Heating Rate Profiles in Galaxy Clusters

Edward C. D. Pope[1,2,3], Georgi Pavlovski[2], Christian R. Kaiser[2] and Hans Fangohr[3]

[1] School of Physics and Astronomy, University of Leeds, Leeds, LS2 9JT
e.c.d.pope@leeds.ac.uk
[2] School of Physics and Astronomy, University of Southampton Highfield, Southampton, SO17 1BJ
[3] School of Engineering Sciences, University of Southampton Highfield, Southampton, SO17 1BJ

1 Abstract

The results of hydrodynamic simulations of the Virgo and Perseus clusters suggest that thermal conduction is not responsible for the observed temperature and density profiles. As a result it seems that thermal conduction occurs at a much lower level than the Spitzer value. Comparing cavity enthalpies to the radiative losses within the cooling radius for seven clusters suggests that some clusters are probably heated by sporadic, but extremely powerful, AGN outflows interspersed between more frequent but lower power outflows.

2 Introduction

The two candidates for heating cluster atmospheres are Active Galactic Nuclei (AGNs) and thermal conduction. Heating by AGN is thought to occur through the dissipation of the internal energy of plasma bubbles inflated by the AGN at the centre of the cooling flow. Since these bubbles are less dense than the ambient gas, they are buoyant and rise through the intracluster medium (ICM) stirring and exciting sound waves in the surounding gas. This energy may be dissipated by means of a turbulent cascade, viscous processes, or aerodynamic forces. Deep in the central galaxy other processes such as supernovae and stellar winds will also have some impact on the ambient gas.

Thermal conduction may also play a significant role in transferring energy towards central regions of galaxy clusters given the temperature gradients which are observed in many clusters.

3 The Model

3.1 General heating rates

Starting from the assumption that the atmospheres of galaxy clusters are spherically symmetric, and in a quasi steady-state, it is possible, using the fluid energy equation, to derive what the radial time-averaged heating rate must be in order to maintain the observed temperature and density profiles. The flow of the gas is assumed to be subsonic meaning that the cluster atmosphere is in approximate hydrostatic equilibrium allowing the gravitational acceleration to be calculated from observations of the temperature and density profiles. To avoid anomalies when calculating spatial derivatives, continuous analytical functions are fitted through the density and temperature data. This ensures that there are not any large discontinuities which may result in extreme, and erroneous, heating rates later on in the calculations. This model is described in greater detail in [9]

3.2 Thermal conduction

Thermal conduction of energy from the cluster outskirts may provide the required heating of the central regions without an additional energy source, like an AGN. The thermal conductivity is assumed to be given by [11], but includes a suppression factor designed to take into account the possible effects of magnetic fields. For a steady-state to exist, the heating by thermal conduction must equal the heating rate. From this criterion, the radial suppression factor can be deduced.

3.3 Heating by AGNs

The time-averaged mechanical power of an AGN can be estimated by dividing the cavity enthalpy by a characteristic timescale, see for example [1]. We assume that the radio-emitting plasma that fills the cavities is relativistic and that half of the outburst energy is deposted in the ICM by shocks. An accurate estimate of the time-averaged jet power requires the average time between consecutive AGN outbursts to be known. However, since this parameter is rarely the known, a typical choice would be the buoyant timescale required for the cavity to rise to its current location. An alternative method is to assume a particular value for the period of the AGN. In this study it is initially assumed that the period of each AGN is 10^8 yrs.

Note that this is simply an estimate of the rate at which energy is injected by the AGN and is not related to any particular physical process by which this energy is dissipated, e.g. the viscous dissipation of sound waves.

An estimate of the period required to balance the radiative losses within the cooling radius is obtained by calculating the volume integral of the heating rate within this region and comparing this with the bubble enthalpy.

4 Results:1

Radial suppression factors and AGN periods are calculated for a sample of seven objects for which temperature and density were available, as well as the information about the X-ray cavities inflated by their central AGNs. These objects are the Virgo [5], Perseus [10] and Hydra [3] clusters, A2597 [6], A2199 , A1795 [4] and A478 [12] with cavity parameters taken from [1].

4.1 Suppression factors

The results show that the suppression factors must be finely tuned if thermal conduction is to balance the radiative losses. Such a high degree of fine-tuning suggests that thermal conduction is unlikely to be a dominant heating mechanism in galaxy clusters. Furthermore, in many cases, the required suppression factors exceed the physical maxmimum of unity. This is most true for the Virgo , Hydra and A2597 clusters. In contrast, it appears that thermal conduction could, in principle, balance the radiative losses in the Perseus , A2199 , A478 and probably A1795 . The effect of thermal conduction on a cluster from each of these two groups is investigated in more detail using numerical simulations discussed in the next section.

4.2 AGN Duty Cycles

The periods for Virgo and A478 are of the order of 10^6 yrs which is very short compared to the predicted lifetimes of AGN [7]. In contrast, the Hydra cluster requires recurrent outbursts of magnitude similar to the currently observed one only every 10^8 yrs, or so. The required duty cycles for the remaining AGNs are of the order of 10^7 yrs. From this, the obvious conclusion is that if thermal conduction is negligible and if this sample is representative of galaxy clusters in general, then many, if not all, clusters will probably be heated, at certain points in time, by extremely powerful AGN outbursts. Furthermore, it is worthwhile pointing out that roughly 71% of cD galaxies at the centres of clusters are radio-loud [2] which is larger than for galaxies not at the centres of clusters. This may suggest that the galaxies at the centres of clusters are indeed active more frequently than other galaxies.

5 The Simulations

Numerical simulations of mock Virgo and Perseus clusters were performed using the FLASH hydrodynamics code. Four simulations were performed for each cluster to investigate the effect of different values of the thermal conduction on the evolution of the cluster temperature and density profiles. The simulations of the Virgo cluster are described in more detail in [8].

6 Results:2

6.1 Temperature and Electron Number Density Profiles

For the Virgo cluster, the temperature and density data are presented as spherically averaged profiles, rather than 1-d slices through the cluster. The temperatures and densities for two cases are compared to the observations of [5] in figure 1. The two cases shown here are: zero thermal conduction and Spitzer thermal conduction.

The simulations of the Perseus cluster were 1-d, but spherically symmetric, meaning that the data did not require spherical averaging. Results are shown in figure 2 for the same cases as the Virgo cluster.

The qualitative response of the two clusters to the presence of thermal conduction is rather similar: it seems that thermal conduction probably cannot indefinitely prevent a cooling catastrophe from occuring. This is characterised by a large dip and a peak in the temperature and density profiles, respectively.

In the case of the Virgo cluster, even full Spitzer thermal conduction can only postpone the cooling catastrophe for a few Gyrs. The result is roughly the same for simulations of the Perseus cluster where the thermal conduction is sub-Spitzer. The main difference is that in the Perseus cluster the time taken for a cooling catastrophe to develope is significantly longer than for the Virgo cluster. To some extent this is because the density of the gas is lower in Perseus but also because the energy transport by thermal conduction is greater, due to the higher gas temperatures.

In the Perseus cluster, the simulations show that including full Spitzer thermal conduction can avert a cooling catastrophe, for at least a Hubble time, by transfering energy at such a high rate that it essentially keeps the temperature profile flat. This also prevents the density profile from evolving significantly. However, the rapid transfer of energy by thermal conduction leads to an additional problem: thermal conduction 'heats' the central regions of galaxy clusters by transfering thermal energy from outskirts yet there is not an infinite supply. Thus, while energy is being transfered the average gas temperature drops. Eventually the entire ICM would cool to temperatures where it is no longer observed in the X-rays. Essentially the problem with thermal conduction is that it does not 'add' energy to a system, it merely transfers it from one region to another.

7 Conclusion

The results of simulations including thermal conduction qualitatively agree with predictions, based on energetic arguments, for determining which clusters will be most influenced by thermal conduction. However, for clusters such as Perseus, where thermal conduction can balance the radiative losses, the

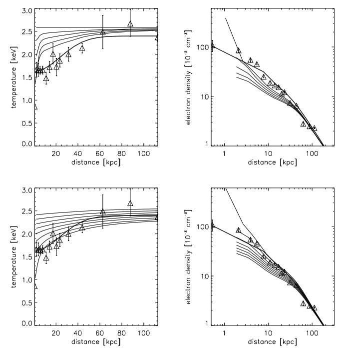

Fig. 1. Temperature and density profiles evolving with time for zero thermal conduction (top) and Spitzer thermal conduction (bottom). The thick lines for both temperature and density are the functions fitted to the data points (triangles) by [5]. For zero thermal conduction the top line in the temperature plot shows the temperature profile after 3.17×10^8 yr and the bottom line at time of the end of the simulation. The intermediate lines represent the temperatures at intervals of 3.17×10^8 yr after the top temperature profile. The temporal sequence of the lines is reversed (bottom to top) in the density plot. For Spitzer thermal conduction the data are plotted every 6.34×10^8 yrs.

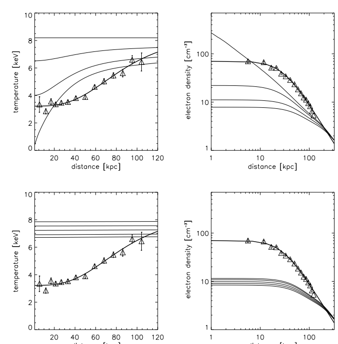

Fig. 2. Temperature and density profiles evolving with time for zero thermal conduction (top) and Spitzer thermal conduction (bottom). The thick lines for both temperature and density are the functions fitted to the data points (triangles) by [10]. The top line in the temperature plot shows the temperature profile after 6×10^9 yr and the bottom line at time of the end of the simulation. The intermediate lines represent the temperatures at intervals of 3×10^9 yrs after the top temperature profile. The temporal sequence of the lines is reversed (bottom to top) in the density plot.

simulated temperature profile never converges with the observations. The results of these simulations suggest that thermal conduction must be drastically reduced compared to the Spitzer value.

Current techniques of estimating AGN power output are still relatively uncertain. Nevertheless, the values obtained using these methods sometimes require periods as short as a few Myrs to balance the radiative losses. An alternative possibility is that the AGN power output is currently underestimated, meaning that the period is actually longer. Another strong possibility is that extemely powerful outbursts occur between more frequent but less powerful outbursts.

References

1. L. Bîrzan, D. A. Rafferty, B. R. McNamara, M. W. Wise, and P. E. J. Nulsen. A Systematic Study of Radio-induced X-Ray Cavities in Clusters, Groups, and Galaxies. *ApJ*, 607:800–809, June 2004.
2. J. O. Burns. Numerical Models of Extragalactic Radio Sources: An Observer's Perspective. *Bull. Am. Astron. Soc.*, 22:821–+, March 1990.
3. L. P. David, P. E. J. Nulsen, B. R. McNamara, W. Forman, C. Jones, T. Ponman, B. Robertson, and M. Wise. A High-Resolution Study of the Hydra A Cluster with Chandra: Comparison of the Core Mass Distribution with Theoretical Predictions and Evidence for Feedback in the Cooling Flow. *ApJ*, 557:546–559, August 2001.
4. S. Ettori, A. C. Fabian, S. W. Allen, and R. M. Johnstone. Deep inside the core of Abell 1795: the Chandra view. *MNRAS*, 331:635–648, April 2002.
5. S. Ghizzardi, S. Molendi, F. Pizzolato, and S. De Grandi. Radiative Cooling and Heating and Thermal Conduction in M87. *ApJ*, 609:638–651, July 2004.
6. B. R. McNamara, M. W. Wise, P. E. J. Nulsen, L. P. David, C. L. Carilli, C. L. Sarazin, C. P. O'Dea, J. Houck, M. Donahue, S. Baum, M. Voit, R. W. O'Connell, and A. Koekemoer. Discovery of Ghost Cavities in the X-Ray Atmosphere of Abell 2597. *ApJ*, 562:L149–L152, December 2001.
7. C. Nipoti and J. Binney. Time variability of active galactic nuclei and heating of cooling flows. *MNRAS*, 361:428–436, August 2005.
8. E. C. D. Pope, G. Pavlovski, C. R. Kaiser, and H. Fangohr. The effects of thermal conduction on the intracluster medium of the Virgo cluster. *MNRAS*, 364:13–28, November 2005.
9. E. C. D. Pope, G. Pavlovski, C. R. Kaiser, and H. Fangohr. Heating rate profiles in galaxy clusters. *MNRAS*, 367:1121–1131, April 2006.
10. J. S. Sanders, A. C. Fabian, S. W. Allen, and R. W. Schmidt. Mapping small-scale temperature and abundance structures in the core of the Perseus cluster. *MNRAS*, 349:952–972, April 2004.
11. L. Spitzer. *Physics of Fully Ionized Gases*. Wiley-Interscience, New York, 1962.
12. M. Sun, C. Jones, S. S. Murray, S. W. Allen, A. C. Fabian, and A. C. Edge. Chandra Observations of the Galaxy Cluster A478: The Interaction of Hot Gas and Radio Plasma in the Core, and an Improved Determination of the Compton y-Parameter. *ApJ*, 587:619–624, April 2003.