On conduction, cooling flows and galaxy formation

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ABSTRACT
On the basis of the universal gas fraction in clusters of galaxies, we estimate that the effective thermal conductivity required to balance radiative cooling in the cores, where the gas temperature is 3–10 keV, is about one tenth of the Spitzer rate. This confirms that thermal conduction can be important for the energy balance provided that it is not highly suppressed by magnetic fields in the gas. We determine the global effective conductivity in a sample of 29 clusters using published X-ray data on the inferred cooling rates and show that most lie between one and one tenth of the Spitzer rate. More work on the profiles in cooling flow clusters is required to test the conduction hypothesis further. We examine the possibility that conduction operates during galaxy formation, and show that it provides a simple explanation for the upper-mass cutoff in galaxy masses.

Key words: galaxies: clusters – cooling flows – X-rays: galaxies – conduction

1 INTRODUCTION
Recent X-ray data on the cores of clusters of galaxies from XMM-Newton and Chandra indicate that some heat flux must be balancing the radiative cooling losses of the gas (Peterson et al. 2001; Tamura et al. 2001; Fabian et al. 2001; Johnstone et al. 2002, Böhringer et al. 2002; McNamara et al. 2001; Nulsen et al. 2002). The source of heat is unclear, with the central radio source being one possibility (Churazov et al. 2002; Brüggen & Kaiser 2001; Reynolds et al. 2002) and conduction being another (Narayan & Medvedev 2001; Gruzinov 2002; Voigt et al. 2002). Here we examine conduction and its consequences in more detail.

The observations show that large temperature drops, by a factor of three or more, are common close to the centre of clusters. Thermal conduction is therefore an obvious heat transport process. The question is one of the level of conductivity and whether it can be high enough to balance radiative losses, and also whether it can do so in a stable manner over the long time-scales required. For a highly ionized plasma such as the intracluster medium the maximum rate is expected to be that calculated by Spitzer (1962), which we hereafter refer to as Spitzer conductivity with coefficient \( \kappa_S \). Magnetic fields in the plasma should suppress the conductivity by some factor \( f \) so that \( \kappa = f \kappa_S \). The value of \( f \) is not clear, but could be as high as one third for a tangled field (see Narayan & Medvedev 2001 and Malyshkin 2001 and references therein). Suppression should be very high across field lines and appears to be high across the very abrupt temperature drops known as cold fronts found in some clusters (Ettori & Fabian 2000; Markevich et al. 2000; Vikhlinin et al. 2001).

In Section 2 we show that the level of conductivity required to balance radiative cooling in the core of a cluster, where the radiative cooling time is less than the age of the Universe, is less than \( \kappa_S \). This means that if conduction is unimpeded then it can balance radiation. We then compare this result with an effective conductivity from observations, determined by

\[
\kappa_{\text{eff}} = \frac{L(< r)}{4\pi r^2 \frac{dT}{dr}},
\]

where \( L \) is the total luminosity within radius \( r \) at which the temperature gradient \( dT/dr \) is inferred. The sample used is from the brightest 55 in the sky studied using ROSAT data by Peres et al. (1998), supplemented by some luminous clusters from the sample of Allen (2000). We choose objects with known central emission-line nebulosities, indicating probable large temperature drops in the gas.

If thermal conduction (i.e. electron motion) is relatively unimpeded in a radial direction, this forces us to consider that ion motion might not be as restricted as normally assumed. In other words, sedimentation of heavy ions is a possibility, with implications which we consider in Section 3.

Finally we discuss the influence of conduction on galaxy formation, showing that it cannot balance cooling in small-to-medium mass galaxies but can have a significant effect on massive galaxies. It may therefore be responsible for the high-mass cutoff to galaxy masses.

2 THE EFFECTIVE CONDUCTIVITY \( \kappa_{\text{eff}} \)
Consider the gas in the core of a cluster. Within radius \( r \) gas is radiatively emitting energy at a rate \( L \) leading to a decreasing temperature unless heat is supplied at a similar rate, which for conductivity means \( L = 4\pi r^2 \kappa \frac{dT}{dr} \). Ignoring a small factor which depends on the density gradients within that radius, and approximating \( dT/dr \)
as \( aT/r \) (i.e. \( T \propto r^a \)), the effective conductivity required is

\[
\kappa_{\text{eff}} \approx \frac{n_e^2 A r^2}{3a}.
\]

(2)

\( \Lambda \) is the radiative cooling function and \( n_e \) is the r.m.s. electron density within \( r \). Now, the radiative cooling time is given by

\[
t_{\text{cool}} \approx \frac{3}{2} n k T / n_e^2 \Lambda
\]

(3)

where \( n \) is the gas density, and so

\[
\kappa_{\text{eff}} \approx \frac{n k r^2}{2a t_{\text{cool}}}.
\]

(4)

From the virial theorem, \( GM/r \approx kT/m \), where \( m \) is the mean molecular weight, so for a gas mass fraction \( f_{\text{gas}} \) we have

\[
\kappa_{\text{eff}} = \frac{f_{\text{gas}} k^2 T}{8 m^2 G a t_{\text{cool}}}.
\]

(5)

As we shall see, for typical cluster parameters this is less than, but reasonably close to, \( \kappa_{S} \).

We next consider the effective conductivity required by data, \( \kappa_{\text{eff}} \), for a sample of cooling flow clusters drawn from the study of Peres et al. (1998). We use those objects for which optical emission lines have been detected from the central cluster galaxy, indicating that some gas has cooled out there. Peres et al. (1998) tabulate \( L(<r_{\text{cool}}) \), where \( r_{\text{cool}} \) is the radius at which \( t_{\text{cool}} = \frac{4}{3} r_0^{-1} = 13 \) Gyr, as well as the outer (wide-beam) temperature of each cluster. Assuming that \( dT/dr = 0.4T/r \), which is appropriate for conduction balancing bremsstrahlung cooling above \( \sim 2 \) keV in a spherical, constant pressure cluster (Fabian et al. 1994), and is also a reasonable fit to observed temperature gradients, we plot in Fig. 1

\[
\kappa_{\text{eff}} = \frac{L(<r_{\text{cool}})}{1.6 \pi r_{\text{cool}}^2 T / r_{\text{cool}}}.
\]

(6)

The sample has been supplemented to a total of 29 by some massive clusters from the work of Allen (2000), where the integrated mass deposition rate within the cooling radius is again calculated from imaging data (we use IRAS 09104+4109, Abell 963, Zwicky 3146, Abell 1068, RXJ1347.5, Abell 1835, MS2137.3-2353, Abell 2390 and MS 1455.0+223). All exhibit optical emission lines. Where the measured temperature of the cluster is greater than 10 keV, the value is taken from Allen et al. (2001).

The bolometric luminosity emitted from within the cooling radius is calculated from

\[
L(<r_{\text{cool}}) = \frac{5 k T}{m} M
\]

(7)

where a factor of 2 is used to take into account the change in gravitational potential energy of the inflowing mass which is assumed in the estimates of Allen (2000).

Fig. 1 shows that most cooling flow clusters have \( \kappa_{\text{eff}}^p \) between \( \kappa_{S} \) and \( \kappa_{S}/10 \). Conduction may therefore be important, as noted by Narayan & Medvedev (2001) and Gruzinov (2002). Our inclusion of the relation from Equation 5, however, shows that all clusters where the central cooling time is less than a Hubble time and which have the universal gas fraction must lie in this region too. It may, therefore, be a coincidence that \( \kappa_{\text{eff}}^p \) for clusters is close to \( \kappa_{S} \).

Conversely, the results of Equation 5 indicate that clusters lie in an interesting regime, where conduction is potentially very effective, if it operates. Simple global estimates like those plotted in Fig. 1, however, are poor diagnostics as to whether conduction is actually taking place. Detailed study of the temperature profiles is required to determine whether conduction is important or not. We have begun such tests using Chandra data on cluster cores (Voigt et al. 2002), which supports conduction being an important factor in the energy flow from about 100 kpc into the innermost 20 kpc. Within the smaller radius, cooling may dominate and lead to the observed optical nebulosities and star formation.

Loeb (2002) has noted that if conduction operates at the Spitzer rate throughout clusters and beyond, they would leak their thermal energy into the surrounding intergalactic medium. Therefore Spitzer rate conduction may be restricted to a cluster core. Perhaps the formation of a cooling flow and consequent gas infall leads to magnetic field reconnection and reordering and to a more radial field (Soker & Sarazin 1990) which then allows conduction to become important (a possibility mentioned by Bregman & David 1989). In other words the cooling flow produces the conditions which allow conduction to operate.

3 IMPLICATIONS FOR SEDIMENTATION

We note that if thermal conduction is uninhibited by magnetic fields then so may be sedimentation within the cluster core. This could occur if, for example, a significant fraction of the magnetic fields were radial. Basically this means that ions heavier than protons will accumulate towards the centre relative to hydrogen. Although iron may therefore accumulate (Fabian & Pringle 1977) the effect is more important for helium nuclei (Gilfanov & Sunyaev 1984). Calculations have recently been performed for a Navarro, Frenk & White (1997) potential by Qin & Wu (2000). The abundance gradients seen in iron, and some other elements, in some cluster cores (Fukazawa et al. 1994; Ezawa et al. 1997, De Grandi & Molendi 2001; Sanders & Fabian 2002; Johnstone et al. 2002) may therefore be partly accounted for.

If helium does undergo sedimentation, then the inferred gas density in the central cooling regions is reduced. Any stars formed from cooled gas will be helium rich and so have short mainsequence lifetimes (Lynden-Bell 1967). Such a radical possibility would imply significant increases in the star formation rate associated with the observed distributed blue light (Johnstone, Fabian et al. 2000).
& Nulsen 1987; Allen 1995; Cardiel et al. 1998; Crawford et al. 1999). This will be studied further in later work.

We note that if conduction is suppressed then so will be sedimentation, but if conduction is balancing cooling then sedimentation does not necessarily operate, unless the field lines are essentially radial.

4 GALAXY FORMATION

Most models for galaxy formation are based on gas falling into dark matter potential wells, being heated and then cooling radiatively to form stars (e.g. White & Frenk 1991). For massive galaxies the cooling process resembles a cooling flow since the gas does not cool immediately but forms a slowly cooling and settling atmosphere. A problem arises then in that there is no simple upper mass limit to a galaxy, and a supermassive galaxy could in principle form at the centre of a cluster as a result of a massive cooling flow. In practice, the models assume that visible stars do not form in potentials above some mass (e.g. Kauffmann et al. 1999). We now investigate the effect of conduction on this cooling process.

Following the models of White & Frenk (1991) and Kauffmann et al. (1999) we adopt a simple isothermal distribution for the dark matter and give the gas a similar density distribution:

\[ n_0 \approx \frac{f_{gas} M_0}{8 \pi r_0^3 \Omega m^2}. \tag{8} \]

where \( M_0 \) is the total mass within radius \( r_0 \). The luminosity within \( r_0 \) is then

\[ L = \frac{f_{gas}^2 M_0^2 \Lambda}{32 \pi r_0^5 \Omega m^2}. \tag{9} \]

We have assumed that gas extends only in to a radius of two thirds \( r_0 \) in order that the luminosity is not dominated by an unphysical central cusp. (We justify this factor from the expression for the cooling rate in the models of Kauffmann et al. 1999 of

\[ \dot{M} = 4 \pi n m r_c^2 \frac{dr_c}{dt}, \]

where \( r_c \) being the cooling radius at time \( t \), which with \( L = \frac{1}{2} c^2 k T \) gives the above value.)

Setting

\[ M_0 = \frac{k T r_0}{G \dot{\Lambda}} \tag{10} \]

from the virial theorem, and balancing \( L \) by a conductive flux gives

\[ \frac{f_{gas}^2 \Lambda}{32 \pi r_0^3 \Omega m^2} \left( \frac{k T}{G} \right)^2 = 4 \pi r_0^2 r \frac{dT}{dr}. \tag{11} \]

Let \( dT/dr = aT/r, \kappa = \kappa_\Lambda T^{5/2} \) and for bremsstrahlung \( \Lambda = \Lambda_0 T^{1/2} \) then

\[ T = \left( \frac{f_{gas}^2 \Lambda_0 k^2}{8 (4 \pi)^2 \kappa_\Lambda m^2 G^2 a} \right)^{2/3}. \tag{12} \]

This is approximately

\[ T \approx 6 \times 10^7 \left( \frac{r}{30 \text{kpc}} \right)^{-2} \left( \frac{f}{0.1} \right)^2 \text{K}. \tag{13} \]

If cooling by metals is important \( (T \lesssim 10^7 \text{K}) \) then \( \Lambda = \Lambda_m \) and

\[ T = \left( \frac{f^2 \Lambda_m k^2}{8 (4 \pi)^2 \kappa_\Lambda m^2 G^2 a} \right)^{2/3}. \tag{14} \]

so

\[ T \approx 3 \times 10^7 \left( \frac{r}{30 \text{kpc}} \right)^{-4/3} \left( \frac{f}{0.1} \right)^{4/3} \text{K}. \tag{15} \]

These constraints are shown in Fig. 2. \( \Lambda_m \) has been taken to be \( 10^{-23} \text{erg cm}^3 \text{s}^{-1} \) and \( \kappa_\Lambda = 5 \times 10^{-7} \text{erg cm}^{-1} \text{s}^{-1} \text{K}^{-3.5} \).

We parametrize the gas fraction here as \( f = 0.1 \); the fraction drops as stars form, or have formed at earlier stages. Above the solid line, conduction can overwhelm radiative cooling and below, cooling dominates. Dotted lines of constant mass from the virial theorem, and balancing \( L \) by a conductive flux gives

\[ \frac{f_{gas}^2 \Lambda}{32 \pi r_0^3 \Omega m^2} \left( \frac{k T}{G} \right)^2 = 4 \pi r_0^2 r \frac{dT}{dr}. \tag{11} \]

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350 km s$^{-1}$ (which corresponds to a temperature of about $10^7$ K) does not form visible stars.

Conduction provides a simple explanation for the upper-mass cutoff in galaxy formation. Something must be suppressing continued cooling in massive haloes and conduction close to the Spitzer rate should become effective in the required mass range. If the alternative is heating by a central black hole, then it is not obvious why this becomes effective in massive galaxies, where the atmosphere is most extensive, and does not dominate in lower mass ones.

5 DISCUSSION

The level of conductivity required to balance radiative cooling at the cooling radius in most of the cores of 29 cooling flow clusters lies within an order of magnitude of the Spitzer rate. This need not indicate that conduction is operating but may merely be a coincidence, given the age of the Universe and the universal gas fraction. The detailed shape of the temperature profile and a comparison with conduction models may be required to test whether conduction is a significant factor in suppressing cooling flows, Essentially, Fig. 1 just shows that it is energetically feasible for conduction to play a significant role in cluster cores.

The total energy required to suppress a flow can be considerable. We plot this energy, determined from $L(< r_{\text{cool}})t$, in Fig. 3. In the diagram $t$ is the age of the Universe, and may be reduced by a factor of a few, but the energy is nevertheless large. Whatever the heat source, it is to be among the major heat flows in the Universe. If accretion onto the central black hole is responsible, with the energy flowing out in jets (see e.g. Churazov et al. 2002, and references therein), then assuming an efficiency of 0.1 of the accreted rest mass, the accumulated black hole masses lie between about $10^{9}$ and $10^{10}$ $M_\odot$, varying inversely with the assumed efficiency. This is often taken as the radiative efficiency of accretion, but it is likely to be significantly smaller for the total jet power dissipated in ions. This may more than counterbalance the likely factor of a few overestimate for the cluster age (say 5 Gyr rather than the 13 Gyr assumed). We therefore consider that the masses indicated are lower limits for this process.

Determining the extent to which conduction operates in cluster cores from observation will be difficult. Cold fronts indicate that it is suppressed at least locally in some situations. The reasonable agreement over a range of radii which we found in a study of the $\kappa_{\text{eff}}$ profile in two clusters (Voigt et al. 2002) is good supporting evidence for conduction operating in general. Work is in progress to study more clusters. Of great importance is the magnetic field structure and its connectedness. If the intracluster medium consists of many separate small magnetic structures then large scale conduction would be inhibited except where reconnection allows structures to merge. Faraday rotation studies indicate in some objects that the fields have coherence scales of a few kpc (Carilli & Taylor 2002 and references therein). The temperature profiles of clusters so far appear to be smooth on the scales studied, although projection effects are important, and observational exposures generally not long enough to probe subtle variations. In some objects (e.g. the Perseus cluster, Fabian et al. 2000; and the Centaurus cluster, Sanders & Fabian 2002) spiral-like X-ray structures are seen which could reflect changes in conductivity associated with magnetic field structure.

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