Limits on thermal conduction in galaxy clusters

Mikhail V. Medvedev$^{1,4}$, Adrian L. Melott$^{1,5}$, Chris Miller$^{2,6}$, Donald Horner$^{3,7}$

ABSTRACT

We have calculated lower limits for the global effective thermal conductivity in a sample of 165 Abell clusters. We assumed that cluster X-ray luminosity is compensated by a conductive heat flux which we then compare with an upper limit to the temperature gradient inferred from the cluster temperature and radius. This gives a lower limit to the thermal conductivity and therefore to the relative suppression from the Spitzer conductivity, $\kappa_{Sp}$. Not a single cluster requires super-Spitzer values of thermal conduction to balance the observed X-ray luminosity. The suppression coefficient $f = \kappa / \kappa_{Sp}$ is clustered in a range $10^{-2} < f < 0.4$. A weak dependence of $f$ versus $z$ is observed over $0 < z < 0.41$. Possible biases and/or selection effects are discussed.

Subject headings: galaxies: clusters: general — conduction

1. Introduction

For some time it has been believed that the strong excess of X-ray emission in the cores of many galaxy clusters represents a solid evidence of radiatively cooling gas which is in near hydrostatic equilibrium with a surrounding medium. As the cooling time of the core gas is rather short, a gentle inward flow of gas should replenish the cooled gas presumably condensing out. Fabian (1994) contains a review of this picture.

This conventional paradigm of cooling flows turned out to be grossly inconsistent with recent X-ray data on the central regions in galaxy clusters from XMM-Newton and Chandra (Tamura at al. 2001; Fabian et al. 2001; Böhringer et al. 2001; Peterson et al. 2002), which failed to find multi-temperature gas one expects in a cooling flow model. One of the possible explanations, —

$^1$Department of Physics and Astronomy, University of Kansas, Lawrence, KS 66045
$^2$Department of Physics and Astronomy, Carnegie Mellon University, Pittsburgh, PA 15213
$^3$Space Telescope Science Institute, Baltimore, MD 21218
$^4$medvedev@ku.edu
$^5$melott@kusmos.phsx.ukans.edu
$^6$chrism@cmu.edu
$^7$horner@stsci.edu
extra heating via thermal conduction flux — was proposed by Narayan & Medvedev (2001). This mechanism requires sufficiently high values of the thermal conductivity, close to the Spitzer limit. Thus, magnetic fields permeating hot cluster gas may not suppress conductivity by a large factor. Theoretical considerations and numerical simulations of conduction in a turbulent gas agree that the suppression factor, \( f = \kappa / \kappa_{Sp} \), is near unity, typically around 1/3 (Narayan & Medvedev 2001; Malyshkin & Kulsrud 2001; Cho et al. 2003). There is an indication that intermittency in turbulence (if present) may decrease \( f \) by an additional factor of few to ten (Chandran & Maron 2003).

The idea of conduction-heated intra-cluster gas has been tested using some available cluster data (Voigt et al. 2002; Fabian et al. 2002; Zakamska & Narayan 2003). The inferred suppression factor was typically in the range \( 1 < f < 1/10 \), being consistent with the theoretical predictions. In the present paper we perform similar analysis using a much larger sample of cluster data.

2. The sample

We use a sample of 165 Abell clusters (Abell 1958; Abell et al. 1989) with archived ASCA observations. The clusters cover a wide range of richnesses \( 0 \leq R \leq 3 \), redshifts \( 0.02 \leq z \leq 0.41 \) and bolometric luminosities \( 10^{43} \) to \( 10^{46} \) ergs/s for \( H_0 = 50 \) km/s/Mpc). The data were analyzed in semi-automated fashion and the cluster temperatures were determined via spectral fits to the available ASCA data. We fit the spectra with a single temperature MEKAL plasma model using XSPEC. All four ASCA instruments (2 GIS + 2 SIS) were fit simultaneously with the model parameters for each fit constrained to be the same, except for the relative normalizations and the hydrogen column density. The column density was fixed at the Galactic value for the GIS since it is relatively insensitive below 1 keV but left as a free parameter for the SIS since radiation damage to the CCDs manifests itself as spuriously high column densities. For more information about the sample and the analysis, see Horner et al. (2003).

The temperatures were determined for broad-band (0.8-10.0 keV) fluxes measured within a specified extraction radius. The extraction radius was an estimate of the level at which the count rate rises to about 5 sigma above the background level. Note that this is the GIS extraction radius. The SIS extraction radius was chosen to be 0.72 times the GIS radius since the SIS has a smaller PSF and empirical tests showed that this resulted in a similar signal-to-noise ratio for the SIS data. A comparison between our temperatures and those obtained from independent measurements and presented in the literature shows excellent agreement. The temperatures derived for such clusters are generally agree very well with other isothermal fits, usually within about 10%. X-ray luminosities are bolometric, i.e., they are estimated from the best fit model over the 0.01-50 keV range. The luminosities that we derive for the ASCA catalog agree well with luminosities from
ROSAT survey like the BCS or NORAS with a scatter about the mean of about 25%.

This cluster sample cannot be considered complete. The use of ASCA data puts some physical constraints on the types of clusters we have analyzed. For instance, the sensitivity of ASCA was such that no clusters with $T < 5$ keV are expected above $z \sim 0.4$. Likewise, the size of the ASCA observing area prohibits the measurement of large (and usually high temperature) clusters that are nearby. At best, this sample can be considered a heterogeneous sampling of the Abell catalog.

As with any cluster sample, the Abell cluster catalog suffers from projection effects and incompletenesses. The purity of are sample is not an issue for this analysis, since all of our clusters have Xray and galaxy redshift information (to ensure the reality of the systems). In terms of completeness, we have decided to use only Abell clusters as their redshift and richness distributions are well studied in the literature (Peacock & West 1992; Postman et al. 1992; Ebeling et al. 1996; Jones & Forman 1999; Miller et al. 1999, 2002, among others).

We use the following cluster parameters available: the cluster redshift, $z$, the bolometric X-ray luminosity, $L_X$, the temperature with 90% confidence limits, $T$, $T_{lo}$, $T_{hi}$, and the extraction radius used for the spectrum fits, $R_{ext}$.

3. The method

To estimate thermal conduction we use the following method: We assume that the cluster medium is static and is in thermal equilibrium, that is cooling of gas via Bremsstrahlung emission is compensated by the conductive flux of heat from outer parts of the cluster:

$$L(< r) = 4\pi r^2 \kappa \frac{dT}{dr},$$

where $L(< r)$ is the total luminosity within radius $r$. We assume that $L \simeq L_X$. For this sample we have no measurements of the temperature gradients. Therefore we use $R_{ext}$ to estimate it. The gradient scale may be larger or comparable to $R_{ext}$. This implies an upper limit to the temperature gradient, and accordingly a lower limit on the conductivity. Indeed, the larger the conduction, the closer the cluster to being isothermal and, hence, the smaller the temperature gradient. We use the following approximation to estimate the temperature gradient:

$$\frac{dT}{dr} \approx 0.4 \frac{T}{R_{ext}}.$$

Here the factor 0.4 is an empirical factor obtained from clusters with high spatial resolution to ensure reasonable fits to the observed temperature gradients (Fabian 1994; Fabian et al. 2002). Note that since the numerical factor is smaller than unity, we obtain a more conservative lower limit.
limit on the effective $\kappa$. A similar technique has been used by Voigt et al. (2002) and Fabian et al. (2002) for smaller samples. Note that an upper limit to the temperature gradient will imply a lower limit on the thermal conductivity necessary to balance the energy losses due to the X-ray emission.

Finally, we calculate the suppression coefficient as

$$f = \frac{\kappa}{\kappa_{Sp}}$$

obtained from eqs. (1) and (2), and $\kappa_{Sp} = 8.2 \times 10^{20}T_1^{5/2}$ erg/cm/s/keV is the Spitzer thermal conductivity, and $T_1 = T/(10$ keV). We estimated error-bars using $T_{lo}$ and $T_{hi}$ in place of $T$.

4. Results

The result is shown in Fig. 1. Suppression coefficients greater than unity would mean that thermal conduction is insufficient to balance radiative cooling; this sets a global constraint: $f < 1$. In a static gas (i.e., without strong turbulent motions) with tangled magnetic fields, the constraint is more stringent, $f \leq 1/3$ (Narayan & Medvedev 2001). Apparently, not a single cluster violates the first one and only three violate the second one at the statistically significant level ($> 90\%$).

The values of $f$ are clustered in the range $10^{-2} < f < 0.4$.

We examined the distribution of $f$ against $z$. We found a mild redshift dependence of $f$ over the range $0 < z < 0.41$, the slope is $-0.17 \pm 0.03$. This result may however be affected by several biases and selection effects. More distant clusters in the sample (i) tend to have larger $R_{ext}$, (ii) are more luminous, (iii) hence, have higher gas temperatures. The lack of strong $z$-dependence in our inferred values of $f$ may be interpreted as additional support for the hypothesis that cool cores are heated by thermal conductivity.

5. Discussion

Our lower limits on thermal conduction suppression are of course dependent on the assumption that the X-ray emission in the core is approximately balanced by heat flow from the surrounding medium. Of course, other explanations are possible, such as localized heating by compact objects in the cluster core. Therefore our results should be interpreted as a feasibility study for the thermal conductivity scenario.

Recently, numerical simulations with cooling (Motl et al. 2003) have been presented which suggest “cool cores” form in a complex, time-dependent merger process and do not require a steady flow. This view is further supported by Loken, Melott, & Miller (1999), who found that such objects lie preferentially in clusters with a high density supercluster environment, specifically having other clusters in high proximity. Such an environment would be expected to enhance the merger rate.
Motl et al. (2003) comment that their cluster temperature profiles are too steep (the cores too cool). Since the cooling timescale is considerably shorter than the time between major mergers, thermal conductivity should help resolve this discrepancy.

It has been believed (based on results from ordered magnetic fields) that thermal conductivity is too weak to prevent runaway cooling and formation of bright, small-scale X-ray emitting regions in the cores of galaxy clusters. The proposal of Narayan & Medvedev (2001), for enhanced thermal conductivity in the presence of tangled magnetic fields is consistent with the large data set studied here. The data do not seem to require heat transport by strong turbulent motion, reconnection and turbulent resistivity, as proposed by Chandran & Maron (2003). The inclusion of thermal conductivity in numerical simulations of galaxy cluster formation should be given a high priority in order to realistically model the inner regions.

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REFERENCES

Abell, G. O. 1958, ApJS, 3, 211
Abell, G. O., Corwin, H. G., & Olowin, R. P. 1989, ApJS, 70, 1
Böhringer, H., et al. 2001, A&A, 365, L181
Chandran, B. D. G., & Maron, J. 2003, astro-ph/0303214
Cho, J., Lazarian, A., Honein, A., Knaepen, B., Kassinos, S., & Moin, P. 2003, astro-ph/0302503
Ebeling, H., Voges, W., Bohringer, H., Edge, A. C., Huchra, J. P., & Briel, U. G. 1996, MNRAS, 281, 799
Fabian, A. C. 1994, ARA&A, 32, 277
Fabian, A. C., Mushotzky, R. F., Nulsen, P. E. J., & Peterson, J. R. 2001, MNRAS, 321, L20
Fabian, A. C., Voigt, L. M., & Morris, R. G. 2002, astro-ph/0206437
Jones, C., & Forman, W. 1999, ApJ, 511, 65
Horner, D.J., Baumgartner, W.H., Gendreau, K.C., & Mushotzky, R.F. 2003, ApJS, submitted.
Loken, C., Melott, A.L., & Miller, C.J. 1999, ApJ, 520, L5
Malyshkin, L., & Kulsrud, R. 2001, ApJ, 549, 402
Miller, C., Batuski, D., Slinglend, K., & Hill, J. 1999, ApJ, 523, 492
Miller, C. J., Krughoff, K. S., Batuski, D. J., & Hill, J. M. 2002, AJ, 124, 1918
Motl, P.M., Burns, J.O., Loken, C., Norman, M.L., & Bryan, G. 2003, astro-ph/0302427
Narayan, R., & Medvedev, M. V. 2001, ApJ, 562, L129
Peacock, J., & West, M. 1992, MNRAS, 259, 494
Peterson, J. R., et al. 2002, astro-ph/0210662
Postman, M., Huchra, M., & Geller, M. 1992, ApJ, 384, 404
Tamura, T., et al. 2001, A&A, 365, L87
Voigt, L. M., Schmidt, R. W., Fabian, A. C., Allen, S. W., & Johnstone, R. M. 2002, MNRAS, 335, L7
Zakamska, N., & Narayan, R. 2003, ApJ, 582, 162
Fig. 1.— Suppression factors of thermal conduction in 165 Abell clusters as a function of redshift. Error bars result from 90% confidence limits on $T$. Errors in $z$ are negligible for this purpose.