Chandra constraints on the thermal conduction in the intracluster plasma of A2142

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1 INTRODUCTION

The heat stored in the intracluster plasma is conducted down any temperature gradient present in the gas in a way that can be described through the following equations (Spitzer 1956, Sarazin 1988):

\[ q = \kappa \frac{d(kT_e)}{dr} \]

where \( q \) is the heat flux, \( T_e \) is the electron temperature, and \( \kappa \) is the thermal conductivity that can be expressed in terms of the density, \( n_e \), the electron mass, \( m_e \), and the electron mean free path, \( \lambda_e \), as (Cowie and McKee 1977)

\[ \kappa = 1.31 n_e \lambda_e \left( \frac{kT_e}{m_e} \right)^{1/2}. \]

In a fully ionized gas of (mostly) hydrogen, the electron mean free path is function of the gas temperature, density and impact parameters of the Coulomb collisions, \( \Lambda \):

\[ \lambda_e = 30.2 T^2 n^{-1} \left( \frac{\ln \Lambda}{37.9 + \ln \left( T/11^{1/2} \right)} \right)^{-1} \text{ kpc}, \]

where we have adopted the following dimensionless quantities:

\[ T = \left( \frac{kT_e}{10 \text{ keV}} \right), \quad n = \left( \frac{n_e}{10^{-3} \text{ cm}^{-3}} \right). \]

Using this expression and the adopted typical values for cluster plasma, we can then write

\[ \kappa = 8.2 \times 10^{20} T^{5/2} \text{ erg s}^{-1} \text{ cm}^{-1} \text{ keV}^{-1}. \]

If the mean electron free path is comparable to the scale length \( \delta r \) of the temperature gradient, the heat flux tends to saturate to the limiting value which may be carried by the electrons (Cowie and McKee 1977):

\[ q_{\text{sat}} = 0.42 \left( \frac{2kT_e}{\pi m_e} \right)^{1/2} n_e kT_e. \]

In this Letter, we use the recent Chandra observation of Abell 2142 reported by Markevitch et al. to put constraints on thermal conduction in the intracluster plasma. We show that the observed sharp temperature gradient requires that classical conductivity has to be reduced at least by a factor of between 250 and 2500. The result provides a direct constraint on an important physical process relevant to the gas in the cores of clusters of galaxies.

Key words: X-ray: galaxies – galaxies: clusters: general – galaxies: clusters: individual: A2142

2 THERMAL CONDUCTIVITY IN A2142

Markevitch et al. (2000) have analyzed the Chandra observation of the merging cluster of galaxies A2142 and made an important discovery. The X-ray image reveals of sharp edges to the surface brightness of the central elliptical-shaped region. The edges are located about 3 arcmin to the northwest and 1 arcmin to the south with respect to the X-ray centre. Markevitch et al (2000) have analyzed the Chandra observation of the merging cluster of galaxies A2142 from their Figure 4, together with the equations presented in our Introduction, we can estimate whether thermal conductivity is efficient in erasing the observed temperature gradient.

The electron temperature (panel b in their Fig. 4) varies from 5.8 to 10.6 keV on either side of the boundary of the southern edge of the central bright patch in A2142, and from 7.5 to 13.8 keV at the northern edge. The relative uncertainties on these values are about 20 per cent at the 90 per cent confidence level. The electron density (panel d in their Fig. 4) at the edges is \( \sim 1.2 \times 10^{-2} \text{ cm}^{-3} \), \( 3.0 \times 10^{-3} \text{ cm}^{-3} \) to the South and North, respectively.

The scale length \( \delta r \) on which this temperature gradient is observed is spatially unresolved in the temperature profile and ap-
pears enclosed between 0 and 35 kpc ($H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$) for the Southern edge, $0$–$70$ kpc for the Northern edge. However, the surface brightness profiles (panel c) show a radially discontinuous derivative at the positions of the sharp edges, on scales of about $10$–$15$ kpc. We adopt hereafter these values as representative of $\delta r$, using the larger values only for upper limit purposes.

The case for a saturated flux is reached when these scales are comparable with the electron mean free path of about 2 and 12 kpc for the Southern and Northern edge, respectively, calculated using the temperature and density estimates in eqn. 3.

Therefore, we will consider hereafter the two extreme cases where (i) $\delta r \gg \lambda_e$ and the heat flux is un-saturated, (ii) $\delta r \approx \lambda_e$ and the heat flux is saturated and represented by eqn. 4.

The maximum heat flux in a plasma is given by

$$q = \frac{3}{2} n_e k T_e \bar{v},$$

where $\bar{v} = d\tau / d\tau$ is a characteristic velocity that we are now able to constrain equalizing the latter equation to eqn. 3.

In particular, given the observed values (and relative errors) of density and temperature across the two edges and $\delta r$ of (i: non-saturated flux) 10 and 20 kpc (upper limits: 35 and 70 kpc for the edges to South and North, respectively) and (ii: saturated flux) $\sim \lambda_e$, the characteristic time, $\delta \tau$, required to erase the electron temperature gradient and due to the action of the thermal conduction alone would be:

$$\delta \tau = \frac{\delta r}{\bar{v}} = \begin{cases} 3.6 \times 10^4 \text{yrs}, & \delta r \gg 2 \text{kpc} \\ 0.3 \times 10^4 \text{yrs}, & \delta r \approx 2 \text{kpc} \end{cases}$$

for the Southern edge, and

$$\delta \tau = \frac{\delta r}{\bar{v}} = \begin{cases} 2.4 \times 10^4 \text{yrs}, & \delta r \gg 12 \text{kpc} \\ 1.9 \times 10^4 \text{yrs}, & \delta r \approx 12 \text{kpc} \end{cases}$$

for the Northern edge. The upper limits are obtained propagating the uncertainties on the temperature and, for the “$\delta r \gg \lambda_e$” condition only, assuming the spatial resolution of the temperature profile as indicative of the length of the gradient. Here we note that the limit on the timescale for saturated flux is the minimum value given the condition of the gas. Any value of $\delta t$ estimated on scales considerably larger than the electron mean free path has to be longer than the limit for saturated flux (also significantly, given that the timescale is proportional to $\delta r^2$).

When this time interval is compared with the core crossing time of the interacting clumps of about $10^5$ yrs, we conclude that thermal conduction needs to be suppressed by a factor larger than 10 and with a minimum characteristic value enclosed between 250 and 2500. On the other side, Markevitch et al. suggest a dynamical model in which the dense cores of the two interacting clumps are moving through the host, less dense, intracluster medium at a subsonic velocity of less than $1000 \text{ km s}^{-1}$ and $400 \text{ km s}^{-1}$, for the Northern and Southern edge, respectively, leading to a timescale of about $2 \times 10^7$ yrs or larger for the cool and hot phases to be in contact. In this scenario, our results implies that the conduction is suppressed at least by a factor of 2–200 in the South and 2–32 in the North. However, we note that it is unlikely that the cooler gas can have arrived at its present arrangement and settled in the hotter environment on a timescale much shorter than a core crossing time. The frequency of the occurrence of similar structures in other cluster cores will be important in establishing the timescale for their formation and duration and, hence, improve the constraint on the thermal conduction in the intracluster plasma.

3 CONCLUSIONS

In this letter, we calculate the thermal conductivity in the intracluster medium of A2142, a interacting cluster of galaxies observed by Chandra during the calibration phase.

We have shown that the time interval in which the action of thermal conduction should propagate heat to neighbouring regions is shorter by a factor of about 250–2500 than the likely estimated age of the structure. We note that the observed sharp temperature boundary also means that mixing and diffusion are minimal.

The results presented here are a direct measurement of a physical process in the intracluster plasma and imply that thermal conduction is particularly inefficient within $280 h_{70}$ kpc of the central core. The gas in the central regions of many clusters has a cooling time longer than the overall age of the system, so that a slow flow of hotter plasma moves here from the outer parts to maintain hydrostatic equilibrium. In such a cooling flow (Fabian, Nulsen, Canizares 1991; Fabian 1994), several phases of the gas (i.e. with different temperatures and densities) are in equilibrium and would thermalize if the conduction time were short. The large suppression of plasma conductivity in the cluster core allows an inhomogeneous, multi-phase cooling flow to form and be maintained, as is found from spatial and spectral X-ray analyses of many clusters (e.g. Allen et al. 2000).

How the conduction is reduced by so large a factor is still unclear. Binney & Cowie (1981) explain the reservoir for heat observed in the region of M87 as requiring an rms field strength considerably larger than the component of the field parallel to the direction along which conduction occurs. (The transport processes are reduced in the direction perpendicular to magnetic field lines). This would imply either highly tangled magnetic fields or large-scale fields perpendicular to the lines connecting the hotter to the cooler zones. Such fields could become dynamically important. Chandran, Cowley & Albright (1999) use asymptotic analysis and Monte Carlo particle simulations to show that tangled field lines and, with larger uncertainties, magnetic mirrors reduce the Spitzer conductivity by a large factor. Via a phenomenological approach Tribble (1989) argued that a multiphase intracluster medium is an inevitable consequence of the effect of a tangled magnetic field on the flow of the heat through the cluster plasma. Electromagnetic instabilities driven by the temperature gradient (e.g. Pistinner, Levinson & Eichler 1996) can represent another possible explanation for the suppression of thermal conductivity. Finally, we speculate that cooler gas dumped in the cluster core by a merger (see e.g. Fabian & Daines 1991) would be part of a different magnetic structure to the hotter gas and so thermally isolated.

ACKNOWLEDGEMENTS

We acknowledge the support of the Royal Society.

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