Conduction and Turbulent Mixing in Galaxy Clusters

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Abstract

We discuss hydrostatic models of galaxy clusters in which heat diffusion balances radiative cooling. We consider two different sources of diffusion, thermal conduction and turbulent mixing, parameterized by dimensionless coefficients, fand α_{mix} , respectively. Models with thermal conduction give reasonably good fits to the density and temperature profiles of several cooling flow clusters, but some clusters require unphysically large values of f > 1. Models with turbulent mixing give good fits to all clusters, with reasonable values of $\alpha_{\text{mix}} \sim 0.01 - 0.03$. Both types of models are found to be essentially stable to thermal perturbations. The mixing model reproduces the observed scalings of various cluster properties with temperature, and also explains the entropy floor seen in galaxy groups.

1. Introduction

For many years, it was thought that the strong X-ray emission observed in the cores of rich galaxy clusters results in a cooling flow in which gas settles in the gravitational potential and drops out as cold condensations [1]. Mass inflow rates were estimated to be $\sim 10^2 - 10^3 M_{\odot} \text{ yr}^{-1}$ in some clusters. However, recent Xray observations with *Chandra* and *XMM-Newton* have found very little emission from gas cooler than about one-third of the virial temperature [2, 3], suggesting that some heating source must prevent gas from cooling below this temperature. Candidate heating mechanisms include (1) energy injection from a central active galactic nucleus (AGN) [4, 5, 6, 7], and (2) diffusive transport of heat from the outer regions of the cluster to the center via conduction [8, 9, 10, 11, 12] or turbulent mixing [13, 14, 15].

Heating by a central AGN is an attractive idea since many cooling flow

clusters show radio jets and lobes that are apparently interacting with the cluster gas [16]. The power associated with the jets is often comparable to the total X-ray luminosity of the cluster. However, there are some difficulties with this model. Observations reveal that radio lobes are surrounded by X-ray-bright shells of relatively cool gas [17], which is a little surprising if this gas is being heated by the bubble. In addition, if the heating rate (per unit volume) of the gas by the AGN varies as ρ^{α} , thermal stability requires $\alpha > 1.5$ [12]; such a heating law does not seem natural. (Stability is not an issue if AGN heating is episodic [7]). Finally, no good correlation is seen between the AGN radio luminosity and the X-ray cooling rate [15].

Since the cooling cores of clusters have a lower temperature than the rest of the cluster, diffusive processes can bring heat to the center from the outside, provided the diffusion coefficient is large enough. An ordered magnetic field would strongly suppress cross-field diffusion of thermal electrons, and this argument has been traditionally invoked for ignoring thermal conduction. However, if the field lines are chaotically tangled over a wide range of length scales, the isotropic conduction coefficient $\kappa_{\rm cond}$ can be as much as a few tens of per cent of the Spitzer value $\kappa_{\rm Sp}$ [10, 18], which may be sufficient to supply the necessary heat to the cluster core. Turbulent mixing is another diffusive process that can transport energy efficiently to the center [13]. The turbulence might be sustained by the infall of small groups or subclusters, the motions of galaxies [K. Makishima, this conference], or energy input from AGNs [19, 20]. The diffusion coefficient required to balance radiative cooling is typically $\kappa_{\rm mix} \sim 1-6$ kpc² Myr⁻¹, which is similar to values inferred from observations of turbulence in clusters [14, 15].

In a series of papers [12, 14, 21], we have studied equilibrium models of galaxy clusters with thermal conduction and turbulent mixing. We summarize here the main results of this work.

2. Model

We assume that the hot gas in a galaxy cluster is in hydrostatic equilibrium and that it maintains energy balance between radiative cooling and diffusive heating,

$$\frac{1}{\rho}\nabla P = -\nabla\Phi, \qquad \nabla \cdot \mathbf{F} = -j,\tag{1}$$

where P is the thermal pressure, ρ is the density, Φ is the gravitational potential, **F** is the local diffusive heat flux, and j is the radiative energy loss rate per unit volume. For $kT \gtrsim 2$ keV, j is dominated by free-free emission, while for lower temperatures it is mostly due to line cooling.

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We consider two diffusive processes: thermal conduction and turbulent mixing. In the case of the former, the heat flux is proportional to the temperature gradient. In the case of the latter, turbulent motions cause gas elements with different specific entropies to move around and mix with one another, causing a heat flux proportional to the entropy gradient. Thus, we write the net heat flux as

$$\mathbf{F} = -\kappa_{\text{cond}} \nabla T - \kappa_{\text{mix}} \rho T \nabla s, \quad \kappa_{\text{cond}} = f \kappa_{\text{Sp}}, \quad \kappa_{\text{mix}} = \alpha_{\text{mix}} c_s H_p, \tag{2}$$

where T is the temperature, and s is the specific entropy. We assume that the conductivity κ_{cond} is a fraction f of the Spitzer value κ_{Sp} in an unmagnetized plasma, and the mixing coefficient κ_{mix} is a fraction α_{mix} of the product of the sound speed c_s and pressure scale height H_p . We take $H_p \approx (r_c^2 + r^2)^{1/2}$, where r is the local radius and r_c is the core radius [12], and set $s = c_v \ln(P\rho^{-\gamma})$, where c_v is the specific heat at constant volume and $\gamma = 5/3$ is the adiabatic index. For simplicity, we have considered models with either pure conduction or pure mixing.

3. Results

We integrate the basic equations described above to calculate the radial profiles of the electron number density $n_e(r)$ and temperature T(r). For each cluster, we assume that the observed gas temperature $T_{\rm obs}$ in the region outside the cooling core is the virial temperature and use this to determine the gravitational potential, assuming an NFW distribution for the dark matter [22, 23]. We also use $T_{\rm obs}$ as a boundary condition for the gas at large radius. We vary the central density $n_e(0)$ and temperature T(0), along with either f (for the conduction model) or $\alpha_{\rm mix}$ (for the mixing model), to find the solution that best fits the observed density and temperature distributions of the cluster.

We have analyzed ten clusters (A1795, A1835, A2052, A2199, A2390, A2597, Hydra A, RX J1347.5–1145, Sersic 159-03, and 3C 295) for which high resolution data are available. Figure 1 shows the results of the model fitting for four of these clusters. Solid lines indicate the best-fit conduction models, while dotted lines show the best-fit mixing models. Overall, both models explain the observed data reasonably well.

Of the ten clusters, five (A1795, A1835, A2199, A2390, RX J1347.5–1145) are well described by a pure conduction model with $f \sim 0.2 - 0.4$, while the other five (A2052, A2597, Hydra A, Sersic 159-03, and 3C 295, e.g., see Fig. 1c, d) require unphysically large values of f > 1. The latter five clusters exhibit strong AGN activity in their centers and extended radio emission, which might indicate that the gas receives extra heat energy from the AGN [12].

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Fig. 1. Observed and modeled profiles of electron number density and temperature for (a) A1795, (b) A2390, (c) A2597, and (d) Hydra A. The data are from *Chandra*. The solid and dotted lines represent best-fit models based on pure thermal conduction and pure turbulent mixing, respectively. $H_0 = 70 \,\mathrm{km \, s^{-1} \, Mpc^{-1}}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$ have been adopted. While the conduction model requires unphysically large values of f > 1 for A2597 and Hydra A, the mixing model gives good fits to all four clusters with reasonable values of $\alpha_{\rm mix} \sim 0.01 - 0.03$.

The turbulent mixing model fits all ten clusters quite well, with a surprisingly narrow range of $\alpha_{\text{mix}} \sim 0.01 - 0.03$ [14]. The five clusters that were incompatible with the conduction model tend to need a larger value of α_{mix} by a factor of 2 than the other clusters (perhaps because the nuclear activity and the associated jets in these clusters cause enhanced turbulent transport). The values of α_{mix} found from the model fitting correspond to a turbulent diffusion coefficient of $\kappa_{\text{mix}} \sim 1 - 6 \text{ kpc}^2 \text{ Myr}^{-1}$ at $r \sim 50 - 300 \text{ kpc}$, which is similar to the value one infers from typical parameters for intracluster turbulence: turbulent velocities $v_{\text{turb}} \sim 100 - 300 \text{ km s}^{-1}$ and eddy sizes $l_B \sim 5 - 20 \text{ kpc}$ [20, 24].

4. Thermal Stability

Since optically-thin gas at X-ray temperatures is known to be thermally unstable, it is necessary to check the stability of the equilibrium models discussed in §3. The absence of cold material in the centers of clusters indicates that the thermal instability is either absent or at least very weak. Since diffusive processes in general tend to stabilize thermal instability on small scales [25], it is interesting to ask whether thermal conduction with $f \sim 0.2 - 0.4$ or turbulent mixing with $\alpha_{\rm mix} \sim 0.01 - 0.03$ can suppress the growth of large-scale unstable modes in clusters.

We begin with a discussion of local linear modes, where we assume that the perturbations have rapid spatial variations. It is straightforward to derive a dispersion relation for such modes. Using equation (2) for the total heat flux, we find

$$\sigma = \sigma_{\infty} - \kappa_{\rm mix} (1+q) k_r^2, \tag{3}$$

where σ is the growth rate of the model, $\sigma_{\infty} \equiv 3(\gamma-1)j/(\gamma P)$ is the growth rate of isobaric perturbations in the absence of diffusion [21, 25], k_r is the radial wavenumber of the mode, and the dimensionless parameter $q \equiv (\gamma - 1)\kappa_{\rm cond}T/(\gamma\kappa_{\rm mix}P)$ measures the stabilizing effect of conduction relative to mixing. Putting in numerical values, clusters with pure conduction should be marginally stable to local perturbations [12]. Since $q \sim 0.1(f/0.2)(0.02/\alpha_{\rm mix})(r/20\,{\rm kpc})^{-1}(n_e/0.05\,{\rm cm}^{-3})^{-1}$ is normally less than unity in the region r < 20 kpc where most of the cooling occurs, we expect turbulent mixing to have a stronger stabilizing effect relative to conduction.

We have confirmed these predictions by explicitly analyzing the global stability of the equilibrium models. By applying Lagrangian perturbations and solving the perturbed equations as a boundary value problem, we searched for all unstable/overstable modes and calculated their growth times $t_{\rm grow}$. In the presence of conduction, we find that all global modes become stable except for 6 —

the fundamental, nodeless mode. The lone unstable mode has a very long growth time, e.g., A1795 with f = 0.2 has $t_{\text{grow}} \sim 4.1$ Gyr, while Hydra A with f = 3.5has $t_{\text{grow}} \sim 9.3$ Gyr [21]. Turbulent mixing suppresses the instability even more significantly; A1795 with $\alpha_{\text{mix}} = 0.011$ has t_{grow} much longer than the Hubble time, and Hydra A with $\alpha_{\text{mix}} = 0.021$ is completely stable [14]. These results suggest that thermal instability is not a serious issue for clusters that achieve thermal balance through diffusive heat transport.

5. Scaling Laws

The theory of cosmic structure formation indicates that the mass M of a halo should scale with the virial temperature T as $M \propto T^{3/2}$, and that the X-ray luminosity and the entropy should scale as $L_X \propto T^2$ and $S \equiv T n_e^{-2/3} \propto$ T. However, cluster observations show different scaling laws: $M \propto T^{1.7 \sim 1.9}$ $L_X \propto T^{2.5\sim3}$, $S \propto T^{0.6\sim0.7}$, for rich clusters with $kT \gtrsim 2$ keV [26, 27, 28]; and $L_X \propto T^{4\sim 5}, S \propto T^{-0.7\sim 0.2}$, for small clusters or galaxy groups with $kT \lesssim 1$ keV [28, 29]. That is, not only are the observed power-law indices different from the self-similar predictions, there is also a clear break in cluster properties at a characteristic temperature $kT \sim 1-2$ keV. The fact that smaller clusters or groups have relatively constant entropy has been recognized as an "entropy floor." The prevailing explanations for the rather high entropy at low temperatures include pre-heating of intracluster gas [30, 31], removal of cold low-entropy gas via galaxy formation in clusters [32], and supernova feedback [11]. Although some of these suggestions are fairly successful in reproducing the entropy floor and the observed scalings, none of them includes thermal conduction or turbulent mixing. If these processes are at all important in clusters, they should have a large effect on the scaling laws.

It is straightforward to derive scaling relationships that the equilibrium cluster models of §3 should obey. For rich clusters with $kT \gtrsim 2$ keV, where thermal bremsstrahlung $(j \propto n_e^2 T^{1/2})$ dominates, heating by conduction leads to $L_X \propto T^4$ and $S \propto T^{0.3}$, while heating by turbulent mixing predicts $L_X \propto T^3$ and $S \propto T^{0.6}$. On the other hand, for small clusters or groups $(kT \lesssim 1 \text{ keV})$, where cooling is dominated by line transitions $(j \propto n_e^2 T^{-0.7 \sim -1})$, $L_X \propto T^4$ and $S \propto T^{-0.2 \sim 0}$ for the thermal conduction model, and $L_X \propto T^{4.2 \sim 4.5}$ and $S \propto T^{-0.3 \sim -0.1}$ for the turbulent mixing model [14]. We see that the scaling relations predicted by the mixing model are in remarkably good agreement with the observations. The dramatic change of cluster properties at $kT \sim (1-2)$ keV arises because of the change in the cooling mechanism above and below this temperature. Also, the entropy floor observed in groups is reproduced naturally.

6. Conclusion

The thermal conduction and turbulent mixing models have certain attractive properties which ultimately are due to the fact that both models involve diffusive transport. Diffusion not only allows heat to move into the cluster center from the outside, it also irons out perturbations and thereby helps to control thermal instability. What is interesting is that the amount of diffusion required to fit the observations is comparable to that predicted by theoretical arguments.

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Two caveats need to be mentioned. First, the presence of cold fronts in many clusters [33, 34] indicates that large temperature and entropy jumps are able to survive in some regions of the hot gas. Diffusion is clearly suppressed across these surfaces. It is possible that cold fronts are special regions where the magnetic field is combed out parallel to the front, thereby suppressing cross-field conduction temporarily [34, 12].

Second, all we have shown is that a cluster with the observed density and temperature profile would be in hydrostatic and thermal equilibrium and would be fairly stable. However, we have not explained how the cluster reaches the observed state starting from generic initial conditions. Time-dependent simulations show that a cluster with thermal conduction would either slowly evolve to an isothermal state if its initial density is less than a critical density, or develop a catastophic cooling flow otherwise [9]. Does the current observed state result from an initial rapid mass dropout (which decreases the density) and subsequent slow evolution with diffusive heating of an once overdense cluster [21]? Are other heating mechanisms, e.g., AGNs, necessary to explain the present state of clusters? Answers to these questions are of fundamental importance to understanding clusters and more generally galaxy formation.

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