Cooling and Clusters: When Is Heating Needed?

BY GREG BRYAN\textsuperscript{1} AND MARK VOIT\textsuperscript{2}

\textsuperscript{1} Astrophysics, Oxford University, Oxford OX1 3RH
\textsuperscript{2} Dept. of Physics and Astronomy, Michigan State University, East Lansing, MI

There are (at least) two unsolved problems concerning the current state of the thermal gas in clusters of galaxies. The first is identifying the source of the heating which offsets cooling in the centers of clusters with short cooling times (the “cooling flow” problem). The second is understanding the mechanism which boosts the entropy in cluster and group gas. Since both of these problems involve an unknown source of heating it is tempting to identify them with the same process, particularly since AGN heating is observed to be operating at some level in a sample of well-observed “cooling flow” clusters. Here we show, using numerical simulations of cluster formation, that much of the gas ending up in clusters cools at high redshift and so the heating is also needed at high-redshift, well before the cluster forms. This indicates that the same process operating to solve the cooling flow problem may not also resolve the cluster entropy problem.

Keywords: galaxies: clusters – galaxies: cooling flows – galaxies: formation – galaxies: active – methods: numerical

1. Introduction

The physical state of the gas in clusters of galaxies tells us a great deal about the past history of the cluster; however, it is not simple to decode this information. During a typical 10 Mpc (comoving) trip from its initial location at early times to its current resting place, the gas may be heated by shocks, galactic winds, AGN, turbulence and thermal conduction; it may also be cooled by radiative cooling. It is worth noting that of all of these processes, only radiative cooling will always act to reduce specific entropy of the gas, while the others (usually) act to boost the gas to a higher adiabat. It is perhaps not surprising then to find that observations of clusters indicate the gas is at a higher entropy than found in simulations that include only gravitational infall and shocks (Ponman\textit{ et al.} 1999). Moreover, this effect is not uniform across all clusters – the entropy boost is relatively larger for small clusters, which have lower intrinsic entropy, than for larger clusters.

It is this relative effect which changes the slope of the relation between X-ray luminosity and gas temperature in clusters from the self-similar prediction of $L_X \sim T^2$ to the observed $L_X \sim T^3$ (Edge & Stewart 1991; Evrard & Henry 1991; Kaiser 1991). Clearly whatever process raised the entropy, it was operating more effectively for groups than for clusters. However, this alone does not determine the source of the heating. On energetic grounds, none of the sources listed earlier can be excluded (e.g. Finoguenov\textit{ et al.} 2000; Tozzi & Norman 2001; Cavaliere\textit{ et al.} 2002; Wu\textit{ et al.} 2001; Kim & Narayan 2003).
The other piece of evidence for heating in clusters comes from the absence of cooling in so-called “cooling flow” clusters (e.g. Fabian 2003). Probably the most promising resolution to the cooling-flow riddle comes from AGN heating. It is now well established from Chandra and XMM-Newton observations that in the centers of many clusters with cooling times short compared to the Hubble time, there are cavities thought to be inflated by jets powered by a supermassive black hole (Fabian et al. 2000; Mazzotta et al. 2002; McNamara et al. 2001). While the exact mechanism for transferring energy to the gas is not yet perfectly clear there is no shortage of work on this topic (Churazov et al. 2001; Brügen & Kaiser 2001, 2002; Omma et al. 2004; Reynolds, et al. 2004; Begelman & Ruszkowski, these proceedings).

What is not clear is if these two pieces of evidence are related. In other words, is it the same source of heating which solves the cooling flow problem AND reproduces the correct entropy distribution (and hence thermal structure) of X-ray clusters?

In this work, we will first examine a simple model based on the characteristics of cooling and then use numerical simulations to find out at which epoch most of the cooling (and hence heating) occurs. If we know when the heating must occur, this may cast some light on the source of the heating. We will show that the epoch of cooling is generally at much higher redshift than the formation of clusters and so the solution to the $z = 0$ cooling flow problem may not also be the solution to the structure problem.

### 2. Understanding cluster structure

One early model for understanding what appeared to be a floor in the entropy distribution was that the gas was uniformly heated to a high constant adiabat at early times (e.g. Evrard & Henry 1991; Kaiser 1991). While this model did correctly reproduce the observed luminosity-temperature relation (Bialek et al. 2001), it suffered from possible conflicts with the observed low entropy of the Lyman-alpha forest. In addition, the isentropic cores predicted by this model for groups have not been observed (e.g. Pratt & Arnaud 2003; Ponman et al. 2003).

There have been a number of suggested models which attempt to reproduce the structure and scaling of clusters based on particular ways of adding energy to the cluster gas (e.g. Wu et al. 2001; Bower et al. 2001), but it is clear that the result depends on when and where the heating occurs. Instead, here we will focus on a simple model which is based on the entropy distribution and doesn’t specify exactly how the heating occurs. This approach is a useful framework for understanding what physics is required to correctly reproduce the cluster structure and hence reproduce the cluster scaling relations.

To understand these scaling properties – such as the $L_X - T$ relation – it is useful to create an idealized, hydrostatic, spherical model of a cluster in a fixed dark matter potential based on N-body simulation. Then, given an appropriate boundary condition, the state of the gas is entirely specified by the specific entropy distribution. This is true because, in equilibrium, the entropy must be a monotonically increasing function of radius (otherwise convection will occur).

It has become usual to define the mass $M$ of a cluster as the mass within a fixed overdensity, so that the characteristic density $\rho \sim M/R^3$ of all clusters at a given epoch is a constant times the critical density of the universe (see e.g. Bryan & Norman 1998). The temperature then scales as $T \sim M/R$. We can define a measure
Figure 1. This plot shows a measure of the entropy measured at 10% of the virial radius against cluster gas temperature for a collection of clusters from Ponman et al. 1999. Measuring at this radius makes the results insensitive to any central cooling cusp. The points have a slope which is much flatter than the self-similar $K = T n_e^{-2/3} \sim T$. The solid and dashed lines show the locus of points where the cooling time is equal to the value indicated.

Clearly the results do not agree with the self-similar prediction ($K \sim T$), but do match the locus of points where the cooling time equals the age of the universe (a reasonable stand-in for the age of the cluster). This is consistent with a model in which all the gas that is below this line has cooled and either formed stars or been re-heated by supernovae or AGN. This idea was explored further by Voit & Bryan (2001) and Wu & Xue (2002) who constructed a simple spherically symmetric, hydrostatic model that used the entropy distribution from simulations without cooling, star formation or feedback. As shown by the dash-dot line in figure 2, the resulting $L_X - T$ relation agrees with simulations in which there is no cooling (upper dashed line), but it does not agree with observations. When they excluded the low entropy gas that had a cooling time below the Hubble time (i.e. below the line in figure 1), either by simply removing it, or by shifting the entropy distribution so that no gas was below the critical “cooling” entropy, then the resulting $L_X - T$
G. Bryan and M. Voit

Figure 2. The relation between bolometric X-ray luminosity and luminosity-weighted temperature for samples of observed clusters from Arnaud and Evrard (1999), Markevitch (1998) and Helsdon & Ponman (2000). The dot-dashed line is the predicted relation from a hydrostatic equilibrium model with an unmodified entropy distribution, while the solid and dotted lines are the same model with low entropy material removed or heated, respectively. The assumed cosmological parameters for these models are shown in the upper left. The lower (upper) dashed line is a fit to numerical simulation with (without) radiative cooling from Pierce et al. (2000).

relation matched the observations (and simulations that include cooling), as can be seen by the lower lines in figure 2.

This model does not tell us how the gas was heated, it simply predicts how much of the gas needs to have its entropy modified. In fact, it works equally well if the low entropy gas is simply removed and turned into stars (Bryan 2000); however, in this case the resulting baryon fraction in stars exceeds the observed value (e.g. Balogh et al. 2001).

Although the model reproduces observations it is open to a number of criticisms. One is that it implicitly assumes that the fraction of gas that cools and may be re-heated can be found from the present-day distribution of matter. In hierarchical cluster formation models like the cold dark matter (CDM) one, the cluster is formed out of smaller objects at high redshift, and it is not clear if the fraction at $z = 0$ is representative of the total fraction that would cool over the cluster’s lifetime.

In order to understand the evolution of the gas in clusters better, a number of approaches are possible. One is the construction of analytic models of accretion and shock-heating. For example, these are explored extensively in Voit, Bryan & Balogh (2002) and Voit et al. (2003). Here, on the other hand, we examine what can be learnt about the build-up of clusters through numerical simulations.

*Article submitted to Royal Society*
3. Insight from simulations

We examine a simulation of a typical massive cluster in a cosmological-constant dominated, spatially flat CDM model with a Hubble constant of 70 km s$^{-1}$ Mpc$^{-1}$ and $\Omega = 0.3$ (the ratio of the matter density to the critical density). The simulation was performed with an adaptive-mesh refinement (AMR) technique (Bryan 1999). AMR is a grid-based hydrodynamics method that starts with a uniform mesh and adds additional, finer grids as required to model the collapsing structures. Its strengths are that it can both model shocks well, and provide high spatial resolution in regions of interest. Dark matter is modelled through collisionless particles that interact only via gravity, which is computed with Poisson’s equation using an adaptive particle-mesh technique (O’Shea et al. 2004).

The cluster we examine has a mass of $7 \times 10^{14} M_\odot$, where this virial mass is defined as the mass within a sphere that has a mean density 200 times the critical density. The luminosity-weighted temperature is 5 keV. The dark matter particle mass in the simulation is $m_{dm} = 1.6 \times 10^9 M_\odot$ and there are about 400,000 particles in the virial radius at the final epoch. The highest resolution resolved by the adaptive mesh is 10 kpc. Radiative cooling is turned off.

In order to study the evolution of the gas which ends up in the cluster, we have developed a form of massless test particle that moves with the gas flow. The trajectories of these particles are then time-dependent flow lines through the forming cluster, and we can record the changing conditions along these trajectories. The test particles are laid down on a uniform grid at high redshift when the density distribution is nearly uniform so that each one is a representative sample of fixed mass fraction of the cluster. We show in figure 3 an example of two such trajectories randomly selected from those that end up within the virial radius of the cluster at the final time.

The power-law drop in the density at early times (seen in the plot of the electron density) comes from the expansion of the universe. This is reversed after a few Gyr when the particle feels a significant pull from nearby substructure. Based on the relatively small increase in density seen in this figure, it is likely that the gas associated with these tracer particles is in some sort of filamentary structure or in the outskirts of a virialized halo rather than deep inside a halo.

As the trajectories progress in time, they come to be associated with larger sub-structures and the temperature increases, as does the entropy. In particular, there is a major merger shortly after the 5 Gyr mark which appears as a jump in the entropy of nearly all of the trajectories. This merger is clearly associated with a strong shock which propagates from smaller to larger radii and boosts the entropy of almost all of the gas. Note also the nearly monotonic increase in entropy.† This increase in temperature makes, at first, for a decrease in the cooling time (computed assuming 1/3 solar metallicity). As the temperature grows beyond the cooling peak at $10^5$ K, the cooling time then increases dramatically.

Since the simulation does not include radiative cooling, we gauge whether the local gas will cool and condense into stars as follows. We take the maximum of the cooling time and the local dynamical time $t_{dyn} = (3\pi/16G\rho)^{1/2}$ and divide this by one-half of the age of the universe (at that time). If this fraction is less than 1,

† We are following a massless test particle which is not the same thing as a fluid element, so a local decrease in entropy due to mixing with lower entropy gas is physically possible.

*Article submitted to Royal Society*
catastrophic cooling is likely. Using this measure, we see from the last panel that cooling is not likely to be important for the two trajectories shown in figure 3.

The situation is quite different for the two trajectories shown in figure 4 which shows physical conditions along two flow lines which end up in the center of the cluster (more precisely, within 1% of the virial radius of the center). In this case, the power-law decrease of the density is very quickly reversed as the particles fall into massive halos that form at high-redshift. The associated gas shocks to high temperature and a relatively high entropy level. However, unlike in the previous case, the entropy stays relatively constant after that. Only one of the two trajectories experiences the strong shock associated with the merger at \( t \sim 6 \) Gyr and in this case the density decreases while the temperature is unchanged. This is likely to be associated with some sort of ram-pressure stripping event. Note also that the density and temperature values along the trajectories appear to be noisy while the
gas stays on nearly the same adiabat. This comes from merger-driven turbulence which adiabatically expands and compresses the gas.

The cooling time histories are also different for these trajectories which end up in the center of the cluster, with relatively short cooling and dynamical times throughout. This is due mostly to the high densities encountered. In fact, the later history should not be taken too seriously because as can be seen in the lower-right panel of this figure, the two points cross the critical cooling curve quite early in their history and would be expected to have either formed stars or have been re-heated by supernovae or AGN.

From these two figures we see that gas which ends up in the center of clusters has quite a different history than the rest of the cluster gas. It falls into massive halos very early and will surely have been involved closely with some star formation event at high-redshift.

While it is instructive to examine individual trajectories, we can go beyond this. Because the test particles were laid down uniformly at high redshift they are representative (in a mass-weighted sense) of the distribution of gas which ends up in the cluster. Therefore, we can use their trajectories to create distribution functions.
of gas properties (density, temperature, entropy) as a function of time for gas which will be in the cluster at $z = 0$. As a first step along this road, we have computed the fraction of trajectories which satisfy the “cooled” criterion defined earlier (short cooling and dynamical times). In figure 5, we show, as a solid line, the fraction of particles that have met this criterion at any time in their past, and so would have – in the absence of feedback – cooled to form stars. We also show the instantaneous fraction as a dashed line for comparison. While this second value is obviously less accurate it does provide a roughly similar estimate of the total cooled fraction and, at $z = 0$, corresponds to the fraction of gas below the critical “cooling” entropy calculated in the model in section 2 (see also Voit & Bryan 2001).

In the bottom panels of the same figure, we show the differential of the cooled fraction, which can be interpreted as the cooling rate of the gas. This is shown both
as a function of time and redshift. It is interesting to note that there is a burst of cooling a Gyr or two after the big-bang, followed by a long tail to late times.

4. Discussion

Figure 5 goes a long way to answering the question we posed in the beginning – when does the cooling occur? Clearly the vast majority of cooling (and hence heating if we are not to generate too many stars) must occur before \( z \sim 1 \), which is the epoch of the formation of clusters. Therefore, it seems unlikely that any heating process which depends on having a substantial amount of hot gas can solve both the \( z = 0 \) cooling flow problem and the cluster structure/overcooling problem. In particular, processes involving thermal conduction, turbulence in clusters, or the dissipation of heat in sound waves are disfavoured as solutions for the cluster structure problem.

The peak of the cooling rate is at \( z \sim 3 \) with a long tail to \( z \sim 6 \), which overlaps significantly with the epoch of quasar formation so some other form of AGN jet heating is possible. However, it is not obvious how to couple the heating from AGN to the gas at large redshift. AGN jets are often observed to expand well beyond the halo of hot gas associated with elliptical galaxies and mechanical heating models are problematic if this is the norm. In addition, if the gas actually does cool onto massive halos and is then heated, a great deal of energy is required not only to remove the gas from the potential of the galaxy but also to heat it to the minimum entropy levels seen in figure 1. One way in which these requirements are lessened is if feedback works in tandem with gravitational infall and shocking. If AGN can effectively smooth the gas distribution, then Voit et al. (2003) have shown that the resulting accretion onto clusters generates more entropy than if the accretion was clumpy.

GLB acknowledges support from PPARC grant PPA/G/O/2001/00016 and the Leverhulme foundation.

References

Arnaud, M. & Evrard, A.E., 1999, MNRAS, 305, 631
Balogh, M. L., Pearce, F. R., Bower, R. G., Kay, S.T., 2001, MNRAS, 326, 1228
Bialek, J.J., Evrard, A.E., Mohr, J.J. 2001, ApJ, 555, 597
Bower, R.G., Benson, A.J., Lacey, C.G., Baugh, C.M., Cole, S. & Frenk, C.S. 2001, MNRAS, 325, 497
Brüggen, M. & Kaiser, C. R. 2001 MNRAS, 325, 676
Brüggen, M. & Kaiser, C. R. 2002 Nature 418, 301
Bryan, G.L. & Norman, M.L. 1998 ApJ, 495, 80
Bryan, G. L. 1999 Comp. Sci. Eng., 1:2, 46
Bryan, G.L., 2000, ApJ, 544, L1
Cavaliere, A., Lapi, A. & Menci, N. 2002, ApJ, 581, L1
Churazov, E., Brüggen, M., Kaiser, C. R., Böhringer, H. & Forman, W. 2001 ApJ, 554, 261
Edge, A.C. & Stewart, G.C. 1991, MNRAS, 252, 414
Evrard, A. E., & Henry, J. P. 1991, ApJ, 383, 95
Fabian, A. C. et al. 2000 MNRAS, 318, L65

Article submitted to Royal Society
Fabian, A.C. 2003, Galaxy Evolution: Theory & Observations (Eds. Vladimir Avila-Reese, Claudio Firmani, Carlos S. Frenk & Christine Allen) Revista Mexicana de Astronomia y Astrofisica (Serie de Conferencias) Vol. 17, pp. 303-313

Finoguenov, A., David, L.P. & Ponman, T.J. 2000, ApJ, 544, 188

Helsdon, S.F. & Ponman, T.J., 2000, MNRAS, 315, 356

Kaiser, N. 1991, ApJ, 383, 104

Kim, W.-T. & Narayan, R. 2003, ApJ, 596, L139

Markevitch, M. 1998, ApJ, 504, 27

McNamara, B. et al. 2001 ApJ, 562, L149

Mazzotta, P. et al. 2002 ApJ, 567, 37

Omma, H., Binney, J., Bryan, G.L. & Slyz, A. 2004 MNRAS, 348, 1105

O'Shea, B.W., Bryan, G., Bordner, J., Norman, M.L., Abel, T., Harkness, R., Kritsuk, A. to appear in “Adaptive Mesh Refinement - Theory and Applications”, 2004, Eds. T. Plewa, T. Linde & V. G. Weirs, Springer Lecture Notes in Computational Science and Engineering

Pierce, F. R., Thomas, P.A., Couchman, H.M.P., & Edge, A.C.; 2000, MNRAS, 317, 1029

Ponman, T.J., Cannon, D.B., and Navarro, J.F., 1999, Nature, 397, 135

Ponman, T.J., Sanderson, A.J.R. and Finoguenov, A. 2003, MNRAS343, 331

Pratt, G.W., and Arnaud, M., 2003, Astron. Astroph. 408, 1

Reynolds, C.S., McKernan, B., Fabian, A.C., Stone, J.M. & Vernaleo, C. 2004, MNRAS, submitted (astro-ph/0402632)

Tozzi, P. & Norman, C., 2001, ApJ, 546, 63

Voit, G.M., Bryan, G.L. 2001, Nature, 414, 425

Voit, G. M. Balogh, M. L., Bower, R. G., Lacey, C. G., Bryan, G. L. 2003, ApJ, 593, 272

Voit, G. M. Bryan, G. L., Balogh, M. L., Bower, R. G. 2002, ApJ, 576, 601

Wu, K.K.S., Fabian, A.C. & Nulsen, P.E.J., 2001, MNRAS, 324, 95

Wu, X., Xue, Y., 2002, ApJ, 572, L19.