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Heating, Cooling and Conduction in Galaxy Clusters

Marcus Brüggen

International University Bremen, Campus Ring 1, 28759 Bremen, Germany

The cooling flow problem describes the apparent lack of emission of soft X-rays from clusters of galaxies. The inference from this is that the bulk of the intra-cluster medium does not cool below roughly a third of the virial temperature. If this is true, the mechanism halts the cooling at temperatures of about 1 keV still needs to be identified. Among the currently favoured mechanisms are heating by a central active galactic nucleus and thermal conduction. Here, we present a family of hydrostatic models for the intra-cluster medium where radiative losses are exactly balanced by thermal conduction and distributed heating as parametrized by Begelman (2001). We describe the features of this simple model and fit its parameters to the density and temperature profiles of Hydra A.

1. **Introduction**

The riddle of cooling flows in clusters of galaxies denotes the lack of emission of soft X-rays from the intracluster medium (e.g. Sarazin 1988, Fabian 1994). A number of mechanisms have been identified that may impede the cooling below a typical temperature of about 1 keV. It appears that one of the most popular models invoke heating by outflows from active galactic nuclei (AGN) (Tabor & Binney 1993, Churazov et al. 2001, Binney 2001, Brüggen et al. 2002, Brüggen 2003). Recently, the subject of thermal conduction has been revisited. Under certain conditions a substantial amount of heat can be transported from the outer regions of the cluster towards the centre by thermal conduction (Zakamska & Narayan 2003, Brüggen 2003b, Ruszkowski & Begelman 2002, Fabian et al. 2001, Voigt et al. 2002, Gruzinov 2002, Friaca 1986, Bertschinger & Meiksin 1986, Meiksin 1988, Bregman & David 1988). In addition, other physical processed have been put forward, such as viscous dissipation of acoustic waves and turbulence (e.g. Fujita, Suzuki and Wada, these proceedings and Fabian, these proceedings), shocks and magnetic fields. Whatever mechanism impedes the cooling, it must not violate any of the observational constraints: If there is heating, the heating must be distributed (Voigt et al. 2002), and, both, the smooth entropy profiles and the abundance gradients must be conserved.

The role of thermal conduction in the ICM has been the subject of a long debate and, owing to the complex physics of MHD turbulence, the value of the effective conductivity remains uncertain. The thermal conductivity of an unmagnetised, fully ionised plasma was calculated by Spitzer (1962). Originally it has been thought that the magnetic field in clusters strongly supresses the thermal conductivity because the magnetic fields prevent an efficient transport perpendicular to the field lines. Even if the transport can be efficient along the magnetic field lines, the overall isotropic conductivity was thought to be many orders of magnitude less than the Spitzer value. This paradigm has been supported by a number of observations, such as sharp edges at cold fronts, small-scale temperature variations in mergers and sharp boundaries around radio bubbles. It is thought that the existence of these sharp features precludes thermal conduction near the Spitzer value (Markevitch et al. 2000, Vikhlinin, Markevitch & Murray 2001).

Recent theoretical work by Narayan & Medvedev (2001), Malyshkin & Kulsrud (2001), Chandran et al. (1999), Chandran & Cowley (1998) and earlier work by Rechester & Rosenbluth (1978) has shown that a turbulent magnetic field is not as efficient in suppressing thermal conduction as previously thought. It is argued that chaotic transverse motions of the tangled magnetic field lines can enhance the cross-field diffusion to an extent that the effective conductivity is of the order of the Spitzer value. Following this work, Zakamska & Narayan (2003) have looked for hydrostatically stable models in which the radiative cooling is exactly balanced by thermal conduction and where the temperatures on the inner and outer boundaries were fixed. For half of the clusters they investigated they found that a thermal conductivity of around 30 % of the Spitzer value yielded good fits to the observed profiles. However, for the other half of the clusters conduction alone appeared unlikely to halt a cooling catastrophe. Consequently, some form of heating is necessary such as mechanical heating by AGN. The work by Zakamska & Narayan (2003) has motivated us to reexamine cluster models that takes into account thermal conduction as well as heating by central radio sources. We include a more generally valid treatment of radiative cooling by utilising a fit to the cooling function that takes into account line cooling. This becomes particularly important in the central regions of cooler clusters.

Radio-loud AGN drive strong outflows in the form of jets that inflate bubbles or lobes. The lobes are filled with hot plasma, and can heat the cluster gas in various ways. The effect of hot bubbles on the ICM consists primarily of heating via *pdV* work and redistribution of mass via buoyancy-driven mixing. Hydrodynamic simulations (Brüggen 2003) have shown that a significant fraction (~ 10 %) of the energy residing in radio lobes can be dissipated in the cluster gas.

Clearly, the lifetime of the activity of the central AGN (as brief as $\sim 10^4-10^5$ yrs) is short compared to the evolutionary time scale of the cluster gas. Therefore, once the AGN stops supplying energy to the buoyant bubbles, the cluster gas will settle down once again and a full cooling flow may be re-established. The cooling gas flows to the centre of the cluster and may then trigger a further active phase of the AGN. Thus a self-regulating process with cooling periods alternating with brief bursts of AGN activity may be established (Quilis, Bower, & Balogh 2001, Voit & Bryan 2001). The rising bubbles uplift colder material from the vicinity of the AGN and thus disrupt the supply of fresh fuel for the radio jets. This feedback mechanism might automatically regulate the power of the radio jets. It has been found that 71 % of all cD galaxies at the centres of cooling-flow clusters show evidence of radio activity (Burns 1990). This fraction is higher than in non-cooling flow galaxies which again points towards the existence of some form of feedback mechanism where the cooling gas flows to the centre of the cluster and triggers a further active phase of the AGN. The bubbles rise at a speed that is comparable to the sound speed, which in turn is comparable to the dynamical speed. Therefore, the cooling timescale is much longer than the bubble rise timescale, and it is justifiable to treat feedback heating in a time-averaged sense.

In these proceedings, we will present a simple model that incorporates, both, thermal conduction and distributed heating by bubbles. We compute a class of models that are subject to radiative cooling, thermal conduction, heating by AGN and that are in hydrostatic equilibrium. We will investigate those parameters that yield plausible solutions and will compare our solutions to observations.

2. **Model**

In our model of the cluster, we assume that the dark matter distribution is given by a modified NFW profile (Navarro et al. 1997)

$$\rho_{\rm DM}(r) = \frac{M_0/2\pi}{(r+r_c)(r+r_s)^2}\,, \tag{1}$$

where r is the distance from the centre, r_s the scale radius of the NFW profile and r_c a softening radius, within which the density becomes constant and which prevents the temperature from going to zero at $r=0$. The core radius r_c determines the shape of the potential near the centre and here we adopt $r_c = r_s/20$ as recommended by Zakamska & Narayan (2003). We can express the characteristic mass M_0 in terms of the commonly used concentration parameter $c = (3M_{\rm vir}/4\pi 200\rho_{\rm crit}(z)r_c^3)^{1/3}$, where $\rho_{\rm crit}$ is the critical density of the universe at the redshift of the cluster and $M_{\rm vir}$ is the virial mass:

$$M_0 = 2\pi r_s^2 r_c \rho_{\rm crit}(z)\left(\frac{200}{3}\right)\frac{c^3}{\ln(1+c)-c/(1+c)}\,. \tag{2}$$

The conductive heat flux is given by

$$F_{\rm c} = -\kappa\nabla T, \tag{3}$$

where κ is the thermal conductivity and T temperature. If thermal conduction is due to electrons, the conductivity according to Spitzer (1962) is given by

$$\kappa_{\rm sp} \approx 9.2\ 10^{-7}T^{5/2}{\rm erg\ s^{-1}\ K^{-1}\ cm^{-1}}\,, \tag{4}$$

and we write κ as $f\kappa_{\rm sp}$, f being a suppression factor. Here we seek an equilibrium model that is spherically symmetric, static, and time-independent. Moreover, we neglect magnetic fields and the self-gravity of the ICM. In spherical coordinates, the gravitational potential Φ is governed by the dark matter distribution

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\Phi\right) = 4\pi G\rho_{\rm DM}(r) = \frac{2GM_0}{(r+r_c)(r+r_s)^2}\,, \tag{5}$$

where G is the gravitational constant. Following Zakamska & Narayan (2003) the mass-temperature relation of Afshordi & Cen (2002) and the mass-scale relation of Maoz et al. (1997), can be used to determine M_0 and r_s for a given cluster. The equation of hydrostatic equilibrium can now be written as

$$\frac{dp}{dr} = -\rho\frac{d\Phi}{dr}\,, \tag{6}$$

where p is pressure and ρ gas density. Demanding that radiative cooling and heating are balanced by thermal conduction, we can write

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2F_{\rm c}\right) = -\rho\mathcal{L} + \mathcal{H}\,, \tag{7}$$

where $\rho\mathcal{L}$ and $\mathcal{H}$ are the volume cooling and heating functions, respectively. We should point out that we omitted a term for the convective flux in equation (7). However, for the levels of heating considered here the ICM is convectively stable and the neglect of convection is a justifiable assumption.

Pressure is related to n_e and T via the ideal gas law

$$p = \frac{\rho kT}{\mu m_u} = \frac{\mu_e}{\mu}n_e kT\,, \tag{8}$$

where m_u is the atomic mass unit.

For the volume cooling rate $\rho\mathcal{L}$ we use an approximation to the cooling function based on calculations by (Sutherland and Dopita 1993)

$$\rho\mathcal{L} = [C_1(kT)^\alpha + C_2(kT)^\beta + C_3]\frac{\mu_e}{\mu}n_e^2\ 10^{-22}\ {\rm erg\ cm^3\ s^{-1}}\,. \tag{9}$$

The units for kT are keV, n_e is the electron number density, and μ and μ_e denote the mean molecular weight per hydrogen atom and per electron, respectively. As in Zakamska & Narayan (2003) we use $\mu = 0.62$ and $\mu_e = 1.18$, corresponding to a fully ionized gas with hydrogen fraction $X = 0.7$ and helium fraction $Y = 0.28$. For an average metallicity $Z = 0.3Z_\odot$ the constants are $\alpha = -1.7$, $\beta = 0.5$, $C_1 = 8.6\times10^{-3}$, $C_2 = 5.8\times10^{-2}$ and $C_3 = 6.4\times10^{-2}$.

The term $\mathcal{H}$ in equation (7) represents the energy input by a central AGN. The energy is deposited in the ICM by the rising bubbles and thus, averaged over time, the heating will be distributed in radius. To quantify this heating, we use a prescription proposed by Begelman

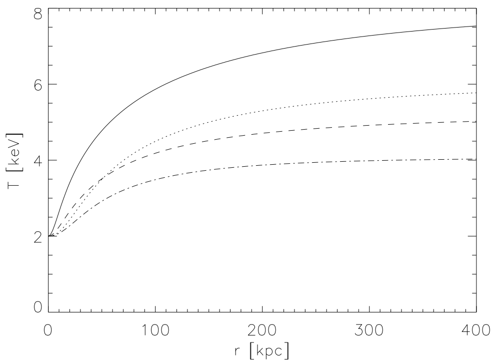

FIG. 1.— Temperature profiles for a cluster with central temperature $T_{\rm in} = 2$ keV and central density of $n_e = 0.05$ cm^{-3} with $f = 0.1$, $L = 3\times10^{43}$ erg s^{-1} (solid) and $f = 0.1$, $L = 3\times10^{44}$ erg s^{-1} (dotted), $f = 0.5$, $L = 3\times10^{43}$ erg s^{-1} (dashed) and $f = 0.5$, $L = 3\times10^{44}$ erg s^{-1} (dash-dot).

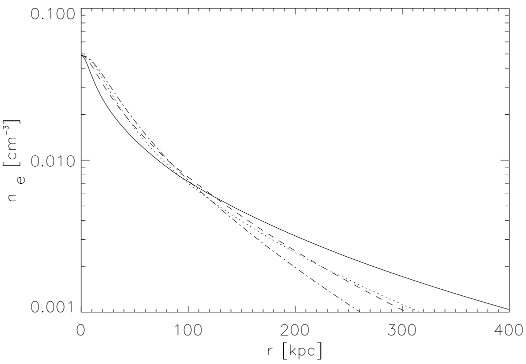

FIG. 2.— Electron number density profiles corresponding to the models presented in Fig. 1.

(2001) which quantifies the heating of the ICM by the rising bubbles. Assuming that this heating mechanism reaches a quasi-steady state, the details of the bubble motions and geometry should cancel and the energy flux may be written as

$$\dot{e} \propto p_{\rm b}(r)^{(\gamma_{\rm b}-1)/\gamma_{\rm b}}\,, \tag{10}$$

where $p_{\rm b}(r)$ is the partial pressure of buoyant gas inside bubbles at radius r and $\gamma_{\rm b}$ is the adiabatic index of buoyant gas which we will take to be 4/3. Assuming that the partial pressure scales with the thermal pressure of the ICM, the volume heating function $\mathcal{H}$ can be expressed as

$$\mathcal{H} \sim -h(r)\nabla\cdot\frac{\dot{e}}{4\pi r^2} = -h(r)\left(\frac{p}{p_0}\right)^{(\gamma_b-1)/\gamma_b} \times\frac{1}{r}\frac{d\ln p}{d\ln r}\,, \tag{11}$$

where p_0 is the central pressure and $h(r)$ is the normalization function

$$h(r) = \frac{L}{4\pi r^2}(1-e^{-r/r_0})q^{-1}\,, \tag{12}$$

where L is the luminosity of the AGN. The normalisation factor q is defined by

$$q = \int_{r_{\rm min}}^{r_{\rm max}}\left(\frac{p}{p_0}\right)^{(\gamma_b-1)/\gamma_b}\frac{1}{r}\frac{d\ln p}{d\ln r}(1-e^{-r/r_0}){\rm d}r\,, \tag{13}$$

where r_0 is the inner heating cutoff radius which is determined by the finite size of the central radio source. Here r_0 was taken to be 10 kpc. This heating function mimics a possible feedback mechanism between the AGN and the ICM in the sense that the volume heating function does not depend on the physical conditions at the source alone but on the pressure gradient (Ruszkowski & Begelman 2002). Thus, it resembles thermal conduction, with the difference that the heating rate depends on the gradient of pressure rather than temperature.

Equations (5) - (8) can be combined to yield a set of four first-order differential equations for n_e, $r^2 d\Phi/dr$, T and $r^2 F_{\rm c}$. We solve these equations as an initial-value problem subject to the initial conditions: $n_e(0) = n_{\rm in}$, $r^2 d\Phi/dr|_{r=0} = 0$, $T(0) = T_{\rm in}$ and $r^2 F_{\rm c}|_{r=0} = 0$, where $n_{\rm in}$ and $T_{\rm in}$ are parameters. Other parameters in this simplified model are M_0, r_s, f and L. We have investigated the dependence of the resulting density and temperature profiles on some of these parameters, which is discussed in the next section.

3. Results and Discussion

We integrate the system of four ordinary differential equations using a Runge-Kutta method and adopt a characteristic mass of $M_0 = 6.6\times10^{14}\ M_\odot$ and a scale radius of $r_s = 460$ kpc (parameters inferred for the cluster Abell 1795, Zakamska & Narayan 2003). For a cluster with a central temperature of 2 keV and a central density of $n_e = 0.05$ cm^{-3} the resulting density and temperature profiles are shown in Figures 1 and 2. Curves plotted in different styles correspond to different values of the suppression factor f and the luminosity of the central source L. The values assumed for L here correspond to typical energies supplied by the jet to the ICM of $\sim10^{44}$ erg s^{-1} (e.g. Owen, Eilek and Kassim 2000). In Figure 1 one can note that the temperature profile rises less steeply with radius if thermal conduction is more efficient. In order to maintain a given central temperature, the temperatures gradient in the cluster has to be higher if conduction is more suppressed. The higher temperature gradient makes up for the smaller suppression factor so that enough energy is conducted inwards to balance the radiative losses. The highest value for the suppression factor that we have adopted here (0.5) is at the upper end of what is physically plausible. Even higher thermal conductivities seem very unlikely. Moreover, one can see, that the heating term has an effect similar to that of thermal conduction, in that a higher luminosity of the central source flattens out the temperature profile. Because the distributed heating depends on the pressure gradient, a higher luminosity of the central source can afford a smaller pressure gradient, leading to a shallower temperature distribution. Physically speaking, the smaller pressure gradient makes the energy transfer from the bubbles to the ICM less efficient.

For higher values of f and L the electron number den-

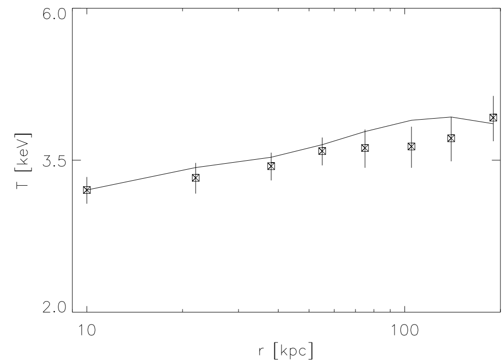

FIG. 3.— Gas temperature profile of the Hydra A cluster. The crosses show the results of ACIS data published in David et al. (2001). The line corresponds to the fit with $f = 0.5$ and $L = 4.0 \times 10^{45}$ erg s^{-1}.

sity is higher in the centre (< 100 kpc) and drops off faster in the outer regions (see Fig. 2).

Clearly, by including a physically motivated heating term, there are more degrees of freedom to fit the density and temperature profiles inferred from observations. This can be demonstrated at the example of Hydra A which is a well-studied cooling flow cluster with a FR I radio source (3C218) at its centre. Zakamska & Narayan (2003) have shown that Hydra A cannot be fitted with a conduction model alone unless one allows for unplausibly high values for κ. The NFW parameters for Hydra A are $r_s = 370$ kpc and $M_0 = 2.9 \times 10^{14}\ M_\odot$. The central electron density is $n_e(0) = 0.08$ cm^{-3}, the temperature at the centre is $T_{\rm in} = 3.11$ keV and at 190 kpc is $T(190\ {\rm kpc}) = 4.04$ keV. In Figure 3 we show the temperature profile as inferred from CHANDRA observations (David et al. 2001) together with our best fit for $f = 0.5$ ($L = 4.0 \times 10^{45}$ erg s^{-1}). As is readily seen, the inclusion of the heating term produces a good fit to the data without having to invoke an abnormally high conductivity. For further discussion see also **?**).

A question that we have not addressed so far is the question of the origin of the energy that is conducted inwards in order to keep the cluster from suffering a cooling catastrophe. If we take a cluster model with no heating, i.e. $L = 0$, and a suppression factor of $f = 0.1$ (all other parameters being those of Fig. 1), the asymptotic value of $r^2 F_{\rm c}$ at large radii is 6.2×10^{44} erg s^{-1}. This means that over a period of 5 Gyrs a total energy of $\sim 10^{62}$ erg has to be conducted into the cluster which amounts to ~ 5 % of the total thermal energy of the cluster ($3M_0 k\bar{T}/2\mu m_p$). For higher values of f this percentage increases. Ultimately, this energy must be provided by infalling gas at the accretion shock. We should point out that we have modelled only the inner region of the cluster which is inside the cooling radius. The temperature turnover near the cooling radius is not reproduced by our model because shock heating, which becomes important at large radii, has been neglected.

It was noted by Loeb (2002) that a significant thermal conductivity will also lead to energy transport out of the cluster because beyond the temperature maximum of the cluster the temperature begins to drop again and the temperature gradient is reversed. Therefore, conduction is also reversed and heat is transported from the cluster to its surrounding envelope in these regions. As estimated by Loeb (2002), heat conduction must be suppressed significantly over the Spitzer value in the outer cluster regions or else the cores of X-ray clusters would have cooled significantly over their life times.

In summary, we have devised a one-dimensional hydrostatic model for the ICM where radiative losses are balanced by, both, thermal conduction and heating by a central source. By including a physically motivated heating term we have shown that it is possible to fit cluster profiles without having to invoke unplausibly high values for the thermal conductivity. It seems to be the general consensus that thermal conduction alone is unlikely to be the solution to the riddle of cooling flows. The fine tuning of the conductivity and the large values of conductivity that would be required to halt the cooling flow in many clusters, cast doubts on a pure conduction model (Soker 2003, Kim & Narayan 2003). However, conduction may well play an important role and is likely to be efficient in suppressing instabilities on small scales.

The model that we have presented here is very simplified: It assumes that the cluster is in hydrostatic equilibrium and spherically symmetric, it does not allow the gas to condense and drop out of the flow, it ignores magnetic fields and includes a heuristic treatment of heating by AGN. But despite its simplicity, we have shown that only a few free parameters suffice to reproduce the observed profiles of X-ray clusters.

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