THE ASTROPHYSICAL JOURNAL, 350:104–109, 1990 February 10


# INFRARED EMISSION FROM DUST IN THE COMA CLUSTER OF GALAXIES

ELI DWEK, YOEL REPHAELI, AND JOHN C. MATHER
Laboratory for Astronomy and Solar Physics, NASA-Goddard Space Flight Center
*Received 1989 April 22; accepted 1989 August 15*

## ABSTRACT

The reported visual extinction ($A_V \approx 0^m.2$) of distant clusters seen through the Coma cluster suggests that dust may be present in the hot X-ray–emitting intracluster gas. However, *IRAS* failed to detect any infrared emission from the cluster at the level expected from the extinction measurements. We present here detailed calculations of the infrared emission from collisionally heated dust in the cluster. Our model includes continuous dust injection from galaxies, grain destruction by sputtering, and transient grain heating by the hot plasma. Our computed infrared fluxes are in agreement with the upper limits obtained from the *IRAS*. The calculations, and constraints implied by the *IRAS* observations, suggest that the intracluster dust in the central region of the cluster must be significantly depleted compared to interstellar abundances. The observed visual extinction can therefore not be attributed to the presence of dust in that region. Extinction due to cluster galaxies or their haloes is ruled out as well. The only alternative explanation is that the extinction is caused by dust at great distances ($R \geq 2$ Mpc) from the cluster center. Only a fraction of the required dust could have been injected by cluster galaxies. Therefore, the observed extinction (if real) requires the presence of a hitherto undetected large mass of gas in the outer regions of the cluster. Other implications of our model, such as cluster cooling by gas-grain collisions and the effect of the dust on the distortion of the cosmic microwave background (CMB) radiation seen through the cluster, are also discussed.

*Subject headings:* cosmic background radiation — galaxies: clustering — galaxies: intergalactic medium — infrared: sources — interstellar: grains

## I. INTRODUCTION

X-ray spectral and line measurements show the presence of hot, metal-enriched gas in clusters of galaxies (for a recent review, see Sarazin 1986). This intracluster (IC) gas is likely to be of galactic origin, suggesting that dust grains, which may have been ejected from galaxies, may also be present in the IC gas. Since any (hypothetical) primordial intergalactic dust accreted into the cluster would not have survived sputtering by the ambient hot gas, the presence of dust in the IC gas can be considered as further evidence for its galactic origin. The detection of dust in the IC gas may therefore provide important clues for galaxy and cluster evolution theories. If the dust-to-gas mass ratio in the cluster is not much smaller than its interstellar value, clusters may constitute the most extended infrared (IR) sources in the universe.

The existence of dust in the IC space had been deduced from the extinction measurements. Zwicky (1962) was first to estimate the extinction of light from distant clusters by nearby ones. For the Coma cluster he found $A_V \approx 0^m.4$. Using the same method, Karachentsev and Lipovetskii (1969, hereafter KL) found a value of $A_V \approx 0^m.3$ for the Coma cluster, and averaging over 15 clusters they estimated a mean cluster extinction of $A_V \approx 0^m.2 \pm 0^m.05$. An upper bound on $A_V$ comparable to these values has been deduced by Hu, Cowie, and Wang (1985, hereafter HCW) from UV-to-optical line ratios. More recently, Boyle, Fong, and Shanks (1988, hereafter BFS) found a value of $A_B = 0^m.2$ ($A_V = 0^m.15$) from a deficiency of ultraviolet excess (UVX) objects behind clusters of galaxies. If all the extinction is attributed to IC dust with optical properties similar to interstellar dust, then the IC dust-to-gas mass ratio in the central $\sim 10'$ of the cluster should be $\sim 0.1 Z_d$, where $Z_d \approx 0.0075$ is its galactic value.

The existence of IC dust can also be inferred from its IR emission. An early theoretical estimate of intracluster dust emission (Yahil and Ostriker 1973) was quantitatively improved by Silk and Burke (1974). Based on the study of the interaction of dust particles with a hot gas (Burke and Silk 1974), they found that a typical dust temperature in the cluster is $\sim 30$ K. Voshchinnikov and Khersonskij (1984*a*; hereafter VK) used more recent studies on the interaction of dust particles with hot plasmas (Draine and Salpeter 1979), and dust optical properties (Draine and Lee 1984), to present more detailed calculations for the IR emission from dust grains in clusters of galaxies. In their analysis, VK assumed that the observed extinction can be attributed to the presence of dust in the hot IC gas. By normalizing the dust abundance to the observed extinction they in effect adopted an dust-to-gas mass ratio equal to $\sim 0.1 Z_d$. Assuming a constant gas temperature throughout the cluster they calculated a dust temperature of $\approx 40$ K in the center of the Coma cluster. The dust spectrum peaks at $\sim 100$ $\mu$m, and has a flux density of $\approx 3 \times 10^3$ MJy sr$^{-1}$ at that wavelength in the center of the cluster. HCW also considered the IR emission from IC dust, and found typical dust temperatures of $\approx 20$ K. Based on the measured extinction and X-ray determined gas mass in the cluster core, HCW derived a 100 $\mu$m flux density of $\sim 3 \times 10^4$ Jy sr$^{-1}$, These values are very similar to those derived in this paper in spite of HCW's incorrect expressions for the dust heating rate and luminosity (compare their eq. [10] with eqs. [4] and [6] in this paper).

In this paper we present a more detailed model for the infrared emission from the Coma cluster. In our model the abundance of the IC dust is determined by the combined effects of continuous mass loss from the galaxies and destruction by the hot gas. Our approach improves upon previous studies in two respects. First, in all earlier calculations the dust temperature was assumed to attain an equilibrium value, obtained by equating the collisional heating rate of the dust to its cooling rate by IR emission. This assumption breaks down below a certain grain size that depends on the temperature and density of the ambient plasma (Dwek 1986). Below this size a dust particle is stochastically heated by the ambient plasma, and its temperature will fluctuate. In the central region of the Coma cluster this effect is important for all grains with sizes below $\approx 0.1$ $\mu$m. Second, an additional simplifying assumption made in the earlier calculations is that the IC grain size distribution is similar to that in the interstellar medium. In our model we obtain a more realistic characterization for the IC dust by assuming that its injection rate into the IC medium is proportional to the spatial density distribution of galaxies in the cluster, and by assuming that its abundance and size distribution are obtained by a steady state between destruction and injection. In all our calculations, the gas temperature and density profile are based on the most recent best-fit analysis of X-ray observations of the Coma cluster (Henriksen and Mushotzky 1986, hereafter HM).

The results of our calculations show that the average dust-to-gas mass ratio in the central 3 Mpc radius of the cluster is significantly smaller, by about two orders of magnitude, than that in the average interstellar medium. As a result, only $\sim 10\%$ of the observed extinction through the cluster can be attributed to dust in the IC gas. We have compared the 100 $\mu$m brightness predicted by our model with the observations obtained with the *Infrared Astronomical Satellite* (*IRAS*). The *IRAS* observations in the central region of the cluster show that the 100 $\mu$m IR brightness is $<7$ MJy sr$^{-1}$. This value is a strict upper limit on the diffuse emission from the cluster since we have made no attempt to correct the observations for any contribution from foreground emission or cluster galaxies. Even so, this upper limit is $\sim 400$ times lower than the brightness predicted by VK, but consistent with the values derived by HCW and in this paper. The discrepancy between the VK model and the *IRAS* observations therefore suggests that IC dust is significantly underabundant compared with its abundance in the interstellar medium. The observed visual extinction through the cluster center can therefore not be attributed to dust within the central 3 Mpc radius of the cluster. We will discuss various possibilities for the source of the extinction in § III. In § II we present our model for the IR emission from the Coma cluster, and in § III we discuss its effect on the cooling of the IC cluster gas, on the diminution in the CMB, and the applicability of our calculations to other clusters.

## II. INTRACLUSTER DUST

### a) *Survival of Intracluster Dust*

Intracluster dust could have been injected into the IC medium abruptly, either during cluster formation or from some more recent violent event, or continuously since that time by galactic mass-loss processes. These injection modes span the entire range of possibilities. The first mode, the abrupt ejection of dust from galaxies in a single event, is of little practical interest, unless the event was very recent (a few $10^8$ yr; see also Hu 1987), since the small amount of dust that survives destruction by sputtering will have no observable consequences. A dust grain that is injected into the intracluster space will be continuously sputtered by the ambient hot gas. For gas temperatures above $\sim 10^7$ K the survival time (in years) of a dust particle of radius $a$ is only weakly dependent on gas temperature, and is given by (Draine and Salpeter 1979):

$$\tau_{\rm sput}(a, r) \approx \frac{10^6\, a(\mu{\rm m})}{n(r)}, \tag{1}$$

where $a$ is the grain radius in microns, and $n(r)$ is the gas density at distance $r$ from the center of the cluster. Typical gas densities in cores of rich clusters are roughly few $10^{-3}$ cm$^{-3}$. Since interstellar grains are smaller than $\sim 0.5$ $\mu$m (Mathis, Rumpl, and Nordsieck 1977, hereafter MRN), grains will survive at most roughly few $\times 10^8$ yr in the central region of a rich cluster. Sufficiently large ($>0.1$ $\mu$m) primordial dust grains can survive only outside the central few Mpc; however, their contribution to the observed extinction depends critically on their abundance, i.e., on the amount of gas in that region. There could be a significant amount of gas beyond 3 Mpc, but so far we have no direct evidence for its presence at such large distances from the cluster center. This possibility will, however, be discussed in more detail in § III. In the following we will consider the other extreme possibility, the continuous injection model, in which the dust is continually being replenished by the cluster galaxies.

### b) *Size and Spatial Distribution of the Dust*

Dust may be continuously injected into the IC space in the form of galactic winds or any other interstellar mass loss process. Grain destruction in transit to the IC medium can be important, however, its details are uncertain. For the sake of simplicity, we will assume that the dust is "instantly" mixed with the hot IC gas and that the initial dust-to-gas mass ratio, $Z_d$, is equal to 0.0075, its value in the interstellar gas (MRN). Our neglect of grain destruction during the injection phase will not affect the general shape of the grain size distribution (see below). However, all our subsequent results will be strict upper limits on the IR emission from the cluster. The steady state size-diffusion equation can be written as

$$\frac{dn_d(a, r)}{da} = \left[\frac{\tau_{\rm sput}(a, r)}{a}\right]\left[\frac{dn_{d,i}(a, r)}{dt}\right], \tag{2}$$

where $dn_d(a, r)$ is the number density of dust grains at distance $r$ in the size interval $a$ and $a + da$, and $dn_{d,i}(a, r)/dt$ is the initial injection rate of dust particles of radius $a$ per unit volume. The dust particles injected into the IC gas are likely to form a dust trail behind their parent galaxy analogous to the dust trails found behind comets. The density profile of the newly injected dust will therefore follow that of the galaxy distribution. We will assume that the grains are ejected from the galaxies with an $a^{-k}$ power law distribution in the size interval $a_1$ to $a_2$, chosen to be 3 Å to 0.2 $\mu$m. If we assume that all the IC gas originated from galaxies, and that the gas outflow remained constant during the cluster lifetime $\tau_0 \approx \frac{2}{3} H_0^{-1}$ (where we take $H_0 = 50$ km s$^{-1}$ Mpc$^{-1}$), then the steady state grain size distribution is given by

$$n_d(a, r) = \frac{\tau_{\rm sput}(a, 0)}{\tau_0}\,\frac{\mu n_g(0) m_{\rm H} Z_d}{\langle m_d \rangle}\left[\frac{g(r)}{f(r)}\right]\left(\frac{a^{-k}}{k-1}\right), \tag{3}$$

where $\mu$ is the mean atomic weight (in amu) of gas, $n_g(0)$ is the gas density at the center of the cluster, $f(r)$ its radial profile distribution, $g(r)$ is the radial distribution of the galaxies in the cluster, $m_{\rm H}$ is the hydrogen mass, and $\langle m_d \rangle$ is the average mass of a grain in the size interval $\{a_1, a_2\}$. Two important characteristics of the IC dust distribution $n_d(a, r)$ are (1) an approx-

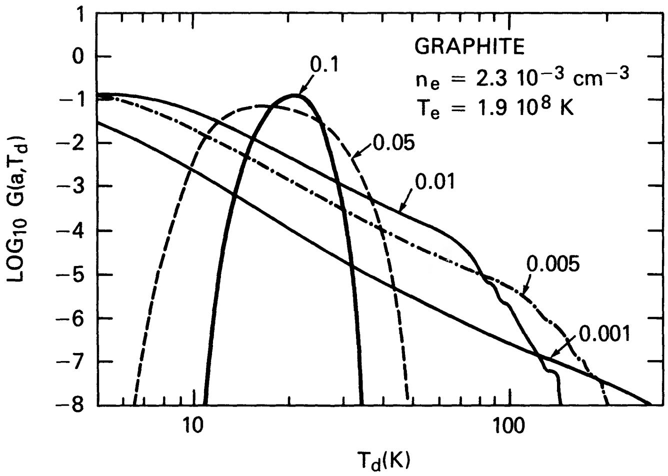


FIG. 1.—The temperature distribution of graphite dust particles in the central region of the Coma cluster is shown as a function of temperature for various grain sizes. Electron temperature and density in this region are $1.9 \times 10^8$ K and $2.3 \times 10^{-3}$ $cm^3$, respectively.

imate $a^{-k+1}$ dependence on grain size, reflecting the flattening of the size distribution due to sputtering; and (2) a $g(r)/f(r)$ radial profile, reflecting the combined effect of diminishing sources (galaxies), and increased grain lifetime with decreasing gas density, as a function of cluster radius. We point out that, strictly speaking, this steady state applies only at distances where the sputtering time does not exceed the age of the cluster. Outside the central 3–4 Mpc region, the dust density monotonically increases if the dust is continually ejected by the galaxies.

### b) *Dust Temperature Distribution*

In low-density astrophysical plasmas a dust particle may be stochastically heated by the ambient gas and undergo temperature fluctuations (Dwek 1986). The dust temperature is then described by a probability $P(a, T_d)dT_d$ of being in the temperature interval $T_d$ and $T_d + dT_d$. Figure 1 shows the temperature distribution of various size graphite particles collisionally heated in the central annulus of the Coma cluster ($n_e = 2.3 \times 10^{-3}$ $cm^{-3}$, $T_e = 1.9 \times 10^8$ K) as a function of dust temperature $T_d$. Only above sizes of $\approx 0.1$ $\mu$m do the probability functions start to converge to the equilibrium dust temperature, which in this region is $\sim 20$ K. For these grain sizes $P(a, T)$ can be approximated by a $\delta$-function at the equilibrium dust temperature. Table 1 lists the equilibrium temperature of 0.2 $\mu$m dust particles in various concentric shells (see below) around the cluster's center. At the high temperatures ($T > 3 \times 10^7$ K) that prevail in clusters an analytical approximation to the dust temperatures is (Dwek 1987):

$$T_d \approx 57 n^{0.18} . \quad (4)$$

Note that HCW and Hu (1987) incorrectly extrapolated the $\sim T^{3/2}$ behavior of the dust heating rate, strictly applicable to temperatures below $\sim 2 \times 10^7$ K, to the high temperature regime, where the dust particles become transparent to the incident electrons.

TABLE 1

EQUILIBRIUM GRAPHITE TEMPERATURE DISTRIBUTION IN THE COMA CLUSTER

| Shell Radii[a] (Mpc) | $n_e$[b] ($cm^{-3}$) | $T_e$ ($10^7$ K) | $T_d$[c] (K) |
|---|---|---|---|
| 0.0–0.2...... | 2.3 (−3) | 19.3 | 20.0 |
| 0.2–0.4...... | 1.5 (−3) | 15.5 | 18.1 |
| 0.4–0.6...... | 8.5 (−4) | 11.7 | 16.5 |
| 0.6–1.0...... | 4.0 (−4) | 8.0 | 14.3 |
| 1.0–1.4...... | 1.8 (−4) | 5.4 | 12.7 |
| 1.4–2.2...... | 7.7 (−5) | 3.5 | 10.5 |
| 2.2–3.0...... | 3.4 (−5) | 2.3 | 8.2 |
| 3.0–3.8...... | 1.9 (−5) | 1.7 | 7.0 |
| 3.8–5.0...... | 1.1 (−5) | 1.3 | 6.5 |
| 5.0–7.0...... | 5.2 (−6) | 0.9 | 5.1 |

[a] Calculated for $H_0 = 50$ km $s^{-1}$ $Mpc^{-1}$.
[b] Numbers in parentheses are powers of 10.
[c] Dust temperature was calculated for 0.2 $\mu$m dust grains.

### c) *Infrared Emission*

The infrared intensity of a cluster at any projected distance $d$ from its center is given by an integral over the line of sight $l$ through the cluster:

$$I_\nu(d) = \int \left\{ \int da \pi a^2 Q_\nu(a) n_d(a, r) \left[ \int P(a, T_d) B_\nu(T_d) dT_d \right] \right\} dl , \quad (5)$$

where $B_\nu$ is the Planck function, and $Q_\nu$ the dust absorption efficiency at frequency $\nu$.

To calculate the infrared intensity of the Coma cluster we divided the cluster into 10 shells centered on $\alpha$(1950); $\delta(1950) = 12^h57^m$; 28°14′. In all our calculations we adopted the dust optical properties presented by Draine and Lee (1984). In characterizing the IC gas we adopted the parameters of the Coma cluster as presented by Henriksen and Mushotzky (1986). The radial profile of the gas density distribution is given by $f(r) = [1 + (r/r_1)^2]^{-1.14}$, and that of the galaxy distribution is given by $g(r) = [1 + (r/r_2)^2]^{-3/2}$, where $r_1$ and $r_2$ are typical scalelengths equal to 0.4 and 0.25 Mpc, respectively. The gas temperature follows a $f(r)^{1/2}$ radial dependence. The central values of the gas density and temperature are $2.5 \times 10^{-3}$ $cm^{-3}$ and $2 \times 10^8$ K, which are representative values within the 90% confidence levels in the best-fit analysis of the X-ray data by HM. The average values of the density and temperature in each shell are given in Table 1. The dust temperature distribution and resulting infrared spectrum in each shell was then calculated using the numerical algorithm and dust properties described by Dwek (1986). The line-of-sight contribution of all the shells to the spectrum in a given annulus was calculated by a numerical integration.

Figure 2 shows the dust spectrum in the central and tenth annulus of the cluster. The figure shows that the effect of the temperature fluctuations is to broaden the infrared spectrum, compared to that of dust emitting at the equilibrium temperature, and that the effect is most pronounced at large distances from the center of the cluster.

Figure 3 shows the dust emission profile across the cluster for several selected wavelengths of interest to the *IRAS* and the future *Cosmic Background Explorer* (*COBE*) mission. Our calculated 100 $\mu$m brightness in the cluster center is $\approx 0.2$ MJy $sr^{-1}$, or $\sim 500$ times lower than the value obtained by VK. The discrepancy can be attributed in part to the fact that our calculated dust temperature is lower than the value derived by VK, and in part to the fact that VK normalized their dust abundance to the observed visual extinction. We emphasize that even our lower calculated fluxes represent upper limits on any actual IR emission, since we assumed that dust is injected with an undepleted interstellar dust-to-gas mass ratio into the IC

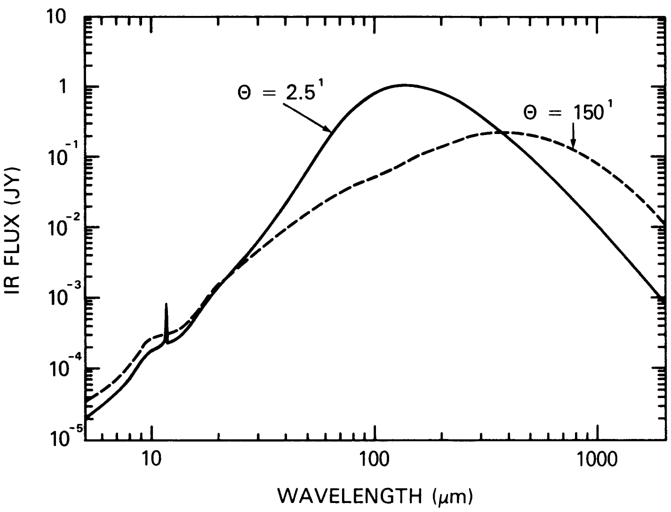


FIG. 2.—The integrated line-of-sight spectrum of the dust in the central (*solid line*), and tenth (*dashed line*) annulus of the cluster. The radii of the annuli are given in Table 1.

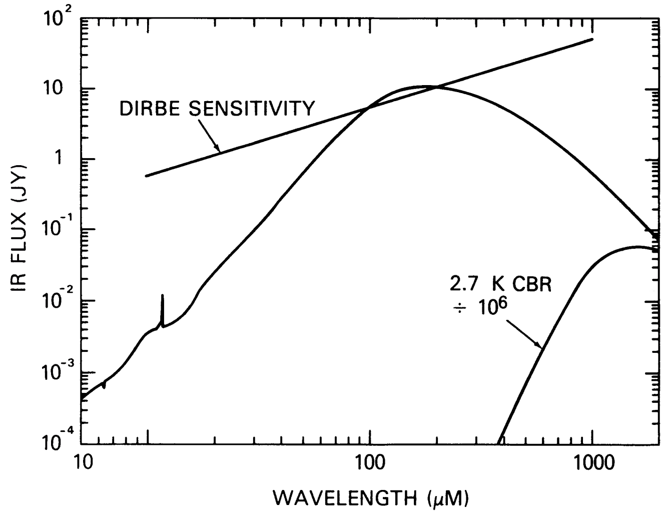


FIG. 4.—The total integrated flux from the Coma cluster. For comparison we also show the CMB flux in a 42′ beam (*dotted line*), and the sensitivity of the DIRBE in the same sized beam.

space. Our results are in general agreement with those of HCW. These authors estimate that $T_d \approx 20$ K, and obtain a core brightness which is roughly comparable to our value.

The stochastic dust-heating model used in this paper predicts a qualitatively different spatial distribution of the infrared emission compared to the equilibrium-heating model. In the equilibrium heating model the infrared fluxes at the Wien side of the spectrum decrease rapidly with distance from the cluster as $\exp\{-[654/\lambda(\mu\text{m})f(r)^{1/2}]\}$. In the stochastic heating model, the decrease in the short wavelength flux with increasing distance is associated with the increase in the time interval between collisions, and therefore declines more gradually as $f(r)^{5/4}$. For comparison we also plot in Figure 3 the 25 and 60 μm emission profiles (*dashed lines*) obtained with the equilibrium heating model.

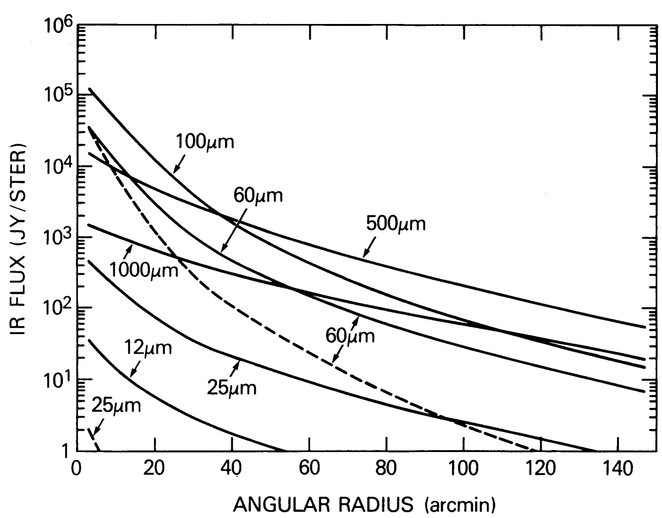


FIG. 3.—The infrared intensity at several selected wavelengths is shown as a function of angular distance from the center of the cluster. The 100 μm upper limit obtained with the *IRAS* (off scale) is 7 MJy sr$^{-1}$. Stochastic heating affects mostly the IR emission profile at wavelengths shorter than $\approx 60$ μm, and for comparison we also show in the figure the 25 and 60 μm intensities (*dashed lines*) of large grains that are at the equilibrium temperature at each point in the cluster.

In Figure 4 we present the total integrated IR flux from the cluster. Also shown in the figure is the sensitivity of the Diffuse Infrared Background Experiment (DIRBE) on the *COBE*, calculated for a 42′ beam, and the flux density of the CMB for the same beam size. The figure shows that the cluster will be barely detectable by the *COBE* satellite if there is no confusion from interstellar cirrus in the Galaxy. The total IR luminosity emitted within the central 3 Mpc radius of the cluster (for a cluster distance of 138 Mpc; $H_0 = 50$ km s$^{-1}$ Mpc) is $\approx 6 \times 10^{44}$ ergs s$^{-1}$, and the total calculated IC dust mass from the same region is $\approx 1.1 \times 10^{10}$ $M_\odot$. The mass of gas within the same radius is $\approx 2 \times 10^{14}$ $M_\odot$ (HM), implying an average dust-to-gas mass ratio of $\sim 5.5 \times 10^{-5}$ in the IC gas. The dust is therefore depleted by a factor of $\sim 140$ compared to its abundance in the general interstellar medium. A similar value for the depletion factor is obtained by comparing the IR luminosity from the cluster with that obtained from a gas with a *normal* dust-to-gas mass ratio. At gas temperatures above $\sim 2 \times 10^7$ K, the total IR luminosity for a gas with an interstellar dust-to-gas mass ratio is approximately given by (Dwek 1987; Fig. 4):

$$L(\text{ergs s}^{-1}) \approx 4 \times 10^{-21} n^2 V , \qquad (6)$$

where $V$ is the volume of the emitting region. The average gas density in the central 3 Mpc region of the cluster is $\sim 7 \times 10^{-5}$ cm$^{-3}$, giving an IR luminosity of $\sim 7 \times 10^{46}$ ergs s$^{-1}$. The dust is therefore depleted by a factor with an average value of $\sim 120$ in the central 3 Mpc region of the cluster. In the cluster core ($R < 0.4$ Mpc) the average dust-to-gas mass ratio is further reduced by about a factor of 3.

## III. DISCUSSION

### a) *Origin of the Visual Extinction*

Our calculations suggest that dust should be depleted by about two orders of magnitude in the central 3 Mpc of the cluster. However, the extinction measurements by Zwicky (1962) and KL, the upper limits from line ratios discussed by HCW, and the observed anticorrelation of UVX objects with galaxy clusters (BFS), all suggest the presence of dust in the cluster. If the dust in Coma has properties similar to that of galactic dust, then the gas column density is related to the extinction by $N_H = 1.9 \times 10^{21} A_V$ cm$^{-2}$ (e.g., Savage and Mathis 1979). For an average value of $A_V = 0^m.2$, we get $N_H \approx 3.8 \times 10^{20}$ cm$^{-2}$. This is the column density of gas (containing an undepleted abundance of interstellar dust) required to account for the observed visual extinction. Suppose that the observed extinction was confined to the central region of the cluster and caused by dust within the cluster core ($R < 0.4$ Mpc). The average gas column density in an annulus of 0.4 Mpc around the cluster's center is $2.7 \times 10^{21}$ cm$^{-2}$. The dust-to-gas mass ratio required to explain the observed extinction must then be $\sim 14\%$ of the interstellar value, giving a total dust mass of $1.1 \times 10^{10}$ $M_\odot$. If the observed extinction is an average over a larger area of the cluster, say between $\theta = 0-55'$ ($R$ = 0–2.2 Mpc), than the amount of dust required to account for the extinction is increased. A calculation similar to the one above gives an average $Z_d$ equal to 27% of its interstellar value, and a total amount of dust equal to $3.4 \times 10^{11}$ $M_\odot$. The presence of that amount of dust within the central region is precluded both on theoretical grounds, because of the finite dust lifetime in the IC medium, and on observational grounds based on the *IRAS* upper limit on the IR emission from the cluster.

There are several possible ways to explain the discrepancy between the observed extinction measurements and the lack of corresponding IR emission from the cluster center. The extinction could be due to dust outside galaxies, but this is not likely, since only a small fraction of the dust and gas can be present in presure-confined clouds in the IC gas (Rephaeli and Wandel 1985). Alternatively, the extinction could arise from dust in galaxies. This possibility is *a priori* unlikely as well, since only a fraction of the lines of sight through the cluster will intercept a galaxy. Ignoring this difficulty, we find that the average mass of gas, containing a normal dust-to-gas mass ratio, required to be present within the 3 Mpc radius from the cluster center is $\pi R^2 m_H N_H \approx 9 \times 10^{13}$ $M_\odot$ (For $N_H = 3.8 \times 10^{20}$ cm$^{-2}$). The number of galaxies within this region is $\sim 1200$ (Rood *et al.* 1972), requiring the average mass of gas and dust in a galaxy to be $\sim 7 \times 10^{10}$ and $\sim 5 \times 10^{8}$ $M_\odot$, respectively. This gas mass is significantly larger than the typical value of $\approx 5 \times 10^{9}$ $M_\odot$, deduced by Canizares, Fabbiano, and Trinchieri (1987) for a sample of early-type galaxies. Spiral galaxies may contain more gas and dust, but they comprise only $\approx 20\%$ of all galaxies in Coma and are found mostly outside the central region of the cluster. If the observed extinction is attributed to dust in spirals, the required mass of dust in each galaxy would be $\approx 3 \times 10^{9}$ $M_\odot$, implying a gas mass of $\sim 4 \times 10^{11}$ $M_\odot$. This is much higher than the average value of $\approx 10^{10}$ $M_\odot$ of gas in spirals (Bothun 1984; Verter 1987). BFS applied arguments similar to those presented above, to rule out the possibility that the extinction could be due to dust in extensive galactic haloes.

An alternative possibility is that the observed extinction could be due to dust at distances larger than some $R_0$ from the cluster center. The value of $R_0$ cannot be too large, since there may not be enough gas to account for the observed extinction. We find that $R_0$ must be at most 2.2 Mpc. The average column density of gas through the cluster is then $3.7 \times 10^{20}$ cm$^{-2}$ ($4.5 \times 10^{20}$ cm$^{-2}$ within a central annulus of 2.2 Mpc, and $2.9 \times 10^{20}$ cm$^{-2}$ through the outer region of the cluster), about equal to the total column density required by the observed extinction. This requires the cluster dust to be virtually undepleted beyond $R = 2.2$ Mpc. At the densities that prevail in these regions ($n \approx 10^{-5}$ cm$^{-3}$) all dust particles with radii less than 0.12 are completely destroyed within a Hubble time. Since the dust extinction efficiency is approximately proportional to grain radius (see Draine and Lee 1984), the extinction cross section will be proportional to the dust mass. For an MRN dust model in which the grain size spectrum extends up to 0.5 $\mu$m, only $\approx 15\%$ (by mass) of the primordial dust will survive in the cluster. (Note that the mass of a dust particle with an initial size of 0.5 $\mu$m will be reduced by about a factor of 2 when its radius is decreased by 0.1 $\mu$m.) Primordial dust at $R > 2.2$ Mpc can therefore account for only $\sim 15\%$ of the observed extinction. Hu (1987), suggests that the dust responsible for the extinction may have been only recently injected into the cluster atmosphere. If so, this dust must have been injected at large distances from the cluster center, otherwise it would give rise to observable *IRAS* emission. Gas poor spirals should therefore preferentially lie on orbits that carry them into the outer regions of the cluster, contrary to the conclusions reached by Dressler (1986). Furthermore, this explanation encounters the same problem as the one that attempted to attribute the observed extinction to member galaxies in the cluster; it requires an excessive amount of gas to be injected by the cluster galaxies into the IC medium.

We conclude that the observed visual extinction cannot be explained by any distribution of dust in the central region of the Coma cluster and cannot be attributed to dust in galaxies. Dust at large distances ($>2$ Mpc) from the cluster center can, in principle, account for the observed visual extinction, however the dust needs then to be undepleted in these regions of the cluster. Our calculations show that only a small fraction of the primordial dust will survive, and the injection of dust from spiral galaxies encounters problems as well. There always remains the possibility that the visual extinction may have been significantly overestimated. For example, in KL, the visual extinction is deduced from a decrease in the number of clusters seen through Coma. The number of observed clusters is 11, whereas 20 are expected on the basis of statistical arguments. Because of the small number of clusters in the sample the resulting value for the extinction is only a 2 $\sigma$ effect. On the other hand, if confirmed, the visual extinction will imply the presence of dust, and by inference gas, at large distances from the cluster center, and in excess of that deduced from current X-ray observations.

We cannot exclude the possibility that there may be a large mass of gas that has so far escaped any direct detection at large distances from the cluster center. The observed extinction may be a manifestation of its presence. Future observations may clarify the issue, and resolve the current discrepancy or ambiguity between the observed extinction and the *IRAS* observations.

### *b) Infrared Cooling of the Intracluster Gas*

The total thermal X-ray luminosity from within 3 Mpc radius of Coma is $\approx 1.7 \times 10^{45}$ ergs s$^{-1}$ (Mushotzky *et al.* 1978). This cooling has led to the suggestion that some heating mechanism may be required for the gas (Tucker and Rosner 1983; Rephaeli 1987*a*). Analysis of the IR emission from supernova remnants showed that infrared cooling by gas-grain collisions dominates the cooling of the remnants by factors ranging from $\sim$5–1000 (Graham *et al.* 1987; Dwek *et al.* 1987). It is therefore interesting to examine whether the collisional heating of dust will be important in the overall thermal balance of the IC gas as well. A comparison of the X-ray luminosity with that in the infrared shows that gas cooling by X-ray emission dominates the IR cooling by at least a factor of $\sim 3$. The IR emission from the IC gas is therefore not a very important gas cooling mechanism.

### c) *Relevance to Other Clusters*

The X-ray properties of clusters are correlated to cluster richness class. The IC gas in a rich cluster will have a higher density and temperature, and hence a higher X-ray emissivity, compared to that of a poor cluster. We do not expect a similar correlation between cluster richness and its IR properties. At gas temperatures above $\approx 2 \times 10^7$ K the collisional heating rate of the dust saturates as a function of gas temperature (Dwek 1987). The dust temperature scales as $n_{\rm gas}^{0.18}$, so that its value may be higher by $\sim 25\%$ compared to poor clusters that have gas densities that are typically lower by a factor of $\approx 3$. Compared to their rich counterparts, the lower gas density in poor clusters will ensure a longer dust survival time in the IC medium; however, their lower gas content may mean that less dust is being injected into the IC medium. To summarize, the most obvious correlation expected is that of dust temperature and cluster richness, but the dependence is weak, and its detectability is dominated by observational constraints.

### d) *Comparison of Dust Centimeter-Wavelength Emission with CMB Diminution*

It is of interest to compare the long-wavelength dust emission with the expected Thomsonization of the cosmic blackbody spectrum along lines of sight through clusters. Such a comparison has been made by Voshchinnikov and Khersonskij (1984*b*), who showed that the IR emission from the dust has a negligible effect on distortions of the CMB. This conclusion is not changed but is somewhat strengthened by the consideration of transient heating of small grains. Grains smaller than 0.1 $\mu$m are mostly at temperatures well below the equilibrium value for larger grains, and the time-averaged temperature is also reduced. This average temperature is the parameter which governs the dust emission in the Rayleigh-Jeans region. The distortion of the CMB due to cluster dust at an effective temperature $T_{\rm eff}$ at wavelength $\lambda$ can be written as

$$\frac{\Delta I(\lambda)}{I(\lambda)} = \mathcal{M}_d K(100\ \mu{\rm m}) \left(\frac{\lambda}{100\ \mu{\rm m}}\right)^{-2} \frac{B_\nu(T_{\rm eff})}{B_\nu(T_{\rm CMB})} \qquad (7)$$

where $K(100\ \mu{\rm m})$ is the dust mass absorption coefficient at 100 $\mu$m, $\mathcal{M}_d$ is the mass column density of dust in the cluster, $B_\nu(T)$ is the Planck function at temperature $T$, and $T_{\rm CMB}$ is the temperature of the CMB. We adopted a $\lambda^{-2}$ long-wavelength emissivity law for the dust. The value of $K(100\ \mu{\rm m}) \approx 45$ cm$^2$ g$^{-1}$ (Draine and Lee 1984), and the dust mass column density in our model is $\mathcal{M}_d \approx 8 \times 10^{-8}$ g cm$^{-2}$. If we assume that the effective grain temperature is 20 K, then $\Delta I/I \approx 3 \times 10^{-9}$ and $7 \times 10^{-6}$ at wavelengths of 1 cm and 1 mm, respectively. In comparison, the predicted distortion of the CMB due to Thomson scattering is $\Delta I/I = -2.5 \times 10^{-4}$ and $9 \times 10^{-4}$ (Rephaeli 1987*b*). Dust emission has therefore a negligible effect on distorting the CMB spectrum in the Rayliegh-Jeans region. The two effects become comparable at 1 mm only if *all* the presumed visual extinction through the cluster is attributed to IC dust.

This work was supported by the NASA *Cosmic Background Explorer* (*COBE*) project.

## REFERENCES


Bothun, G. D. 1984, *Ap. J.*, **277**, 532.
Boyle, B. J., Fong, R., and Shanks, T. 1988, *M.N.R.A.S.*, **231**, 897.
Burke, T. R., and Silk, J. 1974, *Ap. J.*, **190**, 1.
Canizares, C. R., Giuseppina, F., and Trinchieri, G. 1987, *Ap. J.*, **312**, 503.
Draine, B. T., and Lee, H. M. 1984, *Ap. J.*, **285**, 89.
Draine, B. T., and Salpeter, E. E. 1979, *Ap. J.*, **231**, 77.
Dressler, A. 1986, *Ap. J.*, **301**, 35.
Dwek, E. 1986, *Ap. J.*, **302**, 363.
———. 1987, *Ap. J.*, **322**, 812.
Dwek, E., Petre, R., Szymkowiak, A., and Rice, W. L. 1987, *Ap. J.* (*Letters*), **320**, L27.
Graham, J. R., Evans, A., Albinson, J. S., Bode, M. F., and Meikle, W. P. S. 1987, *Ap. J.*, **319**, 126.
Henriksen, M. J., and Mushotzky, R. F. 1986, *Ap. J.*, **302**, 287 (HM).
Hu, E. M. 1987, in *Cooling Flows in Clusters and Galaxies: Proc. NATO Advanced Research Workshop*, ed. A. C. Fabian (Cambridge: Cambridge University Press).
Hu, E. M., Cowie, L. L., and Wang, Z. 1985, *Ap. J. Suppl.*, **59**, 447.
Karachentsev, I. D., and Lipovetskii, V. A. 1969, *Soviet Phys.*, **12**, 909 (KL).
Mathis, J. S., Rumpl, W., and Nordsieck, K. H. 1977, *Ap. J.*, **217**, 425 (MRN).
Mushotzky, R. F., Serlemitsos, P. J., Smith, B. W., Boldt, E. A., and Holt, S. S. 1978, *Ap. J.*, **225**, 21.
Rephaeli, Y. 1987*a*, *M.N.R.A.S.*, **225**, 851.
———. 1987*b*, *M.N.R.A.S.*, **228**, 29p.
Rephaeli, Y., and Wandel, A. 1985, *M.N.R.A.S.*, **215**, 453.
Rood, H. J., Page, T. L., Kintner, E. C., and King, I. R. 1972, *Ap. J.*, **175**, 627.
Sarazin, C. L. 1986, *Rev. Mod. Phys.*, **58**, 1.
Savage, B. D., and Mathis, J. S. 1979, *Ann. Rev. Astr. Ap.*, **17**, 73.
Silk, J., and Burke, J. R. 1974, *Ap. J.*, **190**, 11.
Tucker, W. H., and Rosner, R. 1983, *Ap. J.*, **267**, 547.
Verter, F. 1987, *Ap. J. Suppl.*, **65**, 555.
Voshchinnikov, N. V., and Khersonskij, V. K. 1984*a*, *Astr. Space Sci.*, **103**, 301.
———. 1984*b*, *Adv. Space Res.*, **3**, 443.
Yahil, A., and Ostriker, J. P. 1973, *Ap. J.*, **185**, 787.
Zwicky, F. 1962, in *Problems of Extragalactic Research*, ed. G. C. McVittie (New York: Macmillan), p. 149.



ELI DWEK and JOHN C. MATHER: Code 685, NASA Goddard Space Flight Center, Greenbelt, MD 20771

YOEL REPHAELI: School of Physics and Astronomy, Tel Aviv University, Ramat Aviv, Tel Aviv 69978, Israel