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SEMIEMPIRICAL LIMITS ON THE THERMAL CONDUCTIVITY OF INTRACLUSTER GAS

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ABSTRACT

A semiempirical method for establishing lower limits on the thermal conductivity of hot gas in clusters of galaxies is described. The method is based on the observation that the X-ray imaging data (e.g., *Einstein* IPC) for clusters are well described by the hydrostatic-isothermal β model, even for cooling flow clusters beyond about one core radius. In addition, there are strong indications that noncooling flow clusters (like the Coma Cluster) have a large central region (up to several core radii) of nearly constant gas temperature. This suggests that thermal conduction is an effective means of transporting and redistributing the thermal energy of the gas. This in turn has implications for the extent to which magnetic fields in the cluster are effective in reducing the thermal conductivity of the gas. We present time-dependent hydrodynamic simulations for the gas in the Coma Cluster under two separate evolutionary scenarios. One scenario assumes that the cluster potential is static and that the gas has an initial adiabatic distribution. The second scenario uses an evolving cluster potential. These models along with analytic results show that the thermal conductivity of the gas in the Coma Cluster cannot be less than 0.1 of full Spitzer conductivity. These models also show that high gas conductivity assists rather than hinders the development of radiative cooling in the central regions of clusters.

Subject headings: conduction — cooling flows — galaxies: clustering — intergalactic medium

1. INTRODUCTION

In the early 1970s, X-ray observations of clusters of galaxies revealed the presence of large amounts of hot intergalactic gas in these objects. Observations with the *Einstein Observatory* demonstrated that hot gas is a common feature of clusters of galaxies (Abramopoulos & Ku 1983; Jones & Forman 1984; and references cited therein) and that the total gas mass in a typical cluster is equal to, or greater than, the combined luminous mass of all the galaxies (Blumenthal et al. 1984; and David et al. 1990a). A clear understanding of the evolution of this gas and its effect on the cluster galaxies has become a major goal of extragalactic astrophysics (see, e.g., Forman & Jones 1982; Sarazin 1986; and references therein).

One of the first steps toward this understanding has been the construction of hydrostatic models for the distribution of the gas in the potential well of the cluster. The simplest of these models, and the one most widely used, assumes that the cluster gas is isothermal. This model provides a good fit to the X-ray surface brightness profile for the majority of clusters (e.g., Jones & Forman 1984; Edge 1989). The exceptions are the "cooling flow" clusters in which the radiative cooling time of the hot gas in the central region is less than the Hubble time. Cooling flow clusters typically have central cusps in their X-ray surface brightness profile. Even in these clusters, however, the hydrostatic-isothermal β model (Cavaliere & Fusco-Femiano 1976) fits the data beyond about one core radius. Since the gas in clusters would, in general, not have an isothermal temperature distribution after the gravitational collapse of a cluster, these observations suggest that thermal conduction is an effective means of transporting and redistributing the thermal energy of the gas (Rephaeli 1977). This in turn has implications for the extent to which magnetic fields in the cluster are effective in reducing the thermal conductivity of the intergalactic gas, which has been discussed by Tribble (1989) and Rosner & Tucker (1989), and the theory of cooling flows. In this paper we explore these implications in a general way for the Forman & Jones (1982) sample of clusters, and in detail for the Coma Cluster.

This paper is organized in the following manner. In § 2 we use an order of magnitude analysis to show that the heat conductivity of the gas in the Coma Cluster must be within 0.1 of the full Spitzer value to produce a central 1 Mpc isothermal region by the present epoch. In § 3 we present numerical simulations using both a static and evolving gravitational potential designed to constrain the heat conductivity of the gas in the Coma cluster. The consequences of high heat conductivity on the development of cooling flows in clusters is explored in § 4, and our main results are summarized in § 5.

2. GENERAL CONSIDERATIONS

To an order of magnitude, the isothermality of the intracluster medium within a radius r_1 implies that the thermal conduction time of the gas is less than the age of the cluster, which in turn must be less than the Hubble time:

$$t_{\rm cond}(r_1) < t_{\rm cl} < t_{\rm H} \,, \quad (1)$$

where

$$\begin{aligned} t_{\rm cond}(r_1) &= \left[\frac{(5nkT/2)}{(f\nabla \cdot \boldsymbol{Q})}\right]_{r=r_1} \\ &= 2.1 \times 10^8 \left(\frac{n_0}{10^{-3}\ {\rm cm}^{-3}}\right)\left(\frac{a}{300\ {\rm kpc}}\right)^2 \\ &\quad \times \left(\frac{T_0}{10^8\ {\rm K}}\right)^{-5/2}\left[fG\left(\frac{r_1}{a}\right)\right]^{-1} {\rm yr}\,. \quad (2)\end{aligned}$$

In the above equation, n_0 and T_0 are the density and temperature at a reference point $r = r_0$, $\boldsymbol{Q}$ is the classical Spitzer conductive flux, f is a factor which describes the reduction of thermal conductivity due to magnetic field effects, a is the

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cluster core radius, and

$$G(x) = \left(\frac{n_0}{n_1 \Theta x^2}\right) \frac{d}{dx}\left(x^2 \Theta^{5/2} \frac{d\Theta}{dx}\right), \quad (3)$$

where $x = r/a$, n_1 is the density at $r = r_1$, and $\Theta = T/T_0$.

The temperature and density distributions of the cluster gas depend on the details of how the cluster forms. One possibility is that the bulk of the gravitating matter of the cluster collapses first and the gas then falls into a fixed gravitational potential. Another, perhaps more likely, possibility is that the gas, galaxies, and dark matter all collapse simultaneously. In the former case, assuming that the infall process occurs on a time scale less than the conduction and cooling time scales, the gas will have a final temperature with $T(r) \propto \Phi(r)$, where $\Phi(r)$ is the gravitational potential. Once the gas settles into hydrostatic equilibrium the specific entropy will scale as $S \propto \ln \Phi$. Using a modified King profile for the gravitating mass distribution shows that the specific entropy will vary only by a factor of 2 within 5 core radii. Gull & Northover (1977) also found that infall produced a nearly adiabatic distribution in their numerical simulations. In the first scenario, we assume that the gas has an initial adiabatic distribution with a temperature and density profile given by

$$T(r) = T_0\left[1 + (\alpha - 1)\left(1 - \frac{\Phi(r)}{\Phi_0}\right)\right], \quad (4)$$

and

$$\rho(r) = \rho_0\left[\frac{T(r)}{T_0}\right]^{1/(\gamma-1)} \quad (5)$$

(Sarazin 1986), where $\alpha = 1 - \Phi_0/h_0$, h is the enthalpy of the gas, and the subscripts refer to values at a reference point $r_0 = 0$.

For $\alpha > 0$, the gas distribution is unbound and extends to infinity; if $\alpha < 0$, the gas is bound and extends only a finite distance. Using the analytic King approximation, the virial mass density is given by

$$\rho_b(x) = \rho_{b0}(1 + x^2)^{-3/2} . \quad (6)$$

The temperature distribution for $\alpha = 0$ is given by

$$T = T_0\{\ln[x + (1 + x^2)^{1/2}]\}/x . \quad (7)$$

With the analytic King approximation, $G(2) = 0.02$, and the conduction time at two core radii is

$$t_{\rm cond}(2a) = 1.1 \times 10^{10}\left(\frac{n_0}{10^{-3}\ {\rm cm}^{-3}}\right) \times \left(\frac{a}{300\ {\rm kpc}}\right)^2\left(\frac{T_0}{10^8\ {\rm K}}\right)^{-5/2} f^{-1}\ {\rm yr} . \quad (8)$$

The temperature and density in equations (4) and (5) refer to the initial values of the adiabatic distribution. The central temperature can be determined from the central one-dimensional velocity dispersion of the galaxies:

$$T_0 = \frac{-2}{5}\frac{\mu m_p \Phi_0}{k(1 - \alpha)}, \quad (9)$$

which becomes for $\alpha = 0$

$$T_0 = 2.6 \times 10^8\left(\frac{\sigma_r}{1000\ {\rm km\ s^{-1}}}\right)^2\ {\rm K},$$

where σ_r is the radial velocity dispersion. The central gas density can be estimated by assuming that the gas mass within 10 core radii is conserved. Then, for $\alpha = 0$, the initial value of the central density is

$$n_i(0) \approx 2.5 \times 10^{-4}\left(\frac{a}{300\ {\rm kpc}}\right)^{-3}\left[\frac{M_{\rm gas}(10a)}{10^{14}\ M_\odot}\right]{\rm cm}^{-3}, \quad (10)$$

where $M_{\rm gas}(10a)$ is the mass of the cluster gas within 10 core radii. The surface brightness profile in rich clusters in general is best fitted with $\beta \approx \frac{2}{3}$ (Jones & Forman 1984) which indicates that the gas mass increases linearly with radius so we can write that $M_{\rm gas}(10a) = M_{\rm gas}(3\ {\rm Mpc})(a/300\ {\rm kpc})$ which gives

$$t_{\rm cond}(2a) = 2.5 \times 10^8\left[\frac{M_{\rm gas}(3\ {\rm Mpc})}{10^{14}\ M_\odot}\right]\left(\frac{\sigma_r}{1000\ {\rm km\ s^{-1}}}\right)^{-5} f^{-1}\ {\rm yr} . \quad (11)$$

For the Coma Cluster, $\sigma_r = 900$ km s^{-1}, $a = 300\ h_{50}^{-1}$ kpc, and $M_{\rm gas}(10a) \cong 4 \times 10^{14}\ h_{50}^{-5/2}\ M_\odot$ (Hughes 1989). This gives $t_{\rm cond}(2a) = 1.7 \times 10^9\ h_{50}^{-3/2}\ f^{-1}$ yr, where h_{50} is the Hubble constant in units of 50 km s^{-1} Mpc^{-1}. If we require that $t_{\rm cond}(2a) < 10^{10}\ h_{50}^{-1}$ yr (which is required to produce the observed ~ 1 Mpc isothermal region), then

$$f > 0.17\ h_{50}^{-1/2} , \quad (12)$$

which implies that the conductivity is within an order of magnitude of full Spitzer conductivity.

In Table 1 we show the lower limits on f for a number of clusters for which the core radii, velocity dispersions, and gas masses are reasonably well determined. The data are taken from Jones & Forman (1984) and Edge (1989). In every case $f > 0.004$; in many cases $f > 0.1$. This agrees with the argument

TABLE 1

INTRACLUSTER GAS CONDUCTION TIMES AT 2 CORE RADII

Cluster	$t_{\rm cond}/10^{10}$ yr $\equiv f_{\rm min}$
A1377	5.10
A1142	1.65
A2063	0.92
A262	0.91
A400	0.82
A194	0.74
A1795	0.56
A1991	0.38
A2319	0.31
A1367	0.27
A1314	0.24
Coma	0.17
A2199	0.14
A592	0.12
A2657	0.12
A2029	0.082
A2593	0.080
A2634	0.080
A1060	0.077
A154	0.062
A2670	0.046
A2415	0.040
A2124	0.030
A2255	0.024
A426	0.022
A576	0.019
A85	0.011
A399	0.005
A1775	0.004

advanced by Rosner & Tucker (1989) that the thermal conductivity in intracluster gas should, in general, not be reduced below the Spitzer value by more than about an order of magnitude. For two clusters (A1377 and A1142), the conduction time is $\gtrsim 10^{10}$ yr, so they may not have had time to become isothermal, even with full Spitzer conductivity. It will be interesting to see if future X-ray observations of these clusters are better fitted by adiabatic distributions.

If the gas falls in while the cluster collapses and virializes, the gas will experience a varying gravitational potential, and the final gas distribution will not be adiabatic. Hydrodynamic simulations that include an evolving cluster potential typically have central temperature inversions since the gas in the central regions fall through a shallower potential than the gas farther out (Perrenod 1978a, b; Ikeuchi & Hirayama 1979; Meiksen 1990; Evrard 1990). In the smoothed particle hydrodynamic simulations by Evrard (1990), the gas density can be approximated with a distribution given by $d \log n/d \log r = -1.5$ inside 500 kpc and $d \log n/d \log r = -2.2$ at a radius of 2 Mpc. The temperature distribution has $d \log T/d \log r = 0.3$ inside 1 Mpc and $d \log T/d \log r \simeq -0.3$ out to approximately 3 Mpc. We take as a reference point in this case the values at $r_0 = 500$ kpc, which we assume correspond to two core radii in the final isothermal distribution. The temperature at 500 kpc is $\simeq 10^8$ K. For this temperature profile, $G(2) = 0.32$. The density at 500 kpc can be related to the mass within 10 core radii as above. Scaling as before, the conduction time at what corresponds to two core radii is

$$t_{\rm cond} = 2.7 \times 10^8 \left[\frac{M_{\rm gas}(3 \text{ Mpc})}{10^{14} M_\odot}\right]\left(\frac{\sigma_r}{1000 \text{ km s}^{-1}}\right)^{-5} f^{-1} \text{ yr} . \tag{13}$$

This value is essentially the same as in the adiabatic case, so the comments made above still apply.

The conclusions of this section are limited by the qualitative nature of the analysis and by the uncertainties in the data. We present below a time-dependent numerical analysis for a particular well-studied cluster, the Coma Cluster.

3. NUMERICAL SIMULATIONS

3.1. *Hydrodynamics Equation*

The mass, momentum, and energy conservation equations that determine the evolution of the hot gas in clusters of galaxies are

$$\frac{\partial \rho}{\partial t} + \frac{1}{r^2}\frac{\partial(r^2 \rho u)}{\partial r} = 0 , \tag{14}$$

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial r} = -\frac{\partial P}{\partial r} - \rho g , \tag{15}$$

$$\frac{\partial E}{\partial t} + u\frac{\partial E}{\partial r} - \frac{P}{\rho^2}\frac{\partial \rho}{\partial t} - \frac{Pu}{\rho^2}\frac{\partial \rho}{\partial r} = \frac{1}{r^2}\frac{\partial(r^2 Q)}{\partial r} - \frac{n_e n_{\rm H}}{\rho}\Lambda , \tag{16}$$

where E is the specific internal energy of the gas, P is the gas pressure, u is the radial gas velocity, n_e and $n_{\rm H}$ are the electron and hydrogen number density, g is the acceleration of gravity, and Λ is the Raymond & Smith (1977) radiative cooling function. The heat flux is defined as $Q = \kappa f dT/dr$ where $\kappa = 4.7 \times 10^{-7} T^{5/2}$.

The gravitational potential of the Coma Cluster is determined from the best mass-follows-light model in Hughes (1989). This model uses a King distribution for the gravitating mass given by equation (6). The best-fit values found by Hughes (1989) are $\rho_{b0} = 9.9 \times 10^{-26}$ g cm^{-3} and $r_c = 8'.5$. The distance to the Coma Cluster is determined from its redshift $z = 0.0232$ and a Hubble constant of $H_0 = 50$ km s^{-1} Mpc^{-1}. In our first set of models we assume that the gravitational potential is time independent and that the cluster gas is initially in hydrostatic equilibrium with an adiabatic distribution (eqs. [4] and [5]). For $\alpha < 0$, the temperature becomes negative in equation (4) at some finite distance. From the gravitating mass distribution given in equation (6), the temperature becomes negative at radii less than 5 Mpc if $\alpha \leq -0.28$. In these models, we assume that the gas has a constant temperature of 10^6 K and a uniform density beyond the radius at which equation (6) gives a temperature of 10^6 K. For a given value of α, the value of ρ_0 in equation (5) is determined by assuming that the gas mass within 5 Mpc is conserved and is set equal to $5.5 \times 10^{14} M_\odot$ (Hughes 1989). Thus, the only two free parameters in our models are the reduction factor in the heat flux, f, and the parameter which determines the initial adiabatic gas distribution, α.

Once the initial conditions for a simulation are specified, the dynamic evolution of the intracluster medium (ICM) is followed for 10^{10} yr using a time-dependent, spherically symmetric hydrodynamics code. This is a finite difference, implicit, Eulerian hydrodynamics code and has been used previously to investigate heat conduction in clusters of galaxies by Bregman and David (1988). The model consists of a logarithmically spaced grid with 100 cells. The inner cell is located at 20 kpc from the cluster center and the outer cell is located at 5 Mpc.

3.2. *Evolving Gas Properties*

To illustrate the dynamic evolution of the ICM under the influence of heat conduction, the evolving gas density and temperature profiles in a simulation with $\alpha = -0.2$ and $f = 0.1$ are shown in Figures 1 and 2. At a given time, the temperature profile pivots about the radius at which $\nabla \cdot \boldsymbol{Q} = 0$. Gas interior to this radius loses energy and falls inward while gas beyond this radius gains energy and expands outward. The induced gas velocities are always subsonic in this model and no shocks develop. As heat is transported outward, the central tem-

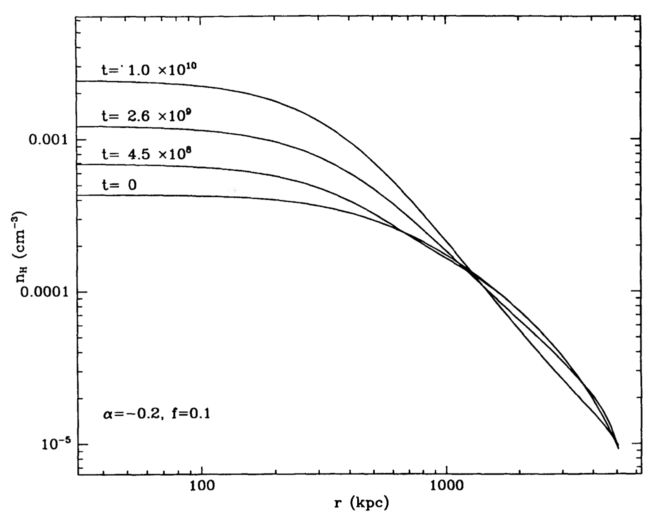

FIG. 1.—The evolving gas density profile in a simulation of the Coma Cluster with $\alpha = 0.2$, $f = 0.1$, and a static potential.

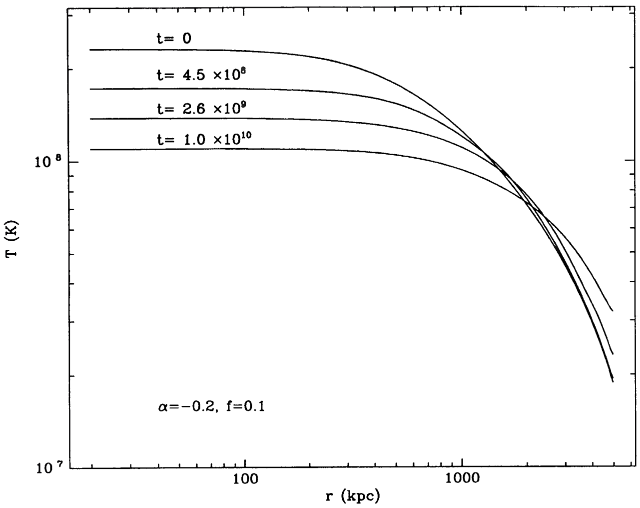

FIG. 2.—The evolving gas temperature profile for the same model shown in Fig. 1.

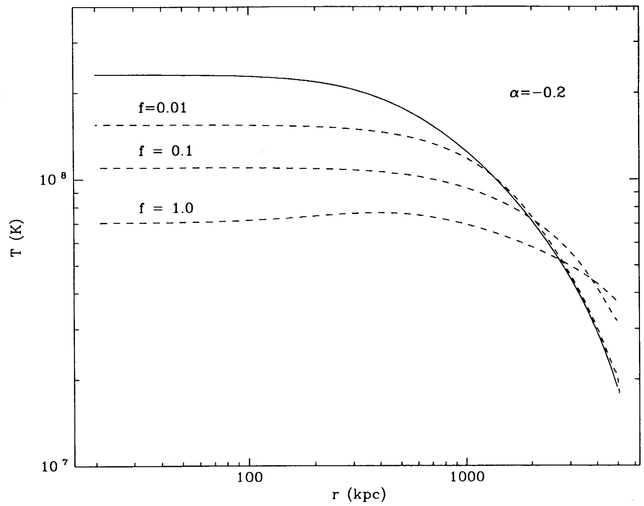

FIG. 4.—The temperature profile after 10^{10} yr for the same models shown in Fig. 3.

perature decreases, an expanding isothermal core develops, and the pivot increases in radius. The diverging gas velocity profile increases the central density and produces a steeper density gradient at large radii (see Fig. 1). Beyond approximately 0.5 Mpc the density distribution is well fitted by a power-law profile at late times. Approximately 11% of the gas escapes from the outer boundary in this model in the form of a conduction-driven wind. As the central density increases and the temperature decreases, the radiative cooling time decreases but remains more than 20 Gyr in this simulation and no significant cooling occurs.

3.3. *Final State*

The efficiency of heat conduction has a significant impact on the thermodynamic state of the ICM after 10^{10} yr of evolution. In Figures 3 and 4 we show the gas and density profiles of the ICM after 10^{10} yr in three models with $\alpha = -0.2$ and $f = 0.01$, 0.1, 1.0 for comparison. As the efficiency of heat conduction increases, a greater amount of heat is transported outward,

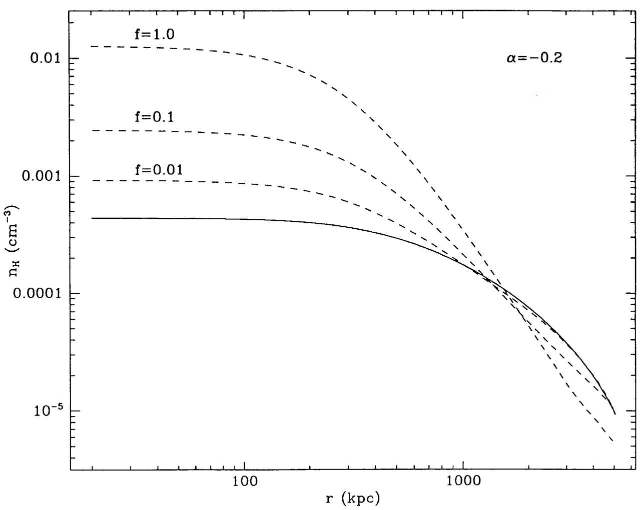

FIG. 3.—The gas density profile after 10^{10} yr (*dashed lines*) in simulations of the Coma Cluster with a static potential for several values of f and $\alpha = -0.2$. The solid curve is the initial density distribution.

producing lower central temperatures and flatter temperature gradients. The induced gas velocities increase with the efficiency of heat conduction which drives stronger inflow and outflow. The greater gas velocities produce higher central densities, steeper density gradients, and more mass loss in winds. Even though f varies by a factor of 100 between these three models, the final central temperature varies only by a factor of ~ 2. However, the final central density differs by a factor of ~ 30.

3.4. χ^2 *Results*

In order to constrain the value of f we have performed a χ^2 fit of our models to eight present-day observed properties of the Coma Cluster. These include the central gas density ($\rho_0 = 6.0 \pm 0.7 \times 10^{-27}$ g cm^{-3}), $\beta = 0.76 \pm 0.1$ (Abramopoulos, Chanon, & Ku 1981), the emission-weighted temperature from the *Ginga* data which has a $1° \times 2°$ field of view ($kT = 8.21 \pm 0.097$ keV; Hughes et al. 1992), the emission-weighted temperature from the *Tenma* data which has a circular 3° field of view ($kT = 7.50 \pm 0.12$ keV; Hughes et al. 1988), and four pointed *EXOSAT* observations each with a 45′ square field of view (central $kT = 8.50 \pm 0.30$ keV, east $kT = 7.78 \pm 0.78$ keV, west $kT = 7.65 \pm 0.60$ keV, and south $kT = 6.82 \pm 0.59$ keV; Hughes, Gorenstein, & Fabricant 1988). At regular time intervals during a simulation the density and temperature profiles are used to generate model spectra. The model spectra are convolved with the various instrument responses, an emission-weighted temperature at the appropriate radius and through the appropriate field of view is determined, and a value of χ^2 is calculated.

The total χ^2 values for a broad range of models with 6 degrees of freedom are shown in Figure 5. For the dashed line in Figure 5, the errors stated above were used to calculate χ^2. These large χ^2 values are due mostly to the 1% statistical error quoted for the *Ginga* temperature. The solid lines in Figure 5 include a 2% systematic uncertainty in all the temperature estimates. With this level of systematic uncertainty, our models can produce reduced values of χ^2 of order unity. For a given α, the value of f that produces the minimum χ^2 increases with increasing α since initially hotter models require greater energy transport to resemble the present temperature distribution in

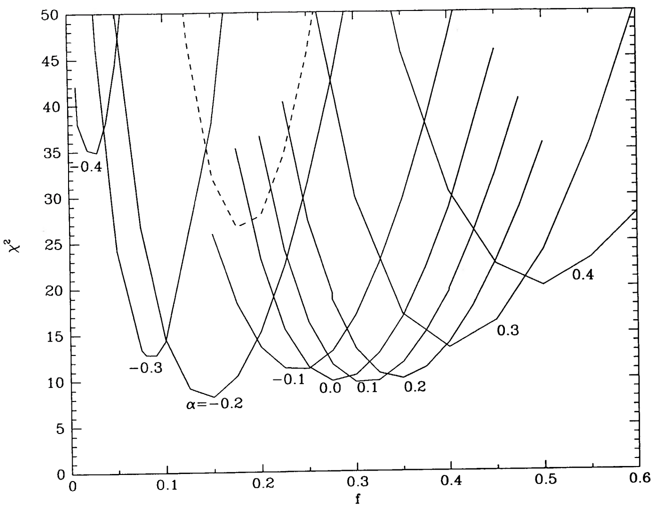

FIG. 5.—The total χ^2 value obtained from fitting our models with a static potential to the observed properties of the Coma Cluster. The dashed curve uses the quoted errors in the temperature. The solid curves include a 2% systematic uncertainty.

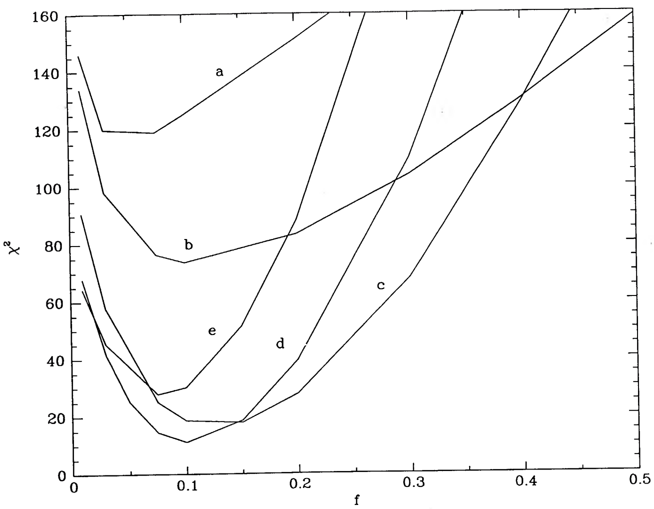

FIG. 6.—The total χ^2 value obtained from fitting our models with an evolving potential to the observed properties of the Coma Cluster. The curves are labeled by the initial gas density as follows: (a) 10^{-29}; (b) 2×10^{-29}; (c) 5×10^{-29}; (d) 7.5×10^{-29}; (e) 10^{-28} g cm^{-3}.

Coma. All models with $|\alpha| \gtrsim 0.3$ have reduced values of χ^2 greater than 2.0 and can be ruled out. The minimum χ^2 in models with $|\alpha| \lesssim 0.3$ is nearly independent of α. While we cannot uniquely constrain α, these results show that f must be greater than 0.1. All models with f significantly less than 0.1 are in strong conflict with the observed X-ray properties of the Coma Cluster.

3.5. *Evolving Cluster Potential*

To determine the evolution of the cluster potential we assume that the total mass distribution at any given time is described by the modified King profile (eq. [6]). Only the evolution of the core radius and central density are then required to determine how the cluster potential evolves with time. N-body simulations of large-scale structure (Davis et al. 1985) and smoothed particle hydrodynamic simulations of rich cluster formation (Evrard 1990) do not have a sufficient number of particles to resolve the core radii in clusters. We therefore assume that the core radius is constant. Meiksen (1990) based his hydrodynamic simulations of cluster evolution on the evolving potential of a rich cluster in the N-body simulations of Davis et al. (1985). The central one-dimensional velocity dispersion of the galaxies in this cluster increases from 570 km s^{-1} at $z = 1.5$ to 1100 km s^{-1} by the present epoch. The galaxy velocity dispersion in the cluster simulated by Evrard (1990) increases from 900 km s^{-1} at $z = 1.1$ to 1150 km s^{-1} by the present epoch. If we assume that the velocity dispersion and central density evolve as power laws in time and take an average of the above two examples we find that $\rho_{b0}(t) \propto (1 + z)^{-1.0}$.

We have run a grid of models for the Coma Cluster which begin with static gas at a temperature of 10^6 K and uniform density. The free parameters in this set of models are the initial gas density and f. The models begin at a redshift of $z = 1.5$ ($t = 3.3$ Gyr; for $\Omega = 1$) and are evolved to the present day ($t = 13$ Gyr). No mass loss from galaxies is included in these simulations. Several recent papers have demonstrated that galaxies need only to eject approximately 25% of their initial luminous mass to account for the observed elemental abundances in clusters (David, Forman, & Jones 1990b, 1991; and White 1991). Since the present-day gas mass in Coma is 3 times the galaxy mass (David et al. 1990a), most of the gas in Coma must be primordial as assumed in these simulations. It is also unlikely that galaxy motions will significantly affect the energy balance of a cluster since the energy per unit mass in galaxies is at best equal to the specific energy of the gas (Edge & Stewart 1991).

As the gas falls into the cluster a shock develops that propagates outward, heating the infalling gas. After the models have evolved for 10 Gyr we perform a similar χ^2 fitting technique as before with the addition of also fitting the data to the observed gas mass within 5 Mpc ($5.5 \pm 0.6 \times 10^{14}\ M_\odot$; Hughes 1989). The total χ^2 values with 7 degrees of freedom are shown in Figure 6. For a given initial gas density, the minimum χ^2 always occurs near a value of $f = 0.1$. The best-fit model is the one with an initial gas density of 7.5×10^{-29} g cm^{-3} which reproduces the present observed gas mass. These models show that even with an evolving cluster potential the heat conductivity of the gas in the Coma Cluster must be within an order of magnitude of full Spitzer conductivity. This result agrees with our analytic estimate in § 2.

4. RELEVANCE TO COOLING FLOWS

It is interesting to note that the Coma model with an initial adiabatic gas distribution and full Spitzer conductivity actually develops a temperature inversion at small radii (see Fig. 4). The central density in this model becomes high enough that the radiative cooling time becomes less than 10 Gyr. Recent research on heat conduction in cooling flow clusters has tried to emphasize the point that efficient heat conduction and cooling flows are mutually exclusive. This conclusion, however, depends completely on the assumed initial conditions. In previous work (Bertschinger & Meiksen 1986; Bregman & David 1988; Gaetz 1989) the gas was assumed to be initially isothermal. As the central gas tries to cool, the large external reservoir of hot gas prevents a temperature inversion from developing, as observed in M87 and Perseus, unless the heat flux is reduced to a value of approximately 1% of the classical value. This contrasts with the simulations of gas infall into a fixed cluster potential by Takahara et al. (1976) and Cowie & Perrenod

(1978). They found that efficient heat conduction actually leads to a central cooling catastrophe.

In our models with adiabatic initial conditions, heat flows outward at all radii until the central cooling time becomes less than the age of the system and a temperature inversion develops. The maximum temperature at a give time is located approximately at the radius where the cooling time equals the age of the system. At the present time in the Coma model with a static potential and $f = 1.0$, the temperature profile has a maximum at 390 kpc. Interior to this radius heat flows inward while exterior to this radius heat continues to flow outward. Thus only a small fraction of the hot gas is able to heat the cooling central gas. These results show that heat conduction does not suppress the growth of a cooling flow but actually drives the ICM to a cooling flow state. In fact, clusters with more efficient heat conduction will develop stronger cooling flows at earlier times.

4.1. *Static Cluster Potential*

To determine how heat conduction affects the development of cooling flows in clusters we have run a variety of models using the same cluster potential as that in Bregman & David (1988). The gravitational potential is calculated assuming a modified King profile for the total mass distribution with a core radius of 250 kpc and a central potential of 1000 km s^{-1}. The first set of models assumes that the gas has an initial adiabatic distribution and that the cluster potential is static. We have run a grid of models varying α from -0.3 to 0.2 and the ratio of gas mass to total gravitating mass from 5% to 20%. The results of these models are summarized in Figure 7. This figure shows the value of f required in a given model to produce a central cooling time less than the age of the system within 10^{10} yr. In general, initially hotter, less dense models require more efficient heat conduction to develop cooling flows by the present epoch. It is obvious from this figure that values of $f \approx 0.2$ are required to produce cooling flows in typical cases. Thus, if clusters form with an initial adiabatic distribution, then efficient heat conduction is a prerequisite for clusters to develop cooling flows by the present epoch. In these models, however, cooling flows do not develop until $z \approx 0.1$ even with

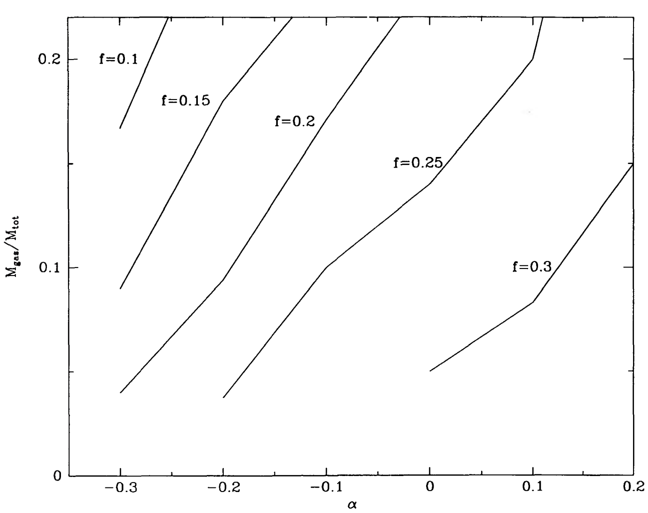

FIG. 7.—The value of f required to produce a cooling flow by the present epoch in our generic cluster model with an initial adiabatic gas distribution and static cluster potential.

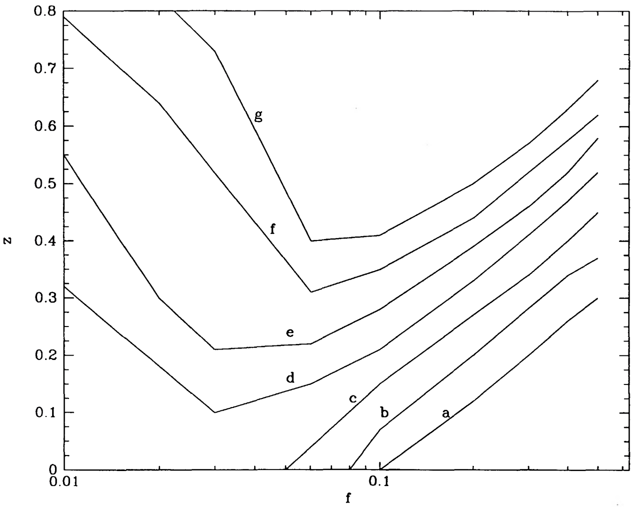

FIG. 8.—The redshift at which the central cooling time in our generic cluster model with an evolving potential becomes less than the age of the system for different values of f. The cluster is assumed to form at a redshift of $z = 1.5$. The curves are labeled according to the ratio of gas mass to total mass with (a) $M_{gas}/M_{tot} = 5\%$; (b) 7.5%; (c) 10%; (d) 12.5%; (e) 15%; (f) 17.5%; (g) 20%.

$f = 0.2$. This is in conflict with the discovery of the cooling flow cluster 3C 295 at $z = 0.46$ (Henry & Henriksen 1986). We now examine the case of an evolving cluster potential.

4.2. *Evolving Cluster Potential*

We have also computed a second grid of models with an evolving gravitational potential with the same rate of change as that in the simulations of the Coma Cluster. These models begin at $z = 1.5$ and are evolved to the present epoch. The gas is assumed to have an initial temperature of 10^6 K and a uniform density. Our grid of models span a range in f from 0.01 to 0.5 and a range in the ratio of gas mass to total gravitating mass from 5% to 20%.

The results of these models are summarized in Figure 8, which shows the redshift at which the central cooling time of the gas becomes less than the age of the cluster. In models with negligible heat conduction ($f = 0.01$), only clusters with $M_{gas}/M_{tot} \gtrsim 0.12$ develop cooling flows by the present time. The onset of cooling flows in these high gas mass models is driven by radiative losses. Models with smaller ratios of gas mass to total mass require efficient heat conduction to develop cooling flows by the present epoch. The onset of radiative cooling occurs at higher redshifts the greater the efficiency of heat conduction in the low gas mass models. As f increases from 0.01 to approximately 0.05 in the high gas mass models, the onset of radiative cooling is delayed to lower redshifts. As f increases further, the onset of radiative cooling is accelerated. These models show that a typical cluster with $M_{gas}/M_{tot} \approx 0.1$ requires $f \approx 0.2$ to develop a cooling flow by a redshift of $z = 0.3$.

5. SUMMARY

We have examined the evolution of the intracluster medium in the Coma Cluster, both analytically and numerically, based upon two separate scenarios for the initial state and evolution of the cluster. One scenario assumes that the cluster potential is static with an initial adiabatic distribution for the gas. The second scenario uses an evolving gravitational potential based upon N-body simulations. In all cases, we find that the thermal conductivity of the gas must be within an order of magnitude of full Spitzer conductivity ($f \gtrsim 0.1$) in order to produce a 1 Mpc isothermal region by the present epoch as observed. Estimates for other clusters indicate that this must be the case in general. This result is in agreement with the arguments by Rosner & Tucker (1989) that the thermal conductivity in clusters should not in general be significantly reduced below the Spitzer value by magnetic field effects.

In addition to modeling the Coma Cluster we have also investigated the effect of heat conduction on the development of cluster flows in general. We find that if rich clusters form with an initial adiabatic distribution and if the cluster potential is approximately static, then cooling flows can develop only if the heat conductivity of the gas is within 0.1 of full Spitzer conductivity. In these models, however, cooling flows do not develop until fairly low redshifts ($z \approx 0.1$), even with efficient heat conduction. In models with an evolving gravitational potential and large gas mass fraction ($M_{\rm gas}/M_{\rm tot} \gtrsim 0.12$), cooling flows develop without any heat conduction due to the high gas density and short radiative cooling time. Models with an evolving gravitational potential and lower gas mass fractions require $f \gtrsim 0.05$ to develop cooling flows by the present epoch. In a typical cluster with $M_{\rm gas}/M_{\rm tot} = 0.1$ and $f = 0.2$, the central cooling time of the gas becomes less than the age of the system at $z \approx 0.3$, which gives a present-day age for the cooling flow of approximately 4 Gyr. Thus, in general, heat conduction does not hinder the development of cooling flows but actually drives clusters to a cooling flow state.

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