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ON THE ORIGIN OF EXTINCTION IN THE COMA CLUSTER OF GALAXIES

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SUMMARY: Visual extinction of distant clusters seen through the Coma cluster seem to suggest 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 have carried out a detailed analysis of the properties of intracluster dust in the context of a model which includes continuous injection of dust by the cluster galaxies, grain destruction by sputtering, and transient grain heating by the hot plasma. Our computed infrared fluxes are in agreement with the upper limit obtained from the IRAS. The calculations, and the constraint implied by the IRAS observations, suggest that the intracluster dust must be significantly depleted compared to interstellar abundances. We discuss possible explanations for the discrepancy between the observed visual extinction and the IRAS upper limit.

The presence of metal-enriched intracluster (IC) gas in clusters of galaxies has been extensively established by X-ray spectral and line measurements. This 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 possible existence of dust in the IC space had been deduced from extinction measurements. Zwicky (1962) was first to estimate the extinction of light from distant clusters by nearby ones. For the Coma cluster he found $A_V \sim 0.4$m. Using the same method, Karachentsev and Lipovetskii (1969) found a value of $A_V \sim 0.3$m for the Coma cluster, and averaging over 15 clusters they estimated a mean cluster extinction of $A_V \sim 0.2\text{m} \pm .05$m. 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. If all the extinction is attributed to IC dust, then the IC dust-to-gas mass ratio in the central $\sim$ 10' of the cluster should be about 0.1xZ, where Z=0.0075 is its galactic value.

The presence of IC dust can also be inferred from its IR emission. An early theoretical estimate of IC 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 about 30 K. Voshchinnikov and Khersonskij (1984; 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 of 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 gas. By normalizing the dust abundance to the observed extinction they in effect adopted a dust-to-gas mass ratio equal to $\sim$ 0.1xZ. Assuming a constant gas temperature throughout the cluster they calculated a dust temperature of $\sim$ 40 K in the center of the Coma cluster. The dust spectrum peaks at about 100 μm has a flux density of $\sim 3\text{x}10^3$ MJy sr^{-1} at that wavelength in the center of the cluster. HCW also considered IR emission from IC dust, and found typical dust temperatures of $\sim$ 20 K. Based on the measured extinction and X-ray determined gas mass in the cluster core, HCW derived a 100 μm flux density of $\sim 3\text{x}10^4$ Jy sr^{-1}. We obtain similar values, in spite of HCW's incorrect expressions for the dust heating rate and luminosity.

We have carried out a more detailed model for the infrared emission from the Coma cluster (Dwek, Rephaeli and Mather 1987). Here we briefly summarize the results of our work, concentrating only on the most basic considerations (see our paper for a more extensive and quantitative discussion). In our model, the abundance of IC dust is determined by the combined effects of continuous mass loss from 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 $\sim$ 0.15 μm. Second, an additional simplifying assumption made in the earlier calculations is that the IC grain size distribution is equal to that in the interstellar medium. In our model we obtain a more realistic characterization off IC dust by assuming that its injection rate into the IC medium is proportional to the spatial density distribution of galaxies in the cluster. The grain size distribution has been obtained assuming 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).

The results of our calculations show that the average dust-to-gas mass ratio in the central 3 Mpc region of the Coma cluster is significantly smaller, by about two orders of magnitude, than that in the average interstellar medium. As a result, only about 10% of the observed extinction through the cluster can be attributed to dust in the IC gas. We have compared the 100 μm brightness predicted by our model with IRAS observations, which set a limit of 7 MJy sr^{-1} on the emission from the cluster at this wavelength. 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 emission from the cluster galaxies. Even so, this limit is about 400 times lower than the brightness predicted by VK, but consistent with values derived also by HCW. 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. Thus, the observed visual extinction through the cluster cannot be attributed to dust within the central 3 Mpc region.

There are several possible ways to explain the discrepancy between the observed extinction measurements and lack of corresponding IR emission from the cluster. First, consider the possibility that the extinction is due to dust in the cluster galaxies. (Note that only a small fraction of the dust and gas can be present in pressure-confined clouds outside galaxies - Rephaeli and Wandel 1985.) If so, the average mass of gas, containing a normal dust-to-gas mass ratio, required to be present within the central 3 Mpc region is about 9×10^{13} M$_\odot$. The number of galaxies within this region is about 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 $\sim 5 \times 10^{9}$ 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 20% of all galaxies in Coma, and are found mostly outside the central region of the cluster. If the observed emission is attributed to dust in spirals, the required mass of dust in each galaxy would be $\sim 3 \times 10^{9}$ M$_\odot$, implying a gas mass of about 4×10^{11} M$_\odot$. This is much higher than the average value of $\sim 10^{10}$ M$_\odot$ of gas in spiral (Bothun 1984, Verter 1987). A second possibility is that the observed extinction could be due to dust at large distances, R>3 Mpc from the cluster center. Assuming that dust is undepleted at such distances, and that the extrapolated gas density profile remains unchanged, this dust can at most account for about one third of the observed extinction. We emphasize, however, that this value should be regarded as a strict upper limit since the assumptions made in its derivation are quite unrealistic. We expect the dust to be depleted somewhat during its transit to the IC space. Moreover, our assumed gas density profile (which has been deduced from the X-ray measurements) in the central cluster region is too shallow, and must steepen in the outer cluster region in order to avoid mass divergence. Hu (1987) suggests that dust responsible for the extinction may have been only recently injected into the IC space. But 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 take them into the outer regions of the cluster, contrary to the conclusions reached by Dressler (1986). In addition, excessive amount of gas has to be injected by the cluster spirals.

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. We also have to bear in mind the possibility that the visual extincion may have been significantly overestimated. 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 exctinction will imply the presence of dust and by gas at large distances from the cluster center. We hope that future observations will resolve the current discrepancy, or ambiguity, between the observed extinction and the IRAS observations.

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