Section C

Theoreticians at work

Outskirts of Galaxy Clusters: Intense Life in the Suburbs
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Intracluster thermodynamics

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Abstract. Most of the baryons in the universe remain undetected. They are thought to be floating in intergalactic space, and their thermal state is highly uncertain. The only places where we have reasonably complete observations of the overall baryon population are in clusters of galaxies, where the baryons reveal themselves through their X-ray emission. There we find that only about 10% of the baryons have turned into stars, probably because feedback processes intervene to prevent more baryons from condensing. These galaxy formation processes seem to have left an imprint on the thermal state of the intracluster medium, but in order to interpret that imprint, one needs to pay close attention to how entropy develops in the intergalactic gas. Many of the global properties of clusters turn out to be determined primarily by the entropy threshold for cooling within a Hubble time. However, *XMM-Newton* observation are revealing a sort of altered similarity among the entropy profiles of clusters seeming to indicate that galactic winds may have smoothed the local intergalactic medium before it accreted onto clusters.

1. Introduction

What is the thermodynamical state of gas as it enters a cluster of galaxies? The question is difficult to answer by direct observation because the X-ray surface brightness of clusters and groups of galaxies is so low in the vicinity of the virial radius. One would like to know whether the accreting gas has been preheated because early energy input by supernova-driven galactic winds and energy injection by active galactic nuclei strongly affect the global properties of clusters. Furthermore, an understanding of how galaxy formation alters the properties of clusters is necessary in order to derive precise values for cosmological parameters from the number density and evolution rate of the overall cluster population.

Because it is so difficult to observe the intergalactic gas outside of clusters, one of the best ways to gather information about that gas is to observe its properties after it has fallen into a cluster. Once that happens, the thermodyamical state of the gas can be determined from its X-ray emission. However, proceeding from those observations back to what must have happened to the gas to produce its current state requires paying close attention to the processes that determine intracluster entropy.

2. 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 $K \equiv kT/(\mu m_p \rho_g^{2/3})$. 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. A cluster achieves convective equilibrium when $dK/dr \geqslant 0$ 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. 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

$$K_{200} = \frac{kT_{200}}{\mu m_p (200 f_b \rho_{\rm cr})^{2/3}} = \frac{1}{2}\left[\frac{2\pi}{15}\frac{G^2 M_{200}}{f_b H(z)}\right]^{2/3} \quad . \tag{2.1}$$

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

$$kTn_e^{-2/3} = 362\, kT_{\rm lum}\, {\rm cm}^2 \left(\frac{T_{200}}{T_{\rm lum}}\right)\left[\frac{H(z)}{H_0}\right]^{-4/3}\left(\frac{\Omega_{\rm M}}{0.3}\right)^{-4/3} \quad . \tag{2.2}$$

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}, where $T_{\rm lum}$ is the emissivity-weighted mean temperature of the intracluster medium.

Hierarchical structure formation without radiative cooling or non-gravitational heating produces entropy 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 (e.g., Voit et al. 2003).

3. Broken similarity

Observations have shown that real clusters are not like the self-similar objects that emerge from simulations without galaxy formation. The X-ray luminosity-temperature relation of clusters simulated without cooling obeys the self-similar expectation $L_{\rm X} \propto T_{\rm lum}^2$ (e.g., Navarro et al. 1995). This scaling law has been known for over a decade to deviate from the observed luminosity-temperature scaling: $L_{\rm X} \propto T_{\rm lum}^{\alpha}$, with $\alpha \approx 2.5 - 3$ (e.g., Edge & Stewart 1991). In the last several years, the observed mass-temperature relation of clusters has been shown to deviate from that of clusters simulated without cooling, in that observed clusters of a given temperature seem to have masses up to 40% lower than expected (Horner et al. 1999; Nevalainen et al. 2000; Finoguenov et al. 2001). These deviations need to be understood because the $L_{\rm X}$-$T_{\rm lum}$ and M-$T_{\rm lum}$ relations are fundamental tools for measuring cosmological parameters using cluster surveys.

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_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_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 $\sim 135\,{\rm keV\,cm^2}$ (Ponman et al. 1999). This result matched well with numerical simulations of cluster formation in which preheating levels of $50-100\,{\rm keV\,cm^2}$ produced clusters with approximately the right L_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, 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 $\sim 135\,{\rm keV\,cm^2}$.

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 $\Delta \ln K^{3/2} = \Delta q/kT$. The entropy threshold $K_c(T)$ below which gas at temperature T cools within the universe’s lifetime turns out to be quite close to the entropy floor inferred from cluster observations (Voit & Bryan 2001). Voit & Ponman (2003) further quantify this point. Figure 1 shows how entropy measurements at $0.1r_{200}$ in a large sample of clusters 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. The cooling threshold in low-temperature clusters at the present time is $\sim$20% of the characteristic entropy K_{200} 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 overcooling problem of hierarchical galaxy formation. Because the observed mass ratio of stars to hot gas in clusters is only $\lesssim 10\%$ (e.g., Balogh et al. 2001), wholesale baryon condensation doesn’t seem to have happened.

Recognition of this overcooling 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,

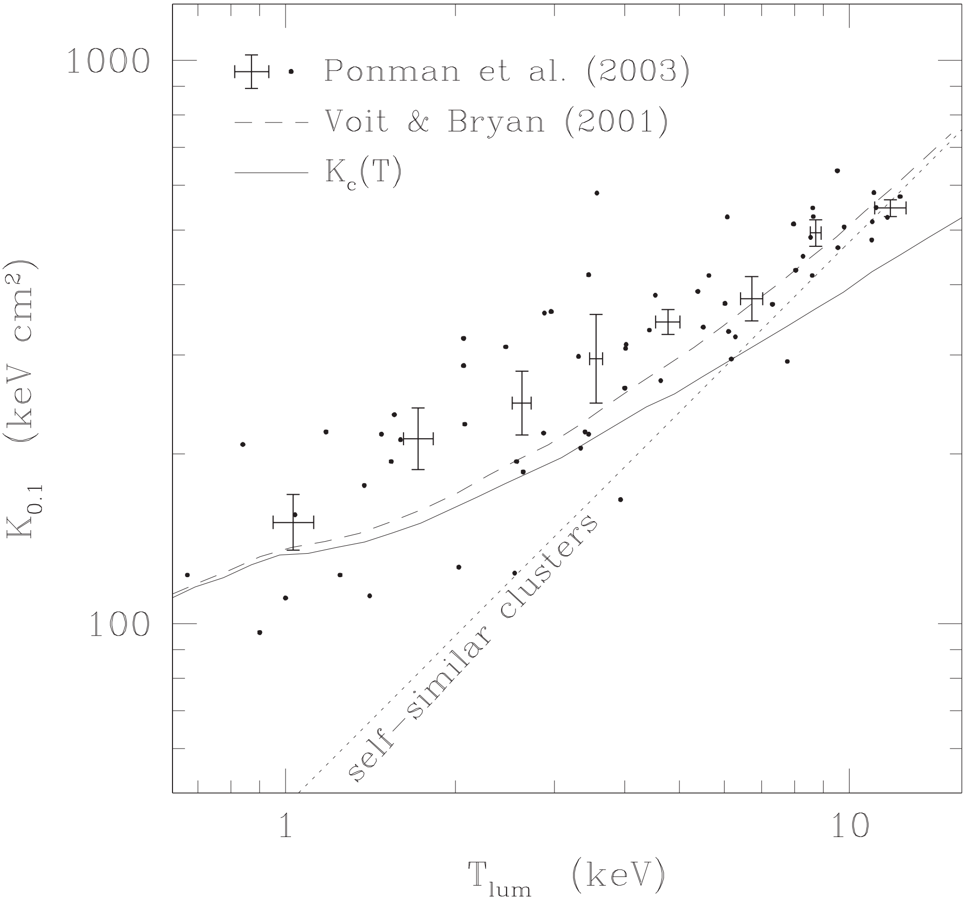

Figure 1. Comparison between entropy measured at $0.1r_{200}$ and the cooling threshold in a large sample of clusters. Small points show the entropy $K_{0.1}$ measured at $0.1r_{200}$ in a sample of 64 clusters, and points with error bars show the mean entropy measurement in temperature bins of eight clusters each. The dotted line gives the mean entropy predicted by simulations of clusters without radiative cooling or feedback. The solid line shows the value of the cooling threshold $K_c(T)$ computed for heavy-element abundances 0.3 times their solar values and $t_0 = 14$ Gyr. The dashed line shows the entropy predicted at $0.1r_{200}$ by the simple analytical model of Voit & Bryan (2001).

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. 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. 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.

4. 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. 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. The resulting L_X-$T_{\rm lum}$ and M_{200}-$T_{\rm lum}$ relations agree well with observations but may slightly overpredict 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.

5. Avoiding overcooling

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 $\sim 1\,{\rm keV}$ per gas particle in the intracluster medium. The amount of energy input needed to explain the mass-observable relations while avoiding overcooling is also ~ 1 keV, but the transfer of supernova energy to the intracluster medium would have to be highly efficient, which seems unlikely (e.g., Kravtsov & Yepes 2001). Supernova energy would have to be converted 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 $100\,{\rm keV\,cm^2}$. An evenly distributed thermal energy input of order $1\,{\rm keV}$ would have to go into gas significantly less dense than $10^{-3}\,{\rm cm^{-3}}$ 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 overcooling (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 overcooling (Borgani et al. 2004).

If supernovae cannot prevent overcooling, then perhaps supermassive black holes in the nuclei of galaxies are what stops it. 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. 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). 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.

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.

6. Presmoothing by galactic winds?

Observations of entropy in the *outer* parts of clusters suggest that galactic winds driven by supernovae or active galaxies may indeed have a pronounced impact on the intergalactic medium, at least in the vicinity of clusters. The entropy profiles of clusters and groups can now be measured out to a significant fraction of the virial radius r_{200}, within which the mean mass density is 200 times the critical density. Surprisingly, these measurements are hinting that the $K(r/r_{200}) \propto T^{2/3}$ scaling relation that applies at $0.1 r_{200}$ also applies to the entire entropy profile. Deep *XMM-Newton* observations of two clusters whose temperatures differ by a factor $\sim$3.5 show that the scaled profile $T_{\rm lum}^{-2/3} K(r/r_{200})$ is independent of cluster temperature (Pratt & Arnaud 2003). Likewise, an analysis of lower-quality data on a larger number of clusters also suggests that $K(r/r_{200}) \propto T_{\rm lum}^{2/3}$ at the scale radius r_{500}, within which the mean matter density is 500 times the critical density (Ponman et al. 2003).

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 characteristics 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 keV cm^2, successfully reproduces both the normalization and shape of the observed entropy profiles. However, it remain to bee seen whether this mechanism works in detail.

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