out, or being ejected as a result of vigorous heating), or shifted by the addition of an entropy boost throughout (corresponding to preheating of the entire IGM). The two different prescriptions for entropy modification produce only subtle differences in observable properties: shifted entropy models have rather flatter gas density profiles at large radii in poor groups, and also slightly higher gas temperatures. These differences are not distinguishable with data of the quality used in the present study, and may well be too challenging even for future studies with *XMM-Newton* and *Chandra*. One impressive feature of these models is that they contain essentially no adjustable parameters, since the entropy threshold is set by equating the cooling time of gas to a Hubble time of 15 Gyr. However, the predicted *L–T* relation fails to steepen sufficiently at low temperatures to pass through the bulk of the galaxy group points, and the *M–T* relation, whilst steeper than the self-similar relation ($M \propto T^{1.5}$), is less steep than that derived from the present sample in Paper I.

One of the most recent numerical studies of cluster structure to incorporate the effects of both cooling and feedback is the work of Borgani et al. (2001, 2002). These simulations explore the effects of setting an entropy floor through instantaneous preheating at high redshift, and also through heating scaled to the expected supernova energy input in overdense regions throughout the evolutionary history of the Universe. The effects of radiative cooling are also included in one of the supernova-heating runs. The main conclusion from this work is that $\gtrsim$1 keV per particle of energy input is required to give a reasonable match to the observed steepening of the *L–T* relation. The authors point out that such a large energy boost appears to exceed what is expected from supernova input alone, even if a high heating efficiency of the IGM is assumed.

Borgani et al. found that a somewhat larger suppression of L_X in groups is achieved by injecting the same amount of energy progressively, compared with global preheating of the IGM. Entropy profiles generally agree well with the Tozzi & Norman (2001) slope of 1.1, but are flattened in low-mass systems by the effects of energy injection, as are gas density profiles. The gas temperature profile becomes more centrally peaked in low-mass haloes subject to additional heating. The *M–T* relation is found to be little affected by heating, either in slope or normalization. However, cooling is found to decrease the normalization and steepen the slope of the relation, bringing it into better agreement with observations. In comparison with these results, we certainly observe flatter gas density profiles in cool systems (Paper I), and Fig. 2 provides some tentative evidence that the entropy slope may be rather shallower in lower-temperature ($T < 3$ keV) systems. In the case of the *M–T* relation, Lloyd-Davies, Bower & Ponman (2002) and Voit et al. (2002) showed that systematic variations in the concentration parameter of dark matter haloes with mass may play a key role in steepening its slope, as discussed in Paper I.

6 CONCLUSIONS AND SUGGESTIONS

6.1 Existing models

Drawing the above results together, it seems that cooling-only models cannot provide a viable explanation for the similarity-breaking observed in clusters, unless one is willing to admit the presence of very large quantities of baryonic dark matter, which would have to dominate the baryon budget in groups.

Preheating models appear to have the generic property of generating large isentropic cores in low-mass systems, in conflict with our observations. This seems to be an inescapable feature of simple preheating models in which the IGM is raised uniformly and 'instantaneously' to a high adiabat, since such gas can only be shocked when falling into potential wells deep enough for its motion to be supersonic. More complex preheating models may enable this problem to be circumvented, as we discuss below.

Models involving a mixture of cooling and star formation (or possibly AGN heating) appear more natural and promising. However, the following features of our data appear to conflict with *all* models proposed to date.

(i) The very large entropy excesses seen at large radii (Figs 6 and 7) are a surprise. Models tend to show entropy enhancement in the inner regions of low-mass systems, with a normal shock-generated entropy profile re-establishing itself at larger radii.

(ii) Closely related to (i) is the fact that the entropy profiles appear to be approximately self-similar apart from a normalization constant, and, in particular, that larger isentropic cores are *not* seen in galaxy groups. In fact, Fig. 1 shows that the lowest-temperature systems actually have entropy profiles that appear to drop all the way into the centre, unlike hotter systems. The fact that the scaling suggested by Dos Santos & Doré (2002) brings our profiles into good agreement (Fig. 2) is a puzzle, given that this scaling is really not justified by their model as a scale factor for entropy *profiles*.

(iii) The temperature profiles shown in Fig. 3 are also not quite what is expected from the models. Any mechanism that gives an entropy boost should produce the strongest results in low-mass systems. Since a rise in entropy has to be coupled with the maintenance of hydrostatic equilibrium, the natural consequence is a rise in central temperature, coupled with a decrease in density. The density drop is certainly observed, and there are indications that the temperature has been raised in cool systems outside the core, but the temperature profiles in groups seem to lack the expected central cusp. This is related to the lack of an entropy core in groups referred to in point (ii), above.

(iv) The behaviour of the gas core radius, discussed in Paper II, is similarly unexpected. As a fraction of R_{200}, the gas core radius is approximately constant at $\sim$10 per cent over most of our temperature range, but falls dramatically, by an order of magnitude, in groups. The only study to predict this sort of behaviour is that of Wu & Xue (2002a), who showed that fitting a convex profile that steepens progressively, with a beta model, can lead to smaller fitted core radii as the outer radius of detection shrinks. In Paper I we reported tests with fits to real data for two clusters, truncated at different radii, which suggested that this effect is not dominating our fits. However, X-ray surface brightness profiles extending to larger fractions of R_{200} for groups are required to settle this issue definitively.

6.2 New possibilities

What might these disagreements with the models be pointing towards? Finoguenov et al. (2002) argued that the large excess entropy at R_{500} in groups indicates that the entropy profiles in cool systems are dominated *throughout* by the effects of preheating. Two features of our results make us uneasy about this conclusion. First, these excesses are now seen (Fig. 7) to extend up to moderately-rich clusters, and to involve entropies several times those expected in the IGM at the present epoch (Valageas & Silk 1999). Secondly, the slope of all our entropy profiles (Fig. 1) seem to scatter about the value predicted from shock heating. This is an uncomfortable coincidence if shock heating plays no role in establishing them. It is certainly possible to devise preheating scenarios which could reproduce any of our profiles, by varying the history of energy injection, and the density gradient of the gas into which this energy was injected, in the vicinity of systems of a given mass. However, such a solution would require a large amount of fine tuning.

If, on the contrary, we wish to retain shock heating as the basic mechanism responsible for generating the rising entropy profiles seen outside the core in both clusters and groups, how can this be achieved? The post-shock temperature is essentially determined by the infall velocity of gas into a halo, which could be reduced by pressure forces, but not increased above the free-fall value. Hence, the only way to raise the whole entropy profile in low-mass systems, in the way implicit in Fig. 1, seems to be to reduce the density of the pre-shock gas accreting into lower-mass systems, relative to that falling into rich clusters. In simple spherical collapse models, the matter turning around and accreting into haloes at a given epoch is expected to have a given overdensity. However, in reality, cosmological simulations show us that accretion is far from spherical, and that much of it takes place along filaments.

This change in topology does not in itself change the relationship between the mass of virialized systems and the density of the gas accreting into them, since structure formation is (almost) self-similar. Bigger systems have bigger filaments, and the mean density of the accretion flow at a given epoch is still set by the overdensity at turnaround, which is independent of system mass. However, this situation changes if preheating of gas in the filaments introduces an additional scale into the problem. In general, the scale height of gas in filaments will be set by hydrostatic equilibrium of the gas in the local gravitational potential of the dark matter (see, for example, Valageas et al. 2002). The temperature to which gas is shock heated during the collapse of filaments will scale with their mass, and hence the effect of any thermal input into the IGM from galaxy formation or the growth of supermassive black holes will be more prominent in the smaller filaments associated with lower-mass systems. Preheating will act to increase the scale height, and hence to reduce the density of gas in filaments. Even in filamentary structures that are still collapsing, preheating of the gas will increase its pressure and retard its collapse relative to that of the dark matter.

The calculations of Tozzi & Norman (2001) showed (albeit in the spherically-symmetric case) that, even in the preheated case, the accretion shock rapidly becomes strong once it is established, so that the post-shock entropy of gas accreting into a cluster will scale as $T_{200}/n_1^{2/3}$, where n_1 is the pre-shock density of the gas, and T_{200} is the virial temperature of the cluster. Hence, if preheating reduces n_1 in lower-mass systems, relative to rich clusters, then the entropy will scale sub-linearly with T_{200}, which is what we observe.

It is worth noting some features of this model. First, the effect we invoke is intimately linked to the fact that the accreting gas is largely confined to filaments, and hence will not be seen in analytical and semi-analytical models such as those of Tozzi & Norman (2001) and Babul et al. (2002), which assume spherically-symmetric accretion. In the spherical case, the gas has nowhere to expand to in response to the initial preheating. Consequently, any entropy rise due to preheating serves to raise the temperature of the gas rather than to lower its density. In the lowest-mass systems, this temperature rise can delay shock formation, and hence result in an isentropic core, but in high-mass systems (and at large radii in low-mass ones) it has essentially no effect, since the post-shock temperature is just $T = \frac{1}{3}\mu m_{\rm p} v_i^2$ (Tozzi & Norman 2001), where v_i is the velocity at which gas, with mean particle mass $\mu m_{\rm p}$, flows into the shock. In contrast, if preheating serves primarily to reduce the density of the pre-shock gas, then this will lead to a rise in post-shock entropy whatever the shock strength, since (for a given shock Mach number) the post-shock density simply scales with n_1, so that the post-shock entropy $S_2 \propto n_1^{-2/3}$.

Secondly, this mechanism is a very efficient way of raising the entropy of intracluster gas for two reasons. As has been noted previously (Ponman et al. 1999), a given injection of energy produces a larger rise in entropy when the gas density is lower. Hence it is more effective to deposit energy into low-overdensity structures such as filaments than into fully-collapsed systems like clusters. Moreover, if this injection places the gas on to a higher adiabat by reducing its density, then the effects of the accretion shock serve to raise it further. For example, Dos Santos & Doré (2002) showed that the ratio between the post- and pre-shock adiabats is well approximated by

$$S_2/S_1 = A\left(1 + \frac{8\mu m_{\rm p} v_i^2}{51 k T_1}\right), \qquad (10)$$

where A is a constant of order unity. So, a rise in S_1 by some factor, due to a density change (and hence with no change in T_1) driven by preheating, will boost S_2 by the same factor. Hence the shock has a multiplier effect, and if S_2/S_1 is large, a modest rise (in absolute terms) in S_1, may result in a much larger rise in S_2. Since the entropy will typically jump by an order of magnitude in the accretion shock, as its temperature is raised from $\sim 10^6$ K to 10^7–10^8 K, entropy excesses of the magnitude reported here within clusters (i.e. 100–1000 keV cm^2), might be generated from a rise in entropy of only $\sim$10–100 keV cm^2 within the filaments which feed them.

Thirdly, if preheating acts primarily to reduce the density of the pre-shock gas, rather than to increase its temperature, then the Mach number of accretion shocks is not much reduced, compared with the unheated case. The post-shock entropy profiles are therefore almost entirely due to the evolution of the accretion shock, and $S(r) \propto r^{1.1}$ profiles are expected, outside a small unshocked central core, in good agreement with observations.

Whilst the viability of this model clearly cannot be investigated by spherically-symmetric analytical treatments, one might hope to find evidence to test it from three-dimensional simulations of cluster formation. Rather few studies have been published incorporating the effects of feedback into the IGM, together with a study of its effects on the entropy profiles of clusters. Results from the work of Borgani et al. (2001, 2002) and Muanwong et al. (2002) are not very encouraging. In both these studies, the effects of heating of the IGM serve to flatten the entropy profiles in clusters, with the effects being more pronounced in lower-mass systems. This accords better with observations than do most one-dimensional analytical models, insofar as distinct isentropic cores are *not* generally present. However, the progressive flattening of $S(r)$ towards lower-mass systems does not agree with our observed properties (Fig. 1).

It is premature to conclude at this stage that the preheated-filament model can be rejected. Feedback is very poorly understood, and its incorporation into numerical codes is notoriously difficult. In the study of Muanwong et al. (2002), feedback was included by simply raising the temperature of all gas particles by 1.5 keV at a redshift of four. Borgani et al. (2001) adopted the approach of imposing an entropy floor on the gas in overdense ($\delta > 5$) regions at a variety of redshifts from 1 to 5, whilst Borgani et al. (2002) attempted to model the effects of energy injection from galaxies in a more realistic way by using a semi-analytic scheme to predict the supernova rate, and sharing the resulting energy amongst gas particles in regions with $\delta > 50$. Unfortunately, the interplay of feedback and cooling is extremely complex, and hard to model. Results tend to depend strongly on spatial resolution, and current simulations (including those of Borgani et al. and Muanwong et al.) generally fail to reproduce the observed low cooled fraction of baryons. A wider exploration of the effects of different feedback schemes, and a study of the density of gas flowing into accretion shocks in simulations, should clarify whether the mechanism proposed here is actually the dominant effect in modifying the entropy of intracluster gas. At the same time, higher-quality observations from *XMM-Newton* and *Chandra* will provide more robust determinations of observed entropy profiles in a wide range of virialized systems. Initial results from *XMM-Newton* for a small number of groups (Mushotzky et al. 2003; Pratt & Arnaud 2003) confirm that no central isentropic core is present in these systems.

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