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CLUSTERS OF GALAXIES AS A PROBE OF THE INTERGALACTIC MEDIUM

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ABSTRACT

X-ray observations of the intracluster gas in clusters of galaxies can be used to restrict the allowed densities and temperatures for a hot diffuse intercluster gas. If there exists a hot, dense intergalactic medium, it can have a significant effect on the mass and energy balance of the cluster gas observed at X-ray wavelengths by the conduction of heat from the hotter medium into the cooler cluster gas. In particular, a thermal bremsstrahlung origin for all of the hard X-ray background (e.g., recent papers by Boldt and recent papers by Marshall and colleagues) is incompatible with the observed luminosities of nearby versus distant clusters if they are embedded in a uniform medium. We also discuss the increasingly stringent limits on the intercluster medium that may arise as the quality of X-ray observations of clusters improves and our knowledge of the X-ray surface brightness and temperature profiles of distant clusters ($z > 0.5$) increases. Finally, we calculate the minimum intercluster gas density required to heat the intracluster gas above the equivalent virial temperature; the ratio of the energy per unit mass in galaxies to that in the intracluster gas is less than 1 for a large sample of nearby clusters (see recent work of Jones and Forman) and is independent of temperature and velocity dispersion. We show that heat conduction from an intercluster medium with a present epoch temperature of ~ 300 million degrees and a number density of 2×10^{-8} cm^{-3} can explain this observed relation. If other mechanisms contribute toward raising the gas temperature or lowering the energy per unit mass in galaxies, then our calculated values of the external temperature and density of the ICM can be considered as upper bounds.

Subject headings: galaxies: clustering — intergalactic medium — X-rays: sources

I. INTRODUCTION

The observed low mean density of the universe compared to the critical closure density of 5×10^{-30} g cm^{-3} ($H_0 = 50$ km s^{-1} Mpc^{-1}) has generated considerable interest in the search for intergalactic matter (see Field 1972 for a comprehensive review). Some of the most intriguing data in this regard have been observations of the spectrum of the diffuse X-ray background. These observations are fitted remarkably well by a thermal bremsstrahlung spectrum such as would be produced by a uniform hot gas with a temperature $T = 40 \pm 5$ keV. A more realistic model for an evolving universe (Field and Perrenod 1977; Sherman 1980) requires a gas density of 10^{-6} cm^{-3} and a temperature of 25 keV at the present epoch to explain the X-ray background (Boldt 1981; Marshall *et al.* 1980). This density is about 40% of the closure density (for $H_0 = 50$ km s^{-1} Mpc^{-1}). Thus if the X-ray background does in fact have a thermal origin, it provides strong evidence for a cosmologically interesting amount of intercluster matter.

The principal objection to a thermal origin for the X-ray background has come from observations with the *Einstein Observatory*, which have demonstrated the increasing importance of the discrete source contribution to the background (Giacconi *et al.* 1979; Maccacaro *et al.* 1982); furthermore, observations of quasars have shown that distant quasars could account for much and perhaps all of the X-ray background (Tananbaum *et al.* 1979; Zamorani *et al.* 1981; Marshall *et al.* 1983). Nevertheless, a substantial contribution to the X-ray background from a hot diffuse plasma is still consistent with these results.

A separate approach to deriving limits on an intergalactic hot gas has employed astronomical objects as probes of the proposed intergalactic gas. If the interactions of this hypothetical gas with the astronomical probes contradicted observations, limits could be placed on the density and the temperature of the gas. For example, Bergeron and Gunn (1977) explored the implications of large H I disks in galaxies and Cowie and McKee (1976) used intergalactic hydrogen clouds as test objects. (These latter probes were subsequently shown to be galactic objects by Haynes and Roberts 1979 and Lo and Sargent 1979 and, therefore, could not be used to constrain the parameters of a hot intercluster medium.)

In this paper, we discuss the use of clusters of galaxies as probes of the intercluster medium. In particular, we examine the effects of a postulated hot intercluster medium, ICM, on the diffuse gas associated with clusters of galaxies. We show that the diffuse intracluster gas, which is observed at X-ray wavelengths, is a powerful probe of intergalactic space. This cluster gas has been observed at moderate redshifts ($z \lesssim 0.9$; Henry *et al.* 1979 and Henry *et al.* 1982) and studied in detail up to redshifts of $z \sim 0.5$ (White, Silk, and Henry 1981; Henry and Henrikson 1982). McKee and Cowie (1977) noted the substantial effects of heat conduction from a hot, dense ICM at the closure density with a temperature of 3×10^8 K. They found a high evaporative mass loss rate with an evaporation time for the gas in the cluster core of $\sim 10^9$ yr. We have explored further the consequences of conduction and used the existence and properties of the intracluster gas derived from X-ray observations to constrain the temperature and density of a uniform gas filling the universe. We also discuss the effects of a nonuniform medium on our results and show that for plausible scenarios the

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evaporative mass loss rates are insensitive to changes in the density and temperature of the intercluster medium in the vicinity of clusters. In addition, we have calculated the parameters of such a gas if it is to provide an additional conductive heat source to the intracluster gas to explain the larger energy per unit mass found in the intracluster gas compared to that in galaxies (see Jones and Forman 1984). Finally, we discuss the importance of future X-ray observations of clusters with $z > 1$ and the severe limitations such observations could place on the density and temperature of the intergalactic gas.

II. HEATING OF THE INTERCLUSTER MEDIUM (ICM)

Field and Perrenod (1977) have presented a simple model for the heating of an ICM to 10^8–10^9 K by galactic explosions. We have adopted their approach (see also Sherman 1979) assuming that an evolving population having a comoving density proportional to $(1+z)^6$ out to $z_c = 3$ (the apparent turn-on time for QSOs; Osmer 1982) is responsible for heating the ICM. We do not, however, assume that the universe is closed. We also assume that the ICM in the vicinity of clusters is not influenced by the cluster itself, i.e., the ICM density is not abnormally high nor is the ICM heated above the average temperature. We discuss these assumptions below. If we denote the average power from each exploding galaxy by Q, then the temperature history of the ICM can be expressed as

$$T(z) = T(0)g(z)\,, \tag{1}$$

where the functions on the right-hand side of the equation can be explicitly evaluated for the two cases $q_0 = 0$ and $q_0 = 0.5$ as

$$T(0) = \frac{2}{3}\frac{Q n_{\rm EG}(0)}{H_0 k n_I(0)}\frac{(1+z_c)^{3-q_0} - 1}{3 - q_0}\,, \tag{2}$$

$$g(z) = (1+z)^2\frac{(1+z_c)^{3-q_0} - (1+z)^{3-q_0}}{(1+z_c)^{3-q_0} - 1}\,, \tag{3}$$

and $n_{\rm EG}(0)$ is the density of exploding galaxies at the present epoch, $\sim 3 \times 10^{-81}$ cm^{-3} (Schmidt 1972), k is Boltzmann's constant, and H_0 is the Hubble constant. Figure 1 shows the behavior of $T(z)/T(0) = g(z)$ for values of q_0 of 0.0 and 0.5. For both values of q_0 two nearly distinct eras are apparent, e.g., heating for $z > 2$ and adiabatic cooling for $z < 2$. For $z < 1$, the heat input is small and $g(z)$ is approximately proportional to $(1+z)^2$. Because we will only be interested in redshifts less than 2 and since this epoch of the universe is readily described by adiabatic cooling, the details of the evolution of the exploding galaxies are not important. All we require is that the ICM be heated at an early epoch ($z > 2$) with little subsequent energy input.

The dependence of the pressure of the ICM is more dramatic than that of the temperature. The density of the ICM is given by

$$n_I(z) = n_I(0)(1+z)^3\,, \tag{4}$$

and therefore the pressure can be calculated as

$$p_I(z) = p_I(0)(1+z)^3 g(z)\,, \tag{5}$$

which is shown in Figure 2.

The temperature of the ICM at the present epoch is shown

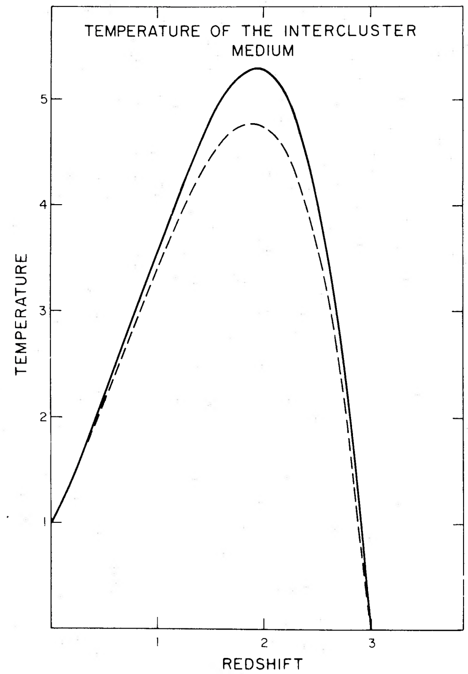

FIG. 1.—The temperature of the intercluster medium (ICM) is shown as a function of redshift. The temperature is normalized to the temperature of the ICM at the present epoch ($z = 0$). The two curves represent the temperature behavior for values of $q_0 = 0.0$ (*solid*) and $q_0 = 0.5$ (*dashed*). For both values of q_0 we identify a phase of rapid heating of the ICM followed by a phase of adiabatic cooling after $z \sim 2$.

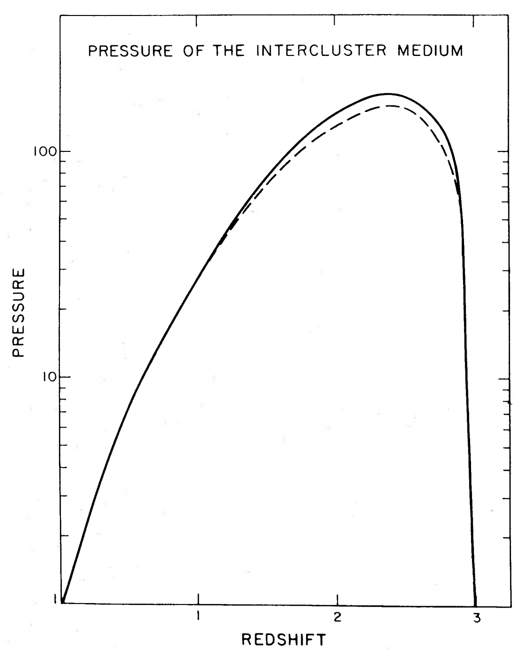

FIG. 2.—The pressure of the ICM is shown as a function of redshift (*solid line* for $q_0 = 0.0$ and *dashed line* for $q_0 = 0.5$). The pressure is normalized to that of the present epoch ($z = 0$). The high value of the pressure at early epochs may have an influence (pressure confinement) on clusters.

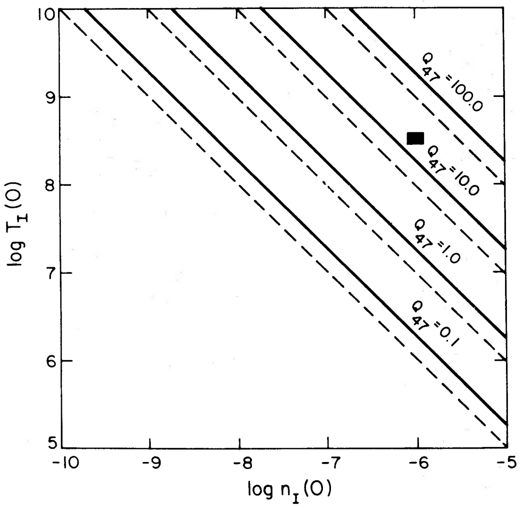

FIG. 3.—The temperature of the ICM is shown plotted against the ICM density for several values of the QSO heating rate Q (in units of 10^{47} ergs s^{-1}). The solid symbol identifies the parameters required for producing all of the hard X-ray background.

in Figure 3 as a function of the density at the present epoch for values of Q ranging from 10^{46} to 10^{49} ergs s^{-1}. To produce the entire X-ray background we would require an ICM with $T(0) = 25$ keV ($\sim 3 \times 10^8$ K) and $n_I(0) = 10^{-6}$ cm^{-3}. In the context of the Field and Perrenod model, this implies $Q \approx 10^{48}$ ergs s^{-1}. As Field and Perrenod (1977) and Field (1980) noted, the very large amount of heating required, makes an explanation of the entire X-ray background in terms of a hot ICM rather implausible. However, as Figure 3 shows, for lower densities of the ICM, plausible values for the heating rate can still produce a hot ICM.

The rapid cosmological evolution of the pressure of the ICM suggests that it could exert a significant dynamical effect on the gas in the outer regions of a cluster (Cavaliere amd Fusco-Femiano 1976). We can approximate the radial dependence of the pressure in the outer regions as $(r_0/r)^2$, where r_0 is the cluster core radius using the hydrostatic-isothermal model (Cavaliere and Fusco-Femiano 1976). The intracluster gas is in pressure equilibrium with the ICM at a confinement radius $r_{\rm conf}$ given by

$$r_{\rm conf}(z) = [T_c M_{\rm gas}/4\pi\mu m_p T_I(0) n_I(0)(1+z)^3 g(z)]^{1/3} , \quad (6)$$

where T_c is the cluster gas temperature, $M_{\rm gas}$ is the mass in cluster gas, μ is the mean molecular weight, m_p is the proton mass, and the remaining variables have been defined above. Numerically, we find

$$r_{\rm conf} = 20A(M_{14.5}\, T_{7.7}/Q_{47})^{1/3}(1+z)g(z)^{1/3} \text{ Mpc} , \quad (7)$$

where $A = 0.84$ or 1.0 (and depends on z_c) for $q_0 = 0$ and 0.5, respectively, and $M_{14.5}$ is the cluster gas mass in units of $3 \times 10^{14}\, M_\odot$, $T_{7.7}$ is the cluster gas temperature in units of 5×10^7 K, and Q_{47} is the heat input rate in units of 10^{47} ergs s^{-1}. However, even for a cosmologically significant intercluster gas density, $r_{\rm conf}$ would be larger than the extents of the cluster gas distribution observed at the present epoch for redshifts less than ~ 2 and for the luminous clusters we will be discussing. Therefore, while this effect is not important for the present discussion, such effects may be relevant in understanding the structure of very distant clusters.

III. EFFECTS OF A HOT INTERCLUSTER MEDIUM ON GAS IN CLUSTERS OF GALAXIES

McKee and Cowie (1977) noted that a hot ($T \sim 3 \times 10^8$ K), dense ($\rho \sim \rho_{\rm critical} \sim 5 \times 10^{-30}$ g cm^{-3}) ICM could evaporate the cooler gas observed in clusters of galaxies on a time scale of 10^9 yr. We now examine this possibility in greater detail.

The cluster gas can dispose of the energy conducted in from the ICM by heating up to the temperature of the ICM, by losing mass (and energy) in a wind, or by radiation. For the densities in the outer regions of clusters, radiation losses are not important. However, a wind will develop if the cluster temperature rises above a critical value given by

$$T_{\rm critical} = -2\mu m_p \phi/5k \quad (8)$$

where ϕ is the gravitational potential (see Parker 1963 and Bregman 1978). Eliminating the potential with the virial theorem we find

$$T_{\rm critical} = 6.5 \times 10^7 (v/1500 \text{ km s}^{-1})^2 \text{ K} , \quad (9)$$

where v is the three-dimensional cluster velocity dispersion (in km s^{-1}). For a typical rich cluster like Coma, the velocity dispersion is 1567 km s^{-1} (Danese, DeZotti, and diTullio 1980) and the gas temperature is 9×10^7 K (Mushotzky and Smith 1980). Therefore, we would expect a wind to have developed.

a) Evaporative Mass Loss

An estimate of the mass loss in the cluster wind is obtained by equating the conductive energy flow into the cluster with the energy carried away by the wind. This leads to the expression developed by Cowie and McKee (1977) for the evaporative mass loss from a cluster of radius r_c:

$$\left(\frac{dm}{dt}\right)_{\rm evap} = 4\pi r_c^{\,2} \mu m_p n_I c_I \phi_s F(\sigma_0) , \quad (10)$$

where $c_I = (kT_I/\mu m_p)^{1/2}$ is the speed of sound in the ICM, ϕ_s is a parameter of order unity that describes the uncertainty in the physics of saturated conductivity, $\sigma_0 = 3 \times 10^4 T_I^{\,2}/n_I \phi_s r_c$ is the ratio of the mean free path of the electrons in the ICM to the scale length of the temperature variation, and $F(\sigma_0)$ is a slowly varying function of σ_0. $F(\sigma_0)$ varies from 2 to about 20 as σ_0 increases from 1 to 10^4.

In computing $F(\sigma_0)$ in the saturated regime, Cowie and McKee (1977) assumed that the cloud is "cold" with respect to the hot ambient medium. We have derived an expression for $F(\sigma_0)$ when this is not the case. This leads us to distinguish two cases which are characterized by $\sigma_0 \ll \sigma_c$ and $\sigma_0 \gg \sigma_c$, where σ_c is defined as

$$\sigma_c = \tfrac{1}{5}(T_I/T_c)^{3/2} . \quad (11)$$

When $\sigma_0 \ll \sigma_c$ (the "cold" case), then $F(\sigma_0)$ is that given by Cowie and McKee (1977). When $\sigma_0 \gg \sigma_c$, then F is given by

$$F = \frac{2}{(1 + M^2/5)}\left(\frac{T_I}{T_c}\right)^{(M^2+1)/2} , \quad (12)$$

where M is the Mach number of the wind.

In addition to the case of saturated conduction discussed by Cowie and McKee (1977) which is valid for $1 < \sigma_0 < 100$, we also used the theory of suprathermal evaporation discussed by Balbus and McKee (1982) for $\sigma_0 > 1000$. The parameters of the ICM during its evolution are such that their STC solution (suprathermal thermal conduction) is also applicable at certain stages ($\sigma_0 \sim 1000$ and $T_I \sim 10^8$–10^9 K). For the STC solution (with the constants defined by Balbus and McKee 1982 taken at their appropriate values of $\phi_s = \frac{1}{3}$, $\phi_c = 1$, $G \approx 1$)

$$F \approx 520(T_{I8}{}^2/n_{I-6}R_{\rm Mpc})^{-2/3}\,, \tag{13}$$

where $T_I = 10^8 T_{I8}$, $n_I = 10^{-6} n_{I-6}$, and $R_{\rm Mpc}$ is the cluster radius in Mpc. In the calculations above for F and below for the mass loss rate we have used $\phi_s = \frac{1}{3}$ as suggested by laser fusion experiments (McKee 1983). Values closer to unity yield higher mass loss rates, and therefore our assumption is a conservative one.

Using equations (1)–(8) and transforming dm/dt to dm/dz, we find a mass loss rate from the intracluster gas in the pressure confined regime given by

$$\left(\frac{dm}{dz}\right)_{\rm evap} = \left[-1.52 \times 10^{52}\pi A^2\left(\frac{M_{14.5}\,T_{7.7}}{Q_{47}}\right)^{2/3} n_I(0)c_I(0)\right] \times \left[(1+z)^{-1}g(z)^{-1/6}\,\frac{\mu m_p \phi_s F(\sigma_0)}{H_0(1+2q_0 z)^{1/2}}\right]. \tag{14}$$

Evaluating this expression and converting the mass loss rate to solar masses per unit redshift, we find

$$\left(\frac{dm}{dz}\right)_{\rm evap} = -1.73 \times 10^{15} A^2\left(\frac{M_{14.5}\,T_{7.7}}{Q_{47}}\right)^{2/3} \phi_s F(\sigma_0) \times \left[\frac{n_I(0)}{10^{-6}}\right]\left[\frac{T_I(0)}{10^8}\right]^{1/2} \Big/ (1+z)g(z)^{1/6}(1+2q_0 z)^{1/2} \tag{15}$$

when the cluster gas is pressure confined by the hot ICM.

As the ICM cools and expands, pressure confinement ceases to be important for $z < z_i$, where we take the maximum cluster radius as 3 Mpc. Setting $r_{\rm conf}$ to this maximum value, we find

$$z_i = 3.1 A^{3/5}(M_{14.5}\,T_{7.7}/Q_{47})^{1/5} - 1\,. \tag{16}$$

For $z < z_i$ or $r_{\rm conf} > R_{\rm max} = 3$ Mpc, we used $r_c = R_{\rm max}$ in equation (10). This yields the following expression for the mass loss rate in the unconfined regime:

$$\left(\frac{dm}{dz}\right)_{\rm evap} = -4\pi(\mu m_p k)^{1/2} H_0{}^{-1}\phi_s F(\sigma_0) \times n_I(0)T_I{}^{1/2}(0)R_{\rm Mpc}{}^2(1+z)^{1-q_0}g(z)^{1/2}\,, \tag{17}$$

where we have used equations (1)–(8), and $R_{\rm Mpc}$ is the maximum cluster radius in Mpc. Eliminating physical constants (with the mass loss rate in units of solar masses per unit redshift) and using the same notation as for equation (15) we find

$$\left(\frac{dm}{dz}\right)_{\rm evap} = -4.32 \times 10^{12}\phi_s F(\sigma_0) \times \left[\frac{n_I(0)}{10^{-6}}\right]\left[\frac{T_I(0)}{10^8}\right]^{1/2} R_{\rm Mpc}{}^2(1+z)^{1-q_0}g(z)^{1/2}\,. \tag{18}$$

We now consider the effects of mass injection to the intracluster gas by galaxies in the cluster. If the total mass injection rate is $\epsilon \times 10^3$ solar masses yr^{-1} then we can write

$$\left(\frac{dm}{dz}\right)_{\rm inject} = 2.05 \times 10^{13}\epsilon(1+z)^{-2-q_0}\,. \tag{19}$$

The net rate of change in mass is given by

$$\left(\frac{dm}{dz}\right)_{\rm net} = \left(\frac{dm}{dz}\right)_{\rm evap} + \left(\frac{dm}{dz}\right)_{\rm inject} \tag{20}$$

which we have integrated numerically with $\epsilon = 1.0$.

The results of our calculations are shown in Figure 4 where we have plotted the net change in cluster gas mass for a range of present epoch densities of the ICM (from 3 to 0.05×10^{-6} cm^{-3}) as a function of redshift. For a given ICM density one can compute the change in gas mass of any cluster for various epochs. For example, consider A85 which has a core radius of $\sim$250 kpc and an X-ray luminosity of 4.2×10^{44} ergs s^{-1} in the energy range 0.5–3.0 keV within 0.5 Mpc. We find that its mass in gas is 2.75×10^{14} $M_\odot$ within 3 Mpc. If the ICM has a density of 1.0×10^{-6} (that required to produce all the X-ray background), then A85 would have had a gas mass of more than twice its present value at a redshift of 1.0. Assuming that its central regions have not changed since that epoch, then it would have had an X-ray luminosity more than 4 times its present value. For the same ICM parameters, more luminous clusters (and hence clusters with more gas) would have smaller observed changes in luminosity in a given time than less luminous clusters.

Several important assumptions have gone into our calculations. First, we have, in the absence of any evidence either pro or con, ignored the effects of magnetic fields in the outer regions of clusters. If even weak magnetic fields exist in these regions and if they are tangled on small scales, then the effects of conduction would be reduced. Second, the idealized model we have envisioned for injection of gas into the

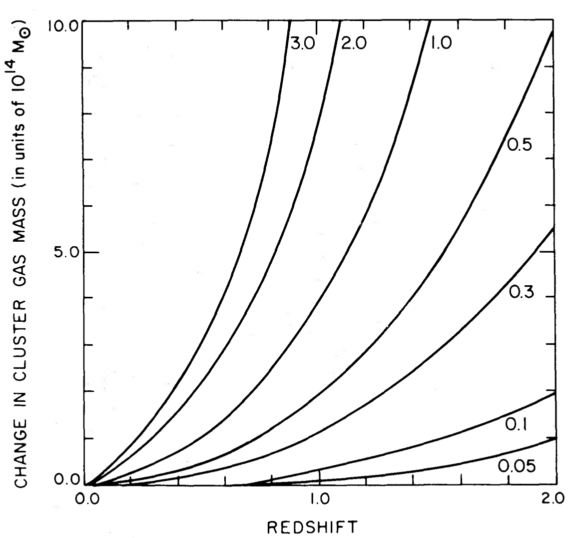

FIG. 4.—The net change (evaporation and injection) in gas mass is shown as a function of redshift for a range of values of the present epoch (local) density of the ICM between 3×10^{-6} and 0.05×10^{-6} cm^{-3} (see labeling of curves in the figure in units of 10^{-6} cm^{-3}).

cluster assumes a prompt injection of the bulk of the observed gas similar to that described by DeYoung (1978). The fact that we observe X-ray luminous clusters with gas masses comparable to those observed at the present epoch implies that most of the gas is already present in the intracluster medium at these early epochs. In addition to the mass initially injected into the intracluster medium (which we already observed), we have allowed additional mass injection ($\dot{M}_{\rm inj}$) of 1 $M_\odot$ yr^{-1} per galaxy in a cluster of 1000 galaxies (Coleman and Worden 1976; Faber and Gallagher 1976; Gisler 1979). This differs somewhat from the models developed to explain the Butcher-Oemler effect (Butcher and Oemler 1978*a*, *b*) by Larson, Tinsley, and Caldwell (1980) and Sarazin (1982). This effect requires a later injection of mass into the intracluster medium. However, recent observations (Mathieu and Spinrad 1981; Dressler and Gunn 1983; and van den Bergh 1983) have cast doubt on the existence of an excess of blue galaxies at the centers of rich clusters at redshifts of $z \sim 0.5$ (most notably the 3C 295 cluster), thus obviating the need for delayed mass injection in otherwise apparently evolved clusters. While our mass injection rates are probably reasonable for moderate redshifts ($z \lesssim 1$), virtually nothing is known about them for $z > 1$. Hence, the calculated curves beyond $z > 1$ in Figure 4 are subject to considerable uncertainty.

One further assumption we have made involves the uniformity in both temperature and density of the ICM. An alternative possibility is that the ICM in the vicinity of clusters is either modified by the clusters themselves or was initially very different. We have considered two possibilities. Both assume that because of the higher density of galaxies in clusters, the energy per unit volume liberated in the cluster vicinity is proportionally higher. The first case assumes the gas remaining from galaxy formation is uniformly spread throughout the universe. The second assumes that galaxy formation consumes a constant fraction of the available gas, and, therefore, the gas density is proportional to the galaxy density and, hence, to the energy liberated by exploding galaxies. We have treated the local cluster environment as an isolated "bubble" which expands adiabatically into the average ICM until pressure equilibrium is achieved. For the two cases described above we find the following temperatures and densities:

$$\begin{array}{ll} \text{Case 1} & \text{Case 2} \\ T_b = N^{3/5}\bar{T} & T_b = N^{-2/5}\bar{T} \\ n_b = N^{-3/5}\bar{n} & n_b = N^{2/5}\bar{n}\,, \end{array} \tag{21}$$

where the subscript b denotes parameters of the bubble, barred parameters are those of the average ICM, and N is the overdensity of exploding galaxies in clusters compared to that in the field.

In the discussion that follows (§ III*a*(i)) in which we discuss the observational limits to the ICM density, the appropriate evaporative mass loss rate is the saturated one (Cowie and McKee 1977). The temperature and density dependence of the saturated mass loss rate, $\dot{m}$, is

$$\dot{m} \propto {n_I}^{0.78}{T_I}^{0.93}\,. \tag{22}$$

The resulting dependences for our two cases are then given by

$$\dot{m}_1 = N^{0.09}\dot{m}_{\rm uniform} \quad \text{and} \quad \dot{m}_2 = N^{-0.06}\dot{m}_{\rm uniform}\,, \tag{23}$$

where the subscripts 1 and 2 refer to the two cases, and $\dot{m}_{\rm uniform}$ is the evaporation rate we had calculated assuming a uniform medium. The small exponents on the galaxy overdensity parameter emphasize the insensitivity of the saturated evaporation rate to inhomogeneities in the ICM.

We have estimated the value of N for the Coma Cluster by finding the number of bright galaxies within a 3 Mpc radius region. We have defined "bright" galaxies as those with a density of 0.003 Mpc^{-3} in the field (see Schmidt 1971). We find $\lesssim 150$ such galaxies in the specified region of the Coma Cluster using both the catalog of Zwicky and Herzog (1963) and the galaxy counts of Godwin and Peach (1977). Before computing the overdensity, N, we note that the epoch of heating is prior to a redshift of 2 (see Fig. 1) and therefore the field galaxy density is that appropriate to $z = 2$. The cluster galaxy density is the same as that at $z = 0$ since it has become detached from the Hubble flow. With this last consideration we find $N \sim 16$ for the ratio of "bright" galaxies in the cluster to that in the field. As long as the galaxy luminosity function in the field and the cluster are the same, this ratio would hold at any magnitude limit.

If we insert this value of N into our expressions for the saturated evaporation rates for our two cases we find $\dot{m}_1 = 1.3\dot{m}_{\rm uniform}$ and $\dot{m}_2 = 0.85\dot{m}_{\rm uniform}$. Thus even for rich cluster like Coma the changes in the evaporation rates are small from these two possible types of inhomogeneities. These effects would be further decreased by the tendency for the temperature to equalize by heat conduction across the interface of the bubble with the average ICM. We conclude that these effects can serve to either increase or decrease the mass loss rates but that in any event they are small.

i) *Observational Limits on the Allowed Change in Luminosity between High- and Low-Redshift Clusters*

To evaluate the effects of the ICM on hot gas in clusters we have compared the X-ray luminosity function of clusters at various epochs and restricted the amount of gas that could have been evaporated. Henry *et al.* (1982) have used *Einstein* observations to derive the luminosity functions of clusters at large redshifts ($z \sim 0.5$ and $z = 0.25$). They find no evidence for a change in the X-ray luminosity function at different epochs. However, from their present observations Henry *et al.* set limits on the change in luminosity for rich clusters of only a factor of 100 which implies a change in the mass of the X-ray emitting gas of no more than a factor of 10 (since $L_x \propto {M_{\rm gas}}^2$ for $z < z_i$; for $z > z_i$, $L_x \propto M_{\rm gas}$).

We have computed the allowed change in luminosity of a sample of six high-redshift ($z > 0.5$), high-luminosity ($L_x > 3 \times 10^{44}$ ergs s^{-1}) clusters (taken from Henry *et al.* 1982) compared to clusters observed at the present epoch. The restriction of our distant cluster sample to high luminosity ensures that all the clusters in our sample are dynamically relaxed systems (even at $z \sim 1.0$). This results from the correlation of velocity dispersion, as a measure of the cluster dynamical time scale, and the cluster X-ray luminosity (e.g., Forman and Jones 1982), since high X-ray luminosity clusters have high velocity dispersions and, therefore, short violent relaxation time scales (e.g., see Gunn and Gott 1972). Merritt (1983, 1984) has argued that the time scales for dynamical friction and galaxy-galaxy collisions in clusters which have completed their violent relaxation are long.

Therefore, the distant clusters in our sample, which have already completed their dynamical collapse, should undergo little, if any, further structural change from redshifts of ~ 1.0 to the present. Cowie and Perrenod (1978) computed the evolutionary changes of cluster X-ray sources in static potentials and found modest changes in X-ray luminosity which would need to be incorporated into the calculations as the limits described below become more stringent.

Most of the clusters in our high redshift ($z > 0.5$) and luminosity ($L_x > 3 \times 10^{44}$ ergs s^{-1}) sample are most likely small core radius clusters (denoted XD; see Forman and Jones 1982; Jones and Forman 1984) since they contain central optically dominant, radio-emitting galaxies. Of the six clusters in our sample, all but one (Cl0016+16) is of this type. Koo (1981) classified it as Bautz-Morgan type II–III. Jaffe (1982) detected no radio source to a limit of 8.8 mJy even though it is the nearest of the clusters in our sample and the other five clusters are 3C or PKS radio sources. The clusters, other than Cl0016+16, probably contain cD galaxies at their centers and have core radii of ~ 250 kpc as is found for similar nearby clusters (Jones and Forman 1984). The 3C 295 cluster, while at a slightly lower redshift and therefore not in our sample, is a good example of such systems.

We have used a complete sample of nearby clusters (Abell's complete sample with $z < 0.075$) to define the luminosity function at the present epoch. The luminosities are taken from Einstein observations when available or else from McKee *et al.* (1980). To determine the maximum amount of gas that the nearby clusters could have lost since a redshift of $z = 0.5$–1.0, we "evolved" the luminosity of each cluster by adding more and more gas mass. We continued this process until the nearby cluster sample was brighter than our distant cluster sample. Specifically, we carried out this process by adding mass to each cluster in units of $2.75 \times 10^{13}\ M_\odot$ (one-tenth of the gas mass of A85). At each step we generated a cumulative luminosity distribution for the nearby "evolved" sample and tested against the cumulative luminosity distribution of the distant clusters using a Kolmogorov-Smirnov (K-S) test and a rank-sum test.

At better than the 95% and 97% confidence levels, for the K-S and the rank-sum tests, respectively, the luminosity distribution of the nearby clusters exceeded that of the distant clusters when the masses of the nearby clusters had been augmented by $1.4 \times 10^{14}\ M_\odot$ or half of A85's present mass. If Cl0016+16 is omitted from the distant cluster sample (on the grounds that it is not an XD system), then the statistical tests become stronger. We conclude that even with our limited sample of distant clusters, the mass of the cluster gas could not have decreased by more than $\sim 1.4 \times 10^{14}\ M_\odot$ since a redshift of ~ 0.75.

Figure 4 shows that the ICM density must then be $\lesssim 0.6 \times 10^{-6}$ cm^{-3}, and thus the corresponding limit on the fraction of the X-ray background produced by this gas is $\lesssim 36\%$. This is a conservative limit since we have tried to err on the side of caution throughout our analysis. For example, the adopted mass injection rate of 1000 $M_\odot$ yr^{-1} is probably too high for some of our clusters. Also when performing our statistical tests we set the luminosities of clusters with upper limits so as to allow for the maximum amount of evaporation. Perhaps, most important, is our use of a maximum radius of 3 Mpc (in equation [18]) for the cluster radius. The rate of evaporation is proportional to the square of this radius while the cluster gas mass is growing, at best, only linearly with radius. Thus, since we detect the cluster gas to radii of at least 3 Mpc (in clusters with long *Einstein* exposure times) we have computed a minimum for the evaporative mass loss and for the change in luminosity.

A second, more qualitative, argument also suggests that clusters could not have lost significant amounts of mass between redshifts of 0.5 and the present. Solinger and Tucker (1972) suggested that, assuming a thermal bremsstrahlung origin for the X-ray emission from clusters, we should expect a correlation between cluster velocity dispersion and X-ray luminosity. With a much more extensive data base we find that such a relation is still valid (Forman and Jones 1984) over a range in cluster X-ray luminosity from 10^{45} to 10^{42} ergs s^{-1}. Clusters with luminosities of 5×10^{42} ergs s^{-1} have typical gas masses of $\sim 3 \times 10^{13}\ M_\odot$, and if the density of the ICM were even as high as 0.3×10^{-6} cm^{-3}, then the gas masses of these clusters would have changed by a factor of 2 (see Fig. 4) and their luminosities by a factor of 4 from $z = 0.5$ to the present. Thus, if large amounts of gas have been evaporated, any luminosity-velocity dispersion relation which is valid for present epoch clusters and is derived from physical arguments would be entirely accidental.

The effects of a hot ICM on rich clusters at early epochs provide a powerful probe of the ICM since the mass evaporated from a cluster is a strong function of redshift and of the ICM density (see Fig. 4). As our knowledge of the X-ray properties of distant clusters improves, one will be able to make more restrictive statements about any hot ICM. In particular, better determined luminosity functions and knowledge of the structure of the intracluster gas for distant clusters will be necessary.

b) Heating of a Gravitationally Bound Cluster Gas

In the previous section (§ III*a*) we showed how a hot ICM could drive evaporative winds that could significantly deplete the cluster gas on a time scale as short as 5×10^9 yr. In this way we were able to constrain the density of a hot ICM and rule out such a hot ICM as the primary source of the X-ray background. Figure 4 shows that evaporation by a hot ICM will have a negligible effect on the mass balance of the cluster if the density of the ICM is less than 10^{-7} cm^{-3} and clusters formed later than $z = 1.0$. However, as we will show below, a low-density, hot ICM can still have an important influence on the energy balance of the cluster.

If we now consider the conduction of heat into a gravitationally bound gas, we find that the thermal energy of the intracluster gas will increase with time according to

$$\frac{dW}{dt} = 4\pi r_c{}^2 q_{\rm cond}\ , \tag{24}$$

where W is the thermal energy of the cluster and $q_{\rm cond}$ is given by (Cowie and McKee 1977)

$$q_{\rm cond} = 0.4\left(\frac{2kT_I}{\pi m_e}\right)^{1/2} n_I\, kT_I\ . \tag{25}$$

Equivalently in terms of redshift, we have:

$$\frac{dW}{dz} = -1.33 \times 10^8 r_c{}^2 T_I{}^{3/2}(0) n_I(0)(1+z)^{4-q_0} . \quad (26)$$

Integrating and finding the fractional change in the thermal energy, we have

$$\frac{\Delta W(z)}{W_0} = \frac{1.81 \times 10^{-7} T_I{}^{3/2}(0) n_I(0) R_{\mathrm{Mpc}}{}^2[(1+z_c)^{5-q_0} - 1]}{(v/1500 \text{ km s}^{-1})^2 (M_{14.5})} \quad (27)$$

where we have computed W_0, the initial thermal energy of the intracluster gas from the equation

$$\beta = \frac{\mu m_p v^2}{3kT} \quad (28)$$

which specifies the ratio of the energy per unit mass in the galaxies to that in the gas with β set to unity and $\Delta W(z)$ represents the energy added between redshift z and the present. Figure 5 shows the fractional energy gain $\Delta W(z)/W_0$ for several plausible values of $T_I{}^{3/2}(0) n_I(0)$ as a function of the redshift at which clusters initially formed. This figure shows that it is feasible to substantially increase the heat content of the gas with respect to that in the galaxies. For example, only a modest ICM density of 2×10^{-8} cm^{-3} is required to provide the additional heat input to a cluster which has been embedded in a hot ($T = 3 \times 10^8$ K) ICM since a redshift of $z = 0.5$.

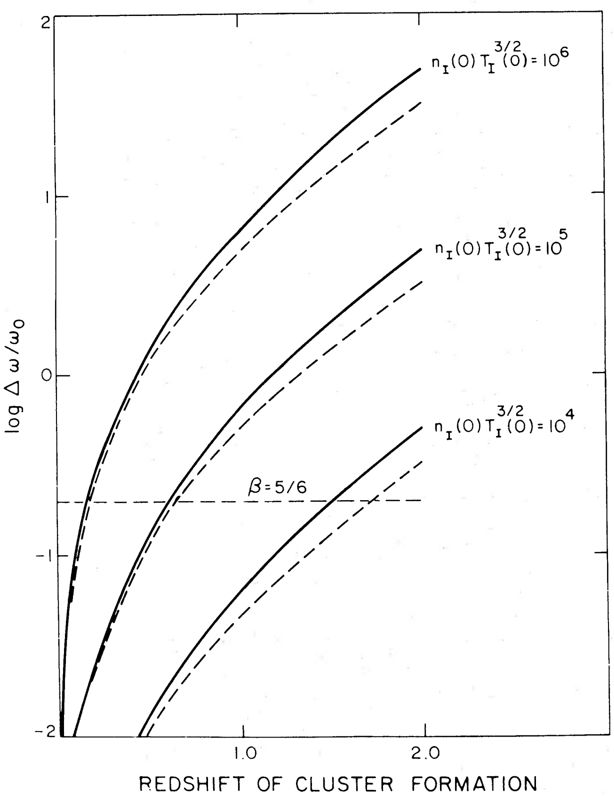

FIG. 5.—The fractional energy gained by a cluster from heat conduction is shown as a function of its redshift of formation (*solid line* for $q_0 = 0.0$, *dashed line* for $q_0 = 0.5$) for several values of $n_I(0)T_I(0)^{3/2}$. The horizontal line corresponding to $\beta = \frac{5}{6}$ as suggested by the X-ray observations and the evaporative wind theory shows that plausible values of the density and temperature of the ICM could be responsible for this excess energy.

The increase in thermal energy of the gas through conduction from a hot ICM also can be used to limit (or measure) the parameters of the ICM. Jones and Forman (1984) studied a sample of 46 clusters which were imaged by the *Einstein Observatory* with sufficient exposure to model their surface brightness distributions. In fitting hydrostatic-isothermal models (Cavaliere and Fusco-Femiano 1976, 1978) to the surface brightness profiles, Jones and Forman determined the parameter β (the ratio of the energy per unit mass in the galaxies to that in the gas) from the X-ray observations alone. Twenty-seven of the β determinations were less than and inconsistent with a value of 1.0 (equal energy per unit mass), and all were consistent with 0.6–0.8. When β was computed from the measured velocity dispersion and X-ray temperature, the result generally agreed with that determined from the X-ray profile (with the exception of Perseus). For six clusters (A194, A262, A400, A1656 = Coma, A1795, and A2063) the computed β value is sufficiently precise to be inconsistent with 1.0. Therefore, it appears to be a general property of clusters that $\beta < 1.0$, i.e., there is more energy per unit mass in the gas than in the galaxies. In terms of β we can write

$$\frac{\Delta W}{W_0} = \frac{1}{\beta} - 1 \quad (29)$$

and for β between 0.6 and 0.8 we find $\Delta W/W_0 \sim 25\%$–70%. This value can be considered an upper limit for conduction alone since one can imagine other effects which could also tend to reduce β (e.g., energy equipartition of the galaxies and ejection from the cluster of galaxies in the high-velocity tail of the galaxy velocity distribution).

However, we could explain the full effect of the additional heat in the intracluster gas as due to conductive heat input, by assuming that a hot ICM heats the cluster gas until a cluster wind develops to carry away any additional heat (see Yahil and Ostriker 1973 for an alternate explanation for the development of a cluster wind). The temperature of the cluster gas would then be given by equation (8). Eliminating the gravitational potential from the virial theorem for the galaxies, we find $\beta = \frac{5}{6}$. Thus, this scenario of the heating of the intracluster gas (above that resulting from the shock heating of the gas as it is removed from galaxies) predicts a universal value of β independent of the details of each cluster. In particular, β should be independent of the cluster velocity dispersion, the gas ejection mechanism from the galaxies, and the dynamical stage of the cluster. Furthermore, we expect $\beta < 1$. These predictions seem to be confirmed by the observations.

If the mass loss by evaporation from clusters has been small and if conduction from a hot ICM is primarily responsible for the additional energy per unit mass contained in the gas compared to that in the galaxies, then by combining equation (2) (Fig. 1) with Figure 5 we can determine both the density and temperature of the ICM. If clusters form at a redshift of ~ 1.0, then from Figure 5, we have

$$n_I(0) T_I{}^{3/2}(0) \sim 3 \times 10^4 . \quad (30)$$

Equation (2) can be evaluated and written as

$$T_I(0) = 18CQ_{47}/n_I(0)\ \mathrm{K}\ . \tag{31}$$

Where we have taken $z_c = 3$ as before, Q_{47} is the average power of the exploding galaxies in units of 10^{47} ergs s^{-1}, and $C = 1.0$ for $q_0 = 0.0$ and 0.59 for $q_0 = 0.5$. We can then solve equations (30) and (31) for the density and temperature of the ICM. Using a value of $Q_{47} = 0.1$, we find an ICM temperature of 2.5×10^8 K and a density of 8×10^{-9} cm^{-3} for $q_0 = 0.0$. While this numerical example is only illustrative, it emphasizes the effectiveness of X-ray emitting clusters as a probe of the ICM.

IV. CONCLUSION

Our initial calculations have provided limits on the contribution to the X-ray background from a hot diffuse ICM and are able to explain the value of the ratio of energy per unit mass in galaxies to that in the intracluster gas and its constancy from cluster to cluster. In particular, we find, from a comparison of the luminosities of nearby and distant clusters, that the density of a hot ICM must be less than 0.6×10^{-6} cm^{-3} which corresponds to a limit of 36% on the contribution to the X-ray background by this gas. If a hot ICM is responsible for increasing the scale height of the gas with respect to that of the galaxies, we expect the ratio of the energy per unit mass in galaxies to that in gas should be $\frac{5}{6}$ and should be constant from cluster to cluster and independent of the cluster's state of dynamical evolution. This expectation is supported by the observations. However, these calculations were done assuming no influence from magnetic fields which might reduce the conductivity. McKee (1983) argued that untangled magnetic fields would become aligned by the evaporating gas along the direction of the temperature gradient. Also, in the outer regions of the cluster, the dynamical time scale is longer and galaxies have not crossed through the region many times. Therefore, we would not expect the magnetic field to be tangled on a small scale.

Future X-ray observations can provide substantial new data to better understand any hot ICM and its influence on cluster gas. In particular, the determination of the cluster X-ray luminosity function at large redshift ($z > 1.0$) would be important in limiting the gas evaporated from clusters as well as determining the mass injection rate. Spatially resolved temperature data could also provide information concerning the effectiveness of conduction and the importance of magnetic fields in the cluster environment. A powerful test would be to determine velocity dispersions of distant clusters. This would allow us to more directly determine the counterparts of clusters at various epochs and to test for changes in the luminosity-velocity dispersion relation which would be very significant even for fairly low densities of the ICM. Nevertheless, the present work shows the importance of clusters of galaxies as a probe of a hot intercluster medium, constrains the contribution of a hot ICM to the X-ray background emission, and offers a possible heating mechanism for the intracluster gas.

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