EXPLAINING THE ENTROPY EXCESS IN CLUSTERS AND GROUPS OF GALAXIES WITHOUT ADDITIONAL HEATING

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ABSTRACT

The X-ray luminosity and temperature of clusters and groups of galaxies do not scale in a self-similar manner. This has often been interpreted as a sign that the intracluster medium has been substantially heated by nongravitational sources. In this Letter, we propose a simple model that instead uses the properties of galaxy formation to explain the available observations. Drawing on available observations, we show that there is evidence that the efficiency of galaxy formation was higher in groups than in clusters. If confirmed, this would deplete the low-entropy gas in groups, increase their central entropy, and decrease their X-ray luminosity. A simple, empirical, hydrostatic model appears to match both the luminosity-temperature relation of clusters and the properties of their internal structure.

Subject headings: cosmology: theory — intergalactic medium

1. INTRODUCTION

Clusters and groups of galaxies are composed of galaxies, hot X-ray-emitting gas, and a gravitationally dominant dark halo. Although this basic picture is well understood, there remain a number of puzzles that prevent clusters from being fully used as standard candles. For example, simple scaling relations (and detailed simulations) predict that the bolometric X-ray luminosity should scale with the temperature of the gas according to $L_X \propto T^2$, while observations indicate that $L_X \propto T^{\beta}$ (Kaiser 1991; Evrard & Henry 1991; Navarro, Frenk, & White 1995; Bryan & Norman 1998). Early on, it was suggested that groups might have a lower baryon fraction because of more efficient star formation (e.g., David & Blumenthal 1992; Thomas & Couchman 1992; Bower 1997), but later thinking has focused on the idea of additional heating of the gas, often assumed to be from supernovae or active galactic nuclei (e.g., Kaiser 1991; Bower et al. 2000). This nongravitational heating would decrease the central density and, because the X-ray emissivity is proportional to the density squared, reduce the luminosity. Because of the lower pressures in smaller clusters and groups, this would preferentially affect them, steepening the $L_X-T$ relation (Cavaliere, Menci, & Tozzi 1997). This viewpoint was strengthened by the discovery of an apparent entropy “floor” in the centers of groups and clusters (Ponman, Cannon, & Navarro 1999). This is consistent with the idea of a source of heat that raises the entropy of the gas to a fixed, minimum level; smaller clusters have lower entropies and so are more affected than large clusters. This model has been developed in some detail in a number of papers (Balogh, Babul, & Patton 1999; Loewenstein 2000; Wu, Fabian, & Nulsen 1999; Cavaliere, Menci, & Tozzi 1999; Valageas & Silk 1999) and appears to be capable of explaining the observations naturally.

The amount of heating required is substantial. Although estimates vary, it seems likely that about 1 keV per particle is needed (Lloyd-Davies, Ponman, & Cannon 2000), an amount that may be challenging to explain from supernova heating alone (Kravtsov & Yepes 2000). Another difficulty is that observations of the Lyα forest indicate a much lower temperature for the majority of the intergalactic medium at $z \sim 2-3$ (Bryan & Machacek 2000; Schaye et al. 1999), a condition that may extend to even lower redshifts (Ricotti, Gnedin, & Shull 2000). Although hardly conclusive, these concerns may be pointing toward another explanation for the observations.

This Letter argues that cooling and the resultant galaxy formation are sufficient, by themselves, to explain all of these observations and that substantial heating is not required. We draw mostly on two simple ideas: (1) small clusters and groups have converted more of their baryonic gas into galaxies than have large clusters, and (2) the gas that goes to form the galaxies is preferentially lower in entropy, thus raising the mean entropy of the gas that remains. This means that not only do small clusters have a smaller gas fraction ($f_g$), but the gas that is there has a higher entropy—and lower density—than it would in simple self-similar scaling models. Because of the density-squared nature of the X-ray emission, this substantially diminishes the luminosity of groups and small clusters, resulting in a steeper $L_X-T$ relation, as observed. The effective entropy increase is most noticeable in the center of the cluster, which is just where the entropy floor is observed. In what follows, we explore a simple model in order to investigate if this hypothesis can match the observations quantitatively. We will also show that there is some empirical support for the first assumption.

2. THE MODEL

The model described here is built on the assumption that galaxy formation is not uniformly efficient in all environments. Since theoretical arguments can and have been made both ways, we attempt to address this point with observations drawn from the literature. We searched the literature and found three studies that computed stellar, gas, and total masses within the same radius (many more computed a subset of these three quantities, but we only used those that computed all of the quantities in order to ensure self-consistency). Mulchaey et al. (1996) used their own ROSAT and optical observations combined with other results from the literature to compile a list of 16 groups with masses computed out to $R_X$, the maximum radius at which X-ray emission could be observed. Hwang et al. (1999) used ASCA observations of five intermediate-mass systems and also computed masses out to $R_X$. Finally, Cirimele, Nesci, & Trèvese...
(1997) studied 12 Abell clusters with ROSAT and tabulated masses computed out to 1.5 Mpc (which is close to $R_v$ for their clusters). All studies used similar, although not identical, stellar mass–to–light ratios (corrected for morphological variations), and all used the same cosmological parameters.

In Figure 1, we plot the relative stellar and gas masses from these three studies. This shows that the hot gas component dominates over galaxies in the most massive clusters of galaxies. For smaller systems, the scatter increases significantly; however, there is a trend toward an increasing stellar contribution and a decreasing gas contribution for lower mass clusters and groups. To make this clearer, we divide the sample into four equal-sized groups, ordered by temperature, and plot the median for each group. To check the statistical strength of the trend, we divided the sample into two groups (those with temperatures below and above 2 keV) and separately computed the median galaxy mass ratios. Then, using median statistics (e.g., Gott et al. 2000), we find the probability to be 0.986 that the median of the high-temperature group is smaller than that of the low-temperature group. The gas mass ratio trend was even more significant.

The most straightforward explanation of the trend shown in Figure 1 is that the efficiency of galaxy formation varies from groups to clusters. This is the hypothesis that we will examine in this Letter, but there are certainly other explanations. For example, it is possible that the relative mix of gas and stars changes outside of the measured region (i.e., $R > R_v$), which is generally a smaller fraction of the virial radius for groups than for clusters. Moreover, it is difficult to be conclusive for a heterogeneous sample of this sort since the groups and clusters were examined by different authors using slightly different methods. However, all of the studies did use the same basic methodology and adopted similar parameters. Also, the trend itself does not depend on correctly determining the total mass since the $M_{\text{gas}}/M_{\text{tot}}$ ratio—which is independent of total mass—also decreases with temperature.

There are a number of other pieces of evidence that support this basic conclusion. For example, Arnaud & Evrard (1999) and Mohr, Mathieson, & Evrard (1999) find a trend of a decreasing hot gas fraction with a decreasing temperature for their samples. This pattern has sometimes been taken to imply that gas has been ejected from smaller clusters and groups, despite the large amount of energy required to do this. However, it seems equally possible that this gas is in the form of stars. This would also be consistent with a higher mass-to-light ratio for large clusters than for groups (Girardi et al. 2000; Adami et al. 1998; Hradecky et al. 2000; Ramella, Pisani, & Geller 1997), although see David, Jones, & Forman (1995). Weak lensing of groups should provide useful constraints; preliminary results indicate the mass-to-light ratios of groups are somewhat lower than those of clusters (Hoekstra, Franx, & Kuijken 2000). Finally, constraints from galaxy clustering indicate that the number of galaxies in a halo must grow more slowly than the mass of the halo (Scoccimarro et al. 2001), consistent with the trend presented here. Despite this circumstantial evidence, we cannot prove that the efficiency of galaxy formation depends on environment; all we can do is show that the available data are consistent with the trend shown in Figure 1. In the rest of this Letter, we will assume this to be true and examine the consequences that follow.

In Figure 1, we show the relation

$$f_{\text{star}} = 0.042(T/10\text{ keV})^{-0.35},$$

which we will take to be the stellar mass fraction in this Letter and which is the result of minimizing the absolute deviation of the mass ratio. The gas fraction is simply $f_{\text{gas}} = f_{\text{baryon}} - f_{\text{star}}$, where $f_{\text{baryon}} = 0.16$ is compatible with the cosmological model that we have chosen. Specifically, this is a flat model with $(\Omega_0, \Omega_k, h) = (0.35, 0.056, 0.65)$, where $\Omega_0$ is the ratio of the mass density to the critical density and $h$ is the Hubble constant in units of 100 km s$^{-1}$ Mpc$^{-1}$. The results are most sensitive to the value of the Hubble constant since the ratio of stellar to gas mass varies as $h^{-3/2}$; the other parameters play almost no role.

In order to build a concrete model for the structure of a group or cluster of galaxies, we assume that (1) the clusters are spherical and symmetric in hydrostatic equilibrium, (2) the hot gas and stellar fractions are as given above, and (3) the gas that is converted into stars comes from the lowest entropy gas in the cluster, and all other fluid elements lie on the same adiabat they would have without cooling or star formation. From experience gained with numerical simulations, we know that while clusters are not in exact hydrostatic equilibrium, this assumption is a reasonable approximation. The second assumption has some empirical basis, as previously discussed. We will return to a discussion of the last assumption.

To create a cluster of a given mass $M$, we assume that the dark matter density is described by (Navarro, Frenk, & White 1996)

$$\rho(x) = \frac{200}{3} \frac{c^2}{\ln(1 + c) - c(1 + c)/(1 + cx)} \frac{1}{x(1 + cx)},$$

where $\rho_0 = 3H^2/8\pi G$ is the critical density, $x = r/r_{200}$, and $c$ is a concentration parameter that depends weakly on mass in the range of interest. We take $c = 8.5(Mh/10^{15} M_\odot)^{-0.086}$. The radius $r_{200}$ is defined by $M = 800\rho_0\pi r_{200}^3/3$.

The gas distribution without galaxy formation is assumed to have the same distribution as equation (2). The temperature profile is determined by solving the equation of hydrostatic

$$\frac{\rho}{\rho_0} = \frac{800}{3} \frac{c^2}{\ln(1 + c) - c(1 + c)/(1 + cx)} \frac{1}{x(1 + cx)}.$$

FIG. 1.—Ratio of mass in hot gas (filled symbols) and in stellar systems (open symbols) to total gravitating mass as a function of temperature. The circles are from Cirimele et al. (1997), the squares from Hwang et al. (1999), and the diamonds from Mulchaey et al. (1996). The solid and dashed lines are median values of the binned distribution for the gas ratio and stellar ratio, respectively. The dot-dashed line is the model discussed in the text. All observations have been adjusted to $h = 0.65$. 

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equilibrium for a spherical profile: \( \frac{dP}{dr} = -\rho GM(r)/r^2 \). We assume that the gas does not contribute to the gravitational potential and therefore adopt a pressure-free external boundary condition (i.e., \( P = 0 \) at \( r = 1 \)). The result matches the density and temperature distribution in numerical simulations over the vast majority of the cluster (e.g., Frenk et al. 1999). It fails in the very center (where the numerical models are the least certain), but this represents a small fraction of the mass (<1%) that will end up being converted to galaxies anyway. An isothermal temperature profile produces results that are broadly similar; however, this density distribution does not describe the simulation results very well, particularly at a large radius (\( x > 0.3 \)) where much of the mass resides.

Once the no-cooling cluster has been constructed, we can then compute the structure of the cluster including galaxy formation. The equation of hydrostatic equilibrium sets the pressure distribution, but we need one more constraint to fix uniquely the density and temperature profiles. This comes from the entropy (\( S = \ln T \rho^{\alpha/\gamma} \)) distribution of the gas, which is a monotonically increasing function of radius. Since, by our earlier assumption, the gas that cools into galaxies comes from the lowest entropy part of the distribution, galaxy formation is equivalent to removing from the center an amount of gas equal to \( f_{\text{star}} M \). The remaining gas is then distributed over the whole cluster, under the assumption that it does not cool at all. The known entropy distribution of this gas combined with the equation of hydrostatic equilibrium are sufficient to specify the gas and temperature profiles uniquely. More precisely, we guess a central pressure and then compute the structure of the cluster including galaxy formation.

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The agreement is good, except at very low temperatures, where the observations fall below the theoretical curve. The surface brightness of these poor groups is very low, and so a significant fraction of their luminosity could be lost. Helsdon & Ponman (2000) estimate that for their lowest temperature cluster group (below 1 keV), the total flux is underestimated by about 40% relative to the higher temperature groups. Also, there is some evidence that the metallicity of small groups may be significantly less than that of larger groups (Davis, Mulchaey, & Mushotzky 1999). These two effects would reduce the predicted luminosity by a factor of 2–3.

There is another line of evidence that has been taken as strong evidence of preheating: Ponman et al. (1999) show that the central entropy (at \( r = 0.1r_{200} \)) in clusters and groups does not scale in a self-similar fashion. Their data are reproduced in...
Figure 4, along with the curve predicted from the model described in this Letter. The model matches the observed data. Also shown is the self-similar relation (with constant $f_{\text{gas}}$).

There is a range of other observations against which this model could be tested; we restrict ourselves to two others. There is some evidence that the profiles of groups are flatter than that of clusters. For example, if the X-ray surface brightness profile is fitted with a $\beta$-model: $S(R) = S_0 \left[1 + (R/R_c)^{2\beta}\right]^{-\beta+1/2}$, then the outer slope $\beta$ is $\approx 0.7$ for large clusters, ranging down to $\beta \approx 0.4$ for groups (Mohr et al. 1999; Helsdon & Ponman 2000). In this expression, $R_c$ is the projected cluster core radius. As might be imagined from Figure 2, our model also shows this trend. After integrating along lines of sight, the resulting surface brightness profile is well fitted by $\beta = 0.75$ for a 10.2 keV cluster and $\beta = 0.5$ for a 1.2 keV group.

The last check that we make is to examine the evolution of the $L_X - T$ relation with redshift. Observations (Mushotzky & Scharf 1997; Schindler 1999; Fairley et al. 2000) show that there is very little change in this relation to $z \approx 0.5$, although the amount of data are still limited. Unfortunately, no high-redshift equivalent of Figure 1 exists; however, if we assume that the ratios do not change appreciably, then this model also predicts little evolution to modest redshifts. Indeed, most models that correctly predict $L_X \approx T^3$ will reproduce this lack of evolution. The reason is simple: for a fixed mass, the luminosity scales roughly as $(1 + z)^3$ as long as the profile does not change very much when expressed as a function of $r/R_{\text{crit}}$. Also, for a fixed mass, the virial temperature scales as $(1 + z)^{3/2}$, and so modifying $z$ moves a cluster parallel to the $L_X \approx T^3$ relation.

4. DISCUSSION

In this Letter, we have described a simple model of cluster formation that reproduces the self-similar breaking observations without recourse to nongravitational heating. There are two key assumptions in this model. The first is that galaxy formation was more efficient in groups than in clusters; as discussed in § 2, there is some empirical evidence for this. Certainly the morphology-density relation shows that galaxies are sensitive to their environment. From a theoretical standpoint, this could arise from biasing (David & Blumenthal 1992) or from the cooling and shocking of gas.

The second important assumption is that the lowest entropy gas is converted into galaxies, while the high-entropy gas retains the same entropy it would have had without galaxy formation. Clearly this is an idealization; in practice, the rest of the gas will suffer some radiative losses (and if it cools substantially, this will invalidate the model assumed here). However, the approximation is self-consistent in that the remaining gas has a cooling time comparable to or longer than the Hubble time. It is also true that the cooling of hot gas tends to occur catastrophically (e.g., Thoul & Weinberg 1995). That is, it remains hot with little cooling until it passes through a cooling front, where the density suddenly increases by orders of magnitude. The gas at large radii moves toward the center without changing its entropy. It seems clear that numerical simulations will be required to test these arguments, although it will be computationally challenging to do so. It is possible that some of the effects described in this Letter may have already been seen in simulations (Pearce et al. 2000).

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