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What is the Fate of Cooling Gas in Clusters?

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Clusters without cooling are unrealistic. Radiative cooling must be included in cosmological simulations of clusters in order to account self-consistently for the luminosity–temperature–mass scaling relations. Feedback is also a necessary part of the overall picture in order to prevent over-cooling. Current mechanisms for implementing feedback in simulations are still incomplete because the simulations do not reproduce the observed features of cluster cores. Simple analytical models, in contrast, *do* approximately reproduce the observed core temperature gradients, perhaps because their simplicity artificially stabilizes the processes of cooling, feedback, and convection in cluster cores, suggesting that some sort of stabilizing mechanism is missing in the simulations. The entropy gradients in cluster cores are an important constraint on AGN feedback models, disfavoring pure conduction as a stabilizing mechanism in many cases.

1. Introduction

The cooling-flow hypothesis has a long and checkered history. Gas at the centers of many clusters can clearly radiate an amount of energy exceeding its thermal energy in a Hubble time, but does it really cool and flow toward the center? The number of astronomers suspecting that it doesn't has gradually grown since the original cooling-flow suggestions of Fabian & Nulsen (1977) and Cowie & Binney (1977). That is because intensive efforts to detect the mass sink into which the cooling gas should flow have turned up much less condensed gas than one would naively infer from the early X-ray imaging data. Now, X-ray spectroscopy is also failing to find gas condensing through temperatures below 10^7 K (Peterson et al. 2001, 2003; David et al. 2001).

Alternative hypotheses for why the hot gas in cluster cores does not simply cool and condense are plentiful, as a quick scan of the proceedings of this conference will confirm. My purpose in this article is not to critically review all of these possibilities but rather to outline in more general terms the broader implications of the cooling-flow problem for cosmology and galaxy formation. While some might like to believe that our ignorance about what regulates cooling flows is a limited problem concerning the innermost regions of clusters, it is actually a far deeper issue intimately linked with the global X-ray properties of clusters and the luminosity function of galaxies.

2. Ignoring Cooling is Unrealistic

Let's begin with a point that is glaringly obvious but under-appreciated: clusters without cooling are unrealistic. Until fairly recently, cosmological simulations of cluster formation did not include radiative cooling and produced galaxy clusters whose X-ray properties did not agree with observations. The X-ray luminosity–temperature relation of clusters simulated without cooling obeys the self-similar expectation $L_X \propto T_{\rm lum}^2$, where $T_{\rm lum}$ is the emissivity-weighted mean temperature of the intracluster medium (e.g., Navarro et al. 1995). This scaling law has been known for over a decade to deviate from the observed luminosity-temperature scaling: $L_X \propto T_{\rm lum}^{\alpha}$, with $\alpha \approx 2.5$–3 (e.g., Edge & Stewart 1991). In the last several years, we have realized that the mass–temperature relation of clusters simulated without cooling also deviates from observations, in that observed clusters of a given temperature seem to have masses up to 40% lower than expected (Horner et al. 1999; Finoguenov et al. 2001). These deviations need to be understood because the L_X–$T_{\rm lum}$ and M–$T_{\rm lum}$ relations are fundamental tools for measuring cosmological parameters using cluster surveys.

Obviously, radiative cooling must occur in the history of a cluster because clusters of galaxies have galaxies in them. Increasingly sophisticated simulations of cosmological cluster formation performed over the last several years now include radiative cooling, and these simulations produce clusters with L_X–$T_{\rm lum}$ and M–$T_{\rm lum}$ relations that agree much more closely with the observed relations. Furthermore, this improved agreement with observations does not depend much on the assumed efficiency of non-gravitational heating and feedback processes, indicating that cooling is the most important physical process to include if one wants to understand the cluster scaling relations used to do cosmology. In order to understand why that is the case, one must pay close attention to the development of intracluster entropy.

3. Why Entropy Matters

Entropy is of fundamental importance for two reasons: it determines the structure of the intracluster medium and it records the thermodynamic history of the cluster's gas. Entropy determines structure because high-entropy gas floats and low-entropy gas sinks. A cluster's intergalactic gas therefore convects until its isentropic surfaces coincide with the equipotential surfaces of the dark-matter potential. Thus, the entropy distribution of a cluster's gas and the shape of the dark-matter potential well in which that gas sits completely determine the large-scale X-ray properties of a relaxed cluster of galaxies. The gas density profile $\rho_g(r)$ and temperature profile $T(r)$ of the intracluster medium in this state of convective and hydrostatic equilibrium are simply manifestations of its entropy distribution.

Here we will adopt the approach of other work in this field and define "entropy" to be

$$K \equiv \frac{kT}{\mu m_p \rho_g^{2/3}} \quad . \tag{1}$$

The quantity K is the constant of proportionality in the equation of state $P = K\rho_g^{5/3}$ for an adiabatic monatomic gas, and is directly related to the standard thermodynamic entropy per particle, $s = k \ln K^{3/2} + s_0$, where s_0 is a constant that depends only on fundamental constants and the mixture of particle masses. Another quantity frequently called "entropy" in the cluster literature is $kTn_e^{-2/3}$. For the typical elemental abundances in the intracluster medium, one can convert between these "entropies" using the relation

$$kTn_e^{-2/3} = 960\,\mathrm{keV\,cm^2}\left(\frac{K}{10^{34}\,\mathrm{erg\,cm^2\,g^{-5/3}}}\right) \quad . \tag{2}$$

A cluster achieves convective equilibrium when $dK/dr \geq 0$ everywhere, and the entropy distribution that determines the gas configuration in this state can be expressed as $K(M_g)$, where the inverse relation $M_g(K)$ is the mass of gas with entropy $< K$.

Comparisons between the entropy distributions of clusters that differ in mass can be simplified by casting those distributions into dimensionless form (e.g., Voit et al. 2002). One can define the mass of a cluster to be the mass M_{200} inside the radius r_{200} within which the mean mass density is 200 times the critical density $\rho_{\rm cr}$. Combining the scale radius r_{200}, the global baryon fraction $f_b = \Omega_{\rm b}/\Omega_{\rm M}$, and the characteristic halo temperature $kT_{200} = GM_{200}\mu m_p/2r_{200}$ then gives the characteristic entropy scale

$$\begin{aligned} K_{200} &= \frac{kT_{200}}{\mu m_p (200 f_b \rho_{\rm cr})^{2/3}} \\ &= \frac{1}{2}\left[\frac{2\pi}{15}\frac{G^2 M_{200}}{f_b H(z)}\right]^{2/3} \quad . \end{aligned} \tag{3}$$

For $f_b = 0.022h^{-2}$, this entropy scale corresponds to

$$\begin{aligned} kTn_e^{-2/3} &= 362\,kT_{\rm lum}\,\mathrm{cm^2}\left(\frac{T_{200}}{T_{\rm lum}}\right) \\ &\times \left[\frac{H(z)}{H_0}\right]^{-4/3}\left(\frac{\Omega_{\rm M}}{0.3}\right)^{-4/3} \quad . \end{aligned} \tag{4}$$

Writing the entropy scale in this way makes explicit the fact that the observed temperature of a cluster is not necessarily a reliable guide to the characteristic entropy K_{200} of its halo. If the intracluster medium of a real cluster is either hotter or cooler than T_{200}, then one must apply the correction factor $T_{200}/T_{\rm lum}$ when computing the cluster's value of K_{200}.

Hierarchical structure formation without radiative cooling or non-gravitational heating produces entropy

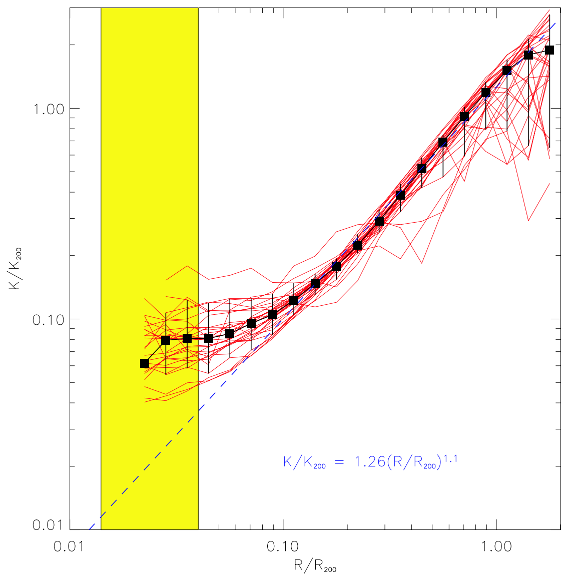

FIG. 1.— Dimensionless entropy K/K_{200} as a function of scale radius r/r_{200} for 30 clusters simulated with the SPH code GADGET (Voit et al. 2004). Black squares show the median profile, and the dashed line illustrates the power-law relation $K/K_{200} = 1.2(r/r_{200})^{1.1}$. Most of the entropy profiles shown lie close to this relation in the radial range $0.1 \lesssim r/r_{200} \lesssim 1.0$.

purely through the shock heating associated with structure formation. Because there is no particular entropy scale associated with these shocks, other than the scale K_{200} set by the halo mass and the redshift, the entropy profiles of clusters simulated in the absence of non-gravitational processes are self-similar, with nearly identical entropy profiles (see Figure 1), and they therefore obey the self-similar scaling relations that disagree with observations. The observed relations require the introduction of another entropy scale that breaks self-similarity.

4. **The Entropy "Floor"**

Early approaches to the problem of similarity breaking in clusters postulated that some sort of heating process imposed a universal minimum entropy—an "entropy floor"—on the intergalactic gas before it collected into clusters (Evrard & Henry 1991; Kaiser 1991). Imposing a global entropy floor helps to bring the theoretical $L_{\rm X}$-$T_{\rm lum}$ relation into better agreement with observations because this extra entropy makes the gas harder to compress in cluster cores, where entropy is smallest, particularly in the shallower potential wells of low-temperature clusters. This resistance to compression breaks cluster similarity by lowering the core density, and therefore the X-ray emissivity, in low-T clusters more than in high-T clusters, thereby steepening the $L_{\rm X}$–$T_{\rm lum}$ relation.

According to this preheating picture, the core entropy level and scaling relations of clusters should reflect the global entropy floor produced at early times. Initial measurements of entropy at the core radius $r_{0.1}$ demonstrated that low-temperature clusters had greater amounts of entropy than expected from self-similarity and suggested that the level of the entropy floor was $\sim 135\,\mathrm{keV\,cm^2}$

(Ponman et al. 1999; Lloyd-Davies et al. 2000). This result matched well with numerical simulations of cluster formation in which preheating levels of $50 - 100\,\mathrm{keV\,cm^2}$ produced clusters with approximately the right $L_{\rm X}$–$T_{\rm lum}$ relation (Bialek et al. 2001).

However, simple preheating now appears to be too crude an explanation for similarity breaking. In the preheating picture, low-temperature clusters should have large isentropic cores (Balogh et al. 1999; Tozzi & Norman 2001), but this prediction disagrees with the observations showing that the shapes of cluster entropy profiles do not depend significantly on temperature (Pratt & Arnaud 2003). In addition, the abundant evidence for intergalactic gas at $\lesssim 10^5$ K from quasar absorption line studies clearly shows that preheating cannot be global at $z \gtrsim 2$, and the preheating models themselves do not explain why the level of the entropy floor should be $\sim 135\,\mathrm{keV\,cm^2}$.

In contrast, the observed entropy scale of similarity breaking emerges naturally from the process of radiative cooling. Cooling that radiates an energy Δq per particle reduces the entropy by $\Delta \ln K^{3/2} = \Delta q/kT$. Thus, the equation expressing these radiative losses can be written

$$\frac{dK^{3/2}}{dt} = -\frac{3}{2}\frac{K_c^{3/2}(T)}{t_0} \; , \tag{5}$$

where

$$K_c(T) = \left[\frac{2}{3}\left(\frac{n_e n_p}{\rho^2}\right)\frac{(kT)^{1/2}\Lambda(T)}{(\mu m_p)^{1/2}}\right]^{2/3} t_0^{2/3} \quad , \tag{6}$$

is the entropy level at which constant-density gas at temperature T radiates an energy equivalent to its thermal energy in the time t_0, and $\Lambda(T)$ is the usual cooling function. The latter formula reduces to

$$K_c(T) \approx 81\,\mathrm{keV\,cm^2}\left(\frac{t_0}{14\,\mathrm{Gyr}}\right)^{2/3}\left(\frac{T}{1\,\mathrm{keV}}\right)^{2/3} \tag{7}$$

when pure bremsstrahlung cooling is assumed.

The fact that the entropy threshold below which gas cools within the universe's lifetime is close to the entropy floor inferred from clusters with ~ 2 keV temperatures suggests that radiative cooling sets the entropy scale for similarity breaking (Voit & Bryan 2001). Voit & Ponman (2003) further quantify this point. Figure 2 shows how entropy measurements at $0.1 r_{200}$ in a large sample of clusters (Ponman et al. 2003) compare with the cooling threshold $K_c(T)$ for gas with heavy-element abundances equal to 30% of their solar values relative to hydrogen. Both the measured core entropies and the entropy threshold for cooling scale as $T^{2/3}$, and they are approximately equal, although the scatter in the data is quite significant.

Cooling therefore appears to set the entropy scale for similarity breaking, but it cannot act alone. Casting equation (7) in dimensionless form illustrates why at least some feedback must compensate for cooling:

$$\frac{K_c(T)}{K_{200}} \approx 0.2\,(Ht)^{2/3}\left[\frac{H(z)}{H_0}\right]^{2/3}\left(\frac{T}{1\,\mathrm{keV}}\right)^{-1/3} \quad . \tag{8}$$

The cooling threshold in low-temperature clusters at the present time is ~20% of the characteristic entropy K_{200}

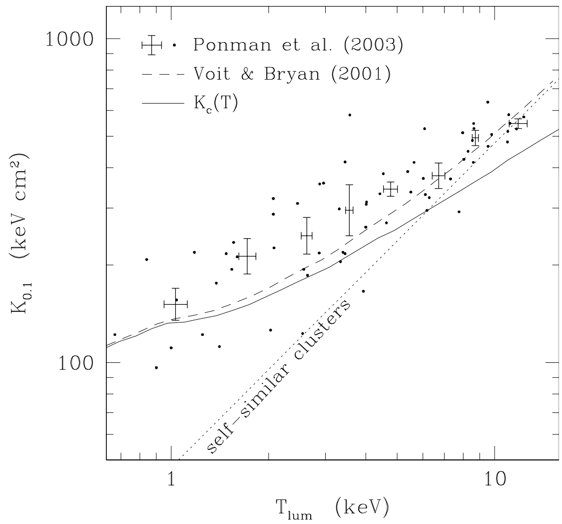

FIG. 2.— Relationship between core entropy and the cooling threshold (see Voit & Ponman 2003). Each point with error bars shows the mean core entropy $K_{0.1}$, measured at $0.1 r_{200}$, for eight clusters within a given bin of luminosity-weighted temperature $T_{\rm lum}$, and small circles show measurements for individual clusters (Ponman et al. 2003). The dotted line shows a self-similar relation calibrated using the median value of $K_{0.1}$ measured in simulation L50+ of Bryan & Voit (2001) which does not include cooling or feedback, and it's misplaced in Voit & Ponman (2003). The solid line shows the cooling threshold $K_c(T)$, defined to be the entropy at which the cooling time equals 14 Gyr, assuming the cooling function of Sutherland & Dopita (1993) for 0.3 solar metallicity. The dashed line shows the entropy at $0.1 r_{200}$ in the model of Voit & Bryan (2001) when this cooling function is used. These simple treatments of cooling reproduce the slope but slightly underestimate the normalization of the observed $K_{0.1}(T_{\rm lum})$ relation, which shows no sign of an absolute entropy floor.

and greater than that if emission-line cooling from heavy elements is included. At earlier times, the dimensionless cooling threshold is even higher, meaning that a large proportion of the baryons belonging to the progenitor objects that ultimately assembled into present-day clusters would have condensed into stars or cold gas clouds if there were no feedback. This is one of the manifestations of the classic over-cooling problem of hierarchical galaxy formation (White & Rees 1978; Cole 1991; Blanchard et al. 1992). Because the observed mass ratio of stars to hot gas in clusters is only $\lesssim 10\%$ (Balogh et al. 2001), wholesale baryon condensation doesn't seem to have happened.

Recognition of this over-cooling problem led Voit & Bryan (2001) to propose a way for radiative cooling to determine the entropy scale of similarity breaking without acting alone. The basic idea is that gas with entropy less than $K_c(T)$ cannot persist indefinitely. It must either cool and condense or be heated until its entropy exceeds $K_c(T)$. At any given time, feedback is triggered by condensing gas parcels with entropy less than the cooling threshold and acts until those parcels are eliminated by either cooling, heating, or some combination of the two. Thus, the joint action of cooling and feedback imprint an entropy scale roughly corresponding to the cooling threshold, regardless of how strong the feedback is.

While it might seem paradoxical, allowing the intracluster medium to radiate thermal energy actually causes its luminosity-weighted temperature to rise. The reason for this behavior is that cooling selectively removes low-entropy gas from the intracluster medium, raising the mean entropy of what remains (Knight & Ponman 1997; Pearce et al. 2000; Bryan 2000). In non-radiative cluster simulations, the entropy of gas in the vicinity of the cluster core is below the cooling threshold K_c. This aspect of non-radiative models is unphysical, because gas with entropy less than K_c would radiate an amount of energy greater than its total thermal energy content over the course of the simulations (e.g., Muanwong et al. 2001). When cooling is allowed to occur, this low-entropy core gas condenses out of the intracluster medium and is replaced by higher entropy core gas having a higher temperature, a lower density, and therefore a lower luminosity.

5. **Entropy Modification**

A simple analytical model for entropy modification illustrates the effect of the cooling threshold on the L_X–$T_{\rm lum}$ and M_{200}–$T_{\rm lum}$ relations (Voit & Bryan 2001; Voit et al. 2002; Wu & Xue 2002). The model assumes that the intracluster entropy distribution in the absence of galaxy formation would lead to a gas density profile similar to that of the dark matter, which can be approximated with the NFW fitting formula $\rho(r) \propto r^{-1}(1 + c_{200}r/r_{200})^{-2}$, where c_{200} is the concentration parameter (Navarro et al. 1997). Assuming that this gas is also in hydrostatic equilibrium yields a baseline entropy distribution for the no-cooling, no-feedback case. Because condensation and feedback both act to eliminate gas below the cooling threshold, one can approximate the effects of the cooling threshold by simply truncating the baseline entropy distribution at $K_c(T_{200})$ and discarding all the gas with lower entropy. One can interpret this gas removal either as condensation or as extreme feedback that heats the sub-threshold gas to a much higher entropy level. This cooling and feedback need not occur at the center of the cluster. In a hierarchical cosmology, much of the low-entropy gas cools, condenses into galaxies, and produces feedback long before the cluster is finally assembled.

Computing the hydrostatic configuration of the modified entropy distribution in the original dark-matter potential gives L_X and $T_{\rm lum}$ as a function of the mass M_{200} and concentration c_{200} of the dark-matter halo. Figures 3 and 4 show that the resulting L_X–$T_{\rm lum}$ and M_{200}–$T_{\rm lum}$ relations agree well with observations but may slightly over-predict L_X for objects cooler than $\sim 2\,{\rm keV}$. Notice that there are no free parameters in this model, other than the cosmological parameters, because the M_{200}–c_{200} relation and the age of the universe used to compute K_c depend only on cosmology, and the heavy-element abundance used to compute the cooling threshold is taken from observations.

Numerical simulations in which feedback is either weak or non-existent produce clusters whose properties are quite similar to the ones in this simple analytical model. Early numerical investigations of cooling in individual clusters gave inconclusive results (Suginohara & Ostriker 1998; Lewis et al. 2000), but simulations by Muanwong et al. (2001) showed that adding cooling to a large-scale cluster simulation could give an L_X–$T_{\rm lum}$ relation like the observed one. A large body of subsequent numerical work has confirmed that result, firmly establishing that

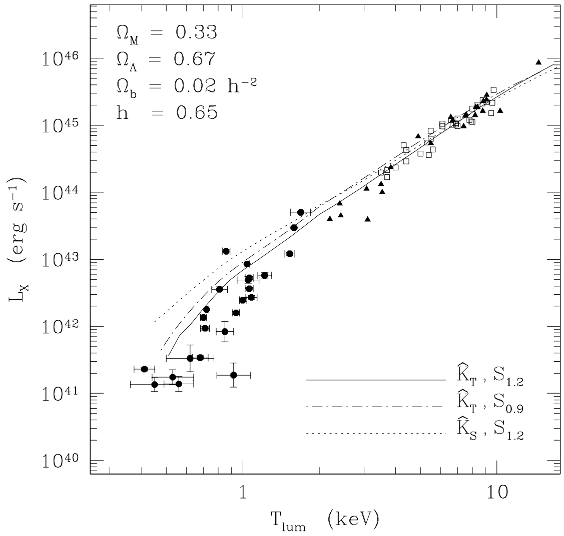

FIG. 3.— Relation between bolometric X-ray luminosity L_X and luminosity-weighted temperature $T_{\rm lum}$. Solid triangles show measurements of clusters with insignificant cooling flows compiled by Arnaud & Evrard (1999). Open squares show cooling-flow corrected measurements by Markevitch (1998). Solid circles show group data from Helsdon & Ponman (2000). The solid and dotted lines show the L_X–$T_{\rm lum}$ relations derived from simple analytical models like those described in the text (see Voit et al. 2002,for details).

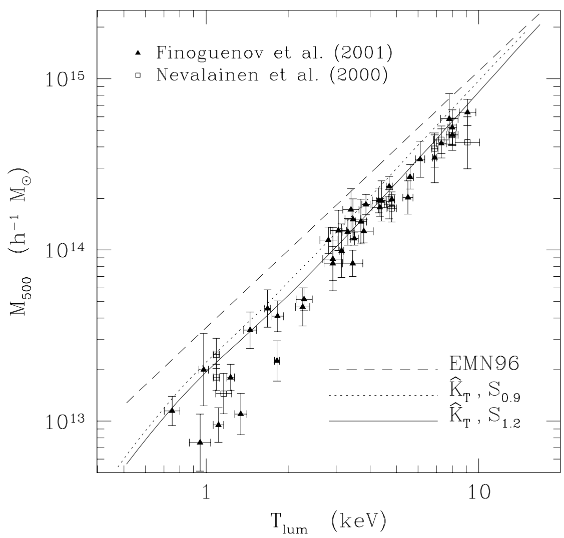

FIG. 4.— Relation between M_{500} and luminosity-weighted temperature ($T_{\rm lum}$). Solid triangles show mass measurements by Finoguenov et al. (2001), using β-model fitting and the assumption of hydrostatic equilibrium. Open squares show mass measurements by Nevalainen et al. (2000), also using β-model fitting and hydrostatic equilibrium. The solid and dotted lines show M_{500}–$T_{\rm lum}$ relations derived from the simple analytical models like those described in the text (see Voit et al. 2002). The dashed line shows the M_{500}–$T_{\rm lum}$ relation derived by Evrard et al. (1996) from simulations that do not include radiative cooling or supernova feedback.

cooling must be included in order to produce realistic clusters (e.g., Davé et al. 2002; Borgani et al. 2002).

6. Avoiding Over-cooling

So what happens to the gas that cools? Supernovae are the most obvious candidate for supplying the feedback that suppresses condensation, but it is not clear that supernova heating and the galactic winds it drives can provide enough entropy to keep the fraction of condensed baryons below about 10%. Heavy-element abundances in clusters imply that the total amount of supernova energy released during a cluster's history amounts to $\sim 1\,\mathrm{keV}$ per gas particle in the intracluster medium (Finoguenov et al. 2000; Pipino et al. 2002). The amount of energy input needed to explain the mass-observable relations while avoiding over-cooling is also ~ 1 keV (Wu et al. 2001; Voit et al. 2002; Borgani et al. 2002), but the transfer of supernova energy to the intracluster medium would have to be highly efficient, which seems unlikely (Kravtsov & Yepes 2000). Supernova energy would have to be converted to almost entirely to thermal energy with very little radiated away.

In order to avoid radiative losses, supernova heating must raise the entropy of the gas it heats to at least $100\,\mathrm{keV\,cm}^2$. An evenly distributed thermal energy input of order 1 keV would have to go into gas significantly less dense than $10^{-3}\,\mathrm{cm}^{-3}$ to avoid such losses. Gas near the centers of present-day clusters, not to mention the galaxies where supernovae occur, is denser than that, particularly at earlier times when most of the star formation happened. Simulations that spread supernova feedback evenly therefore produce too many condensed baryons in clusters (e.g., Borgani et al. 2002). Artificial algorithms that target supernova feedback at gas parcels that would otherwise cool are more successful at preventing over-cooling (Kay et al. 2003). However, efforts to implement a more realistic version of targeted feedback in the form of galactic winds are still not entirely successful at preventing over-cooling (Borgani et al. 2003).

It remains to be seen whether supernova feedback alone can account for the observed entropy profiles of clusters. Voit et al. (2003) and Ponman et al. (2003) have proposed that entropy input from galactic winds preceding the accretion of gas onto clusters could lead to a form of entropy amplification that would explain the observations. If galactic winds are strong enough to significantly smooth out the lumpiness of the intergalactic gas in their vicinity, then the mode of accretion of this gas onto clusters will be closer to smooth accretion than to hierarchical accretion, boosting the entropy generated through accretion shocks without changing the entropy profile's characteristic shape. This effect is a plausible explanation for the characteristic of the observed entropy profiles (Pratt & Arnaud 2003), but it has not yet been thoroughly tested in simulations. Intriguing results by Kay (2004) show that an extremely targeted feedback model, in which feedback triggered by cooling heats the local gas to $1000\,\mathrm{keV\,cm}^2$, successfully reproduces both the normalization and shape of the observed entropy profiles.

If supernovae cannot prevent over-cooling, then perhaps supermassive black holes in the nuclei of galaxies are what stop it (Valageas & Silk 1999; Wu et al. 2001). The omnipresence of supermassive black holes at the centers of galaxies and the excellent correlation of their masses with the bulge and halo properties of the host galaxy strongly suggest that the growth of black holes in the nuclei of galaxies goes hand-in-hand with galaxy formation. Furthermore, the centers of many clusters with low-entropy gas whose cooling time is less than the age of the universe also contain active galactic nuclei that are ejecting streams of relativistic plasma into the intracluster medium, as we saw many times at this conference. It is therefore plausible that supermassive black holes at the centers of clusters provide feedback that suppresses further cooling whenever condensing intracluster gas accretes onto the central black hole.

Such a feedback loop is attractive and consistent with the circumstantial evidence, but the precise mechanism of heating remains unclear. The bubbles of relativistic plasma being inflated by the active galactic nuclei in clusters appear not to be expanding fast enough to shock heat the intracluster medium because the rims of the bubbles are no hotter than their surroundings. Also, if active galactic nuclei simply injected heat energy into the center of a cluster, then one would expect to see a flat or reversed entropy gradient in clusters with strong nuclear activity, indicating that convection is carrying heat outward. Instead, the entropy gradients in these cluster cores increase monotonically outward (David et al. 2001; Horner et al. 2004), as can be seen in Figure 5. One possibility is that heating is episodic (Kaiser & Binney 2003) and that we have not yet found a cluster in the midst of an intense heating episode. Another is that heating is somehow spread evenly throughout the cluster core in a way that maintains the entropy gradient (Brüggen & Kaiser 2002; Ruszkowski & Begelman 2002). Yet another possibility is that bursts of relativistic plasma drive sound waves into the intracluster medium that eventually dissipate into heat (Fabian et al. 2003).

Unfortunately, none of these heating mechanisms have yet been tested in the context of cosmological structure formation, so we do not know their overall impact on either baryon condensation or the global entropy profiles of clusters. Also, many aspects of the relationship between cosmology and nuclear activity in galaxies are highly uncertain. A major role for quasar feedback is plausible. However, the connection between the growth of central black holes in galaxies and galaxy formation itself is not well understood, and the efficiency with which black holes convert accretion energy into outflows is unknown.

7. Allowing for a Cool Core

Any successful explanation for the regulation of cooling in cluster cores must account for the rising temperature gradients in those cores, which tend to rise monotonically with radius (e.g., Allen et al. 2002). The gas responsible for this rising temperature gradient is of course the "cooling flow" gas, whose entropy is below the cooling threshold. Cooling and feedback have not entirely eliminated this gas, but they have eliminated enough of it

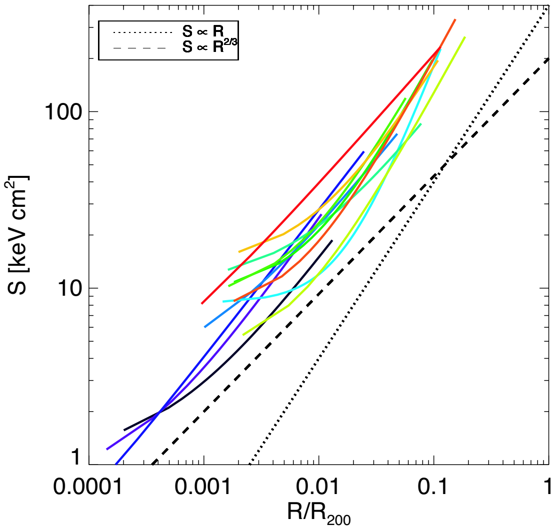

FIG. 5.— Core entropy profiles of twelve clusters from Horner et al. (2004). In the range $0.01 < r/r_{200} < 0.1$, entropy rises roughly linearly with radius. Inside of $0.01 r_{200}$ the entropy profiles appear to flatten at a level consistent with a cooling time of a few hundred Myr, implying that epsiodic heating would need to occur on about this timescale to prevent over-cooling.

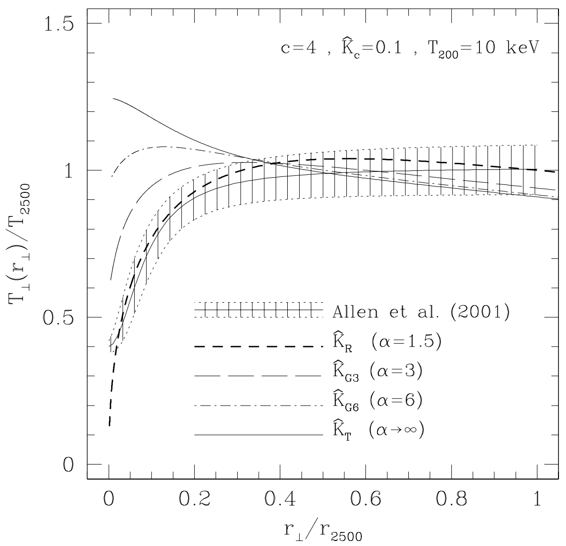

FIG. 6.— Luminosity-weighted projected temperature $T_\perp$ as a function of projected radius $r_\perp$. Radii are given in units of the radius r_{2500} within which the mean matter density is 2500 times the critical density. Temperatures are given in units of the mean mass-weighted temperature T_{2500} within r_{2500}. The hatched area shows the best fit of Allen et al. (2002) to their Chandra data on six hot clusters with strong cooling flows, along with the uncertainty in that fit. Other lines show $T_\perp$ from modified-entropy models with parameters characteristic of hot clusters and varying amount of gas below the cooling threshold. The short-dashed line that best fits the data represents the results of pure cooling (see Voit et al. 2002).

so that it no longer dominates the total luminosity. Differences in the proportion of this sub-threshold gas from cluster to cluster explain much of the scatter in the L_X–$T_{\rm lum}$ relation (Voit et al. 2002).

There is not yet a satisfactory theoretical explanation for these temperature gradients. In the simple analytical models outlined above, no gas is allowed to be below the cooling threshold, resulting in a core that is nearly isentropic and thus has a negative temperature gradient ($dT/dr < 0$). Likewise, simulations with cooling and feedback also tend to have flat or negative temperature gradients in the neighborhood of the core radius (Tornatore et al. 2003).

This problem deserves attention because elevated core temperatures in models with cooling are what bring the theoretical M_{200}–$T_{\rm lum}$ relation into agreement with observations. Making the analytical model slightly more realistic brings the predicted temperature gradient into better agreement with observations. Applying a discontinuous cooling threshold is overly crude because it completely removes gas just below the threshold while gas just above the threshold does not cool at all. Instead, cooling acts upon the entropy distribution as described by equation (6). Voit et al. (2002) show that modifying the baseline entropy profile using this equation with $T = T_{200}$ for a time t_0 leads to an entropy distribution that reproduces the observed temperature gradients (see Figure 6).

Simulations involving pure cooling do not agree with this result. The temperature-gradient discrepancy between analytical models and simulations in the pure-cooling case is still not understood, but may have something to do with the implied stability of the cooling process in the analytical model. In that model the present-day intracluster medium is spherically symmetric with a positive entropy gradient, by definition. Simulations, on the other hand, allow thermal instabilities to produce a more heterogeneous entropy pattern at each radius, which may be at the root of the negative temperature gradient. Perhaps the observations are telling us that a stabilizing influence like conduction erases small-scale thermal instabilities without shutting off global cooling.

8. Core Entropy & Conduction

While conduction may help stabilize the entropy gradients of clusters, it does not seem to be able to shut off cooling altogether in most cases. If conduction at some fixed fraction of the Spitzer rate, with a heat flux proportional to $T^{5/2}\nabla T$ were in equilibrium with bremsstrahlung cooling in a spherically symmetric configuration, then one would expect $rT^{7/2} \propto n^2 T^{1/2} r^3$, implying

$$K \propto T n^{-2/3} \propto r^{2/3} \quad . \tag{9}$$

Observed core entropy gradients are generally steeper than this (see Figure 5), meaning that if Spitzer-like conduction stabilizes the outer parts of cluster cores then it cannot stabilize the inner parts. Interestingly, "cooling-flow" clusters showing no evidence for feedback—neither emission-line nebulae nor radio lobes—also have shallower entropy gradients, suggesting conduction might stabilize a small fraction of cluster cores (Donahue et al. 2004).

9. Cooling Flows & Cosmology

A solution to the cooling-flow problem will ultimately have two major benefits. Currently, the X-ray scaling relations are the major source of uncertainty in our measurements of cosmological parameters from cluster surveys. Understanding how cooling and subsequent feedback affects those relations will greatly aid efforts to measure those parameters more precisely. Also, the way in which feedback regulates galaxy formation remains poorly understood, largely because it is so difficult to observe galaxies as they were forming. However, nearby clusters present us with a similar over-cooling problem that is much easier to observe. Its solution is likely to provide deep insights into galaxy formation. So let's get back to work!

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