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

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ABSTRACT

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: galaxies: clusters: general – galaxies: clusters: individual: A2142 – X-rays: galaxies.

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):

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

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 & McKee 1977):

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

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

\[ \lambda_e = 30.2 T_e^{-2/3} \left( \frac{\ln \Lambda}{37.9 + \ln (T_e/10^{15}/\text{cm}^{-3})} \right)^{-1} \text{ kpc}, \]

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 typical adopted 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 electron mean free path is comparable to the scalelength \( \delta r \) of the temperature gradient, the heat flux tends to saturate to the limiting value that may be carried by the electrons (Cowie & McKee 1977):

\[ q_{\text{sat}} = 0.42 \left( \frac{2kT_e}{\pi m_e} \right)^{1/2} n_e kT_e = 0.023 T^{3/2} n \text{ erg s}^{-1} \text{ cm}^{-2}, \]

where the factor of 0.42 comes from the reduction effect on the heat conducted by the electrons, which is produced from the secondary electric field which maintains the total electric current along the temperature gradient at zero (Spitzer 1956).

In this Letter, we apply these equations to estimate the efficiency of thermal conductivity in the intracluster medium of A2142, a cluster of galaxies observed by the X-ray telescope Chandra during its calibration phase in 1999 August.

2 THERMAL CONDUCTIVITY IN A2142

Markevitch et al. (2000) have analysed the Chandra observation of the merging cluster of galaxies A2142 and made an important discovery. The X-ray image reveals sharp edges to the surface brightness of the central ellipse-shaped region. The edges are located about 3 arcmin to the north-west and 1 arcmin to the south with respect to the X-ray centre. Markevitch et al. (2000) have shown that the bright and fainter regions either side of an edge are in pressure equilibrium with each other, but with a dramatic electron temperature decrease on the inside.

Considering the values of the intracluster gas properties in A2142 from Markevitch et al.’s fig. 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 Markevitch et al.’s 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 densities [panel (d) in their fig. 4] at the edges...
are $-1.2 \times 10^{-2}$ and $3.0 \times 10^{-3}$ cm$^{-3}$ to the south and north, respectively. The scalelength $\delta r$ on which this temperature gradient is observed is spatially unresolved in the temperature profile and appears enclosed between 0 and 35 kpc ($H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$) for the southern edge, and between 0 and 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 to the electron mean free path of about 2 and 12 kpc for the southern and northern edges, respectively, calculated using the temperature and density estimates in equation (3).

Therefore we will consider hereafter the two extreme cases where (i) $\delta r \gg \lambda_e$ and the heat flux is unsaturated, and (ii) $\delta r = \lambda_e$ and the heat flux is saturated and represented by equation (6).

The maximum heat flux in a plasma is given by

$$ q = \frac{1}{2} \, n_e k T_e \, \hat{v}, $$

where $\hat{v} = d\vec{r}/d\tau$ is a characteristic velocity that we are now able to constrain by equalizing the latter equation to equation (1).

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

$$ \delta \tau = \frac{\delta r}{\hat{v}} = \begin{cases} 3.6 & (\ll 80) \times 10^6 \text{ yr}, \quad \delta r \gg 2 \text{ kpc} \\ 0.3 & (\ll 0.4) \times 10^6 \text{ yr}, \quad \delta r = 2 \text{ kpc} \end{cases} $$

for the southern edge, and

$$ \delta \tau = \frac{\delta r}{\hat{v}} = \begin{cases} 2.4 & (\ll 52) \times 10^6 \text{ yr}, \quad \delta r \gg 12 \text{ kpc} \\ 1.9 & (\ll 2.4) \times 10^6 \text{ yr}, \quad \delta r = 12 \text{ kpc} \end{cases} $$

for the northern edge. The upper limits are obtained by propagating the uncertainties on the temperature and, for the $\delta r \gg \lambda_e$ condition only, assuming the spatial resolution of the temperature profile to be indicative of the length of the gradient. Here we note that the limit on the time-scale for saturated flux is particularly inefficient within 280$\,h_{100}^2$ kpc of the central core. The gas in the central regions of many clusters has a cooling time lower 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, multiphase 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).

The conduction is reduced by so large a factor is still unclear. Binney & Cowie (1981) explained 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) used 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. Pidinner, 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 from the hotter gas and so would be thermally isolated.

3 CONCLUSIONS

In this Letter, we have calculated 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 over 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$\,h_{100}^2$ kpc of the central core. The gas in the central regions of many clusters has a cooling time lower 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, multiphase 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).

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