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COLD DUST IN THE ISM?

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ABSTRACT

The spectrum of the Milky Way observed by the *COBE* FIRAS instrument shows an excess of long wavelength emission when compared to a single temperature $\sigma \propto \nu^2$ dust model. This excess could be due to a massive population of large spherical grains or to a very small mass of fractal grains. Fractal dust grains with low equilibrium temperatures can produce the bulk of the IR emission by single photon thermal pulsing with peak temperatures of ≈ 20 K.

1. INTRODUCTION

The search for very cold dust in the ISM has long been motivated by the intriguing coincidence between the energy density of starlight in our galaxy with the energy density of the 2.7 K cosmic microwave background. Hoyle & Wickramasinghe (1969) suggested that a sufficiently high density of impurities in dust grains would allow their equilibrium temperature to be 3 K, so that dust grains could produce the microwave background. However, Purcell (1969) pointed out that the Kramers-Kronig relationship restricts the possible long wavelength absorption behavior of dust grains. The Kramers-Kronig restriction on long wavelength absorption can be relaxed for lower-dimensional grain shapes: the one-dimensional needles or whiskers (Rana 1979; Wright 1982; Hoyle & Wickramasinghe 1988) or fractal dust grains with dimensions between 1.7 and 2.5 (Wright 1987; Wright 1989).

One can also have very cold dust in the ISM by reducing the optical absorption efficiency instead of increasing the sub-mm emission efficiency. Rowan-Robinson (1992) has modelled the emission from galaxies using a mixture of grain types that includes spherical carbon grains with 30 μm radius. These grains have very low cross section per unit mass in the optical, and thus have equilibrium temperatures near 5 K. If any substantial amount of power were radiated by dust at 5 K, then these grains would have to dominate the mass budget for interstellar dust.

Microwave background anisotropy experiments have also provided measurements of the millimeter wave emission from the Milky Way, as shown in Lubin & Villela (1986). The spectrum of the galaxy obtained by Wright *et al.* (1991) using the FIRAS instrument on *COBE* is another example.

The IRAS satellite provides a sensitive survey for almost all the sky at wavelengths $\lambda \leq 100$ μm. Paley *et al.* (1991) examined the IR and optical emission from a number of relatively isolated high latitude dust clouds and decided that three temperatures of dust were needed to explain their data: hot

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dust at 173 K, presumably transiently heated by single photon thermal pulsing (Purcell 1976); warm dust at 22.5 K; and a cold component with T < 15 K seen only in optical scattering with no $\lambda \leq 100\mu$m emission. Paley *et al.* found that these temperatures are very uniform, but that the ratio between the different components varied over the sky. Guhathakurta & Tyson (1989) found that the optical light from high latitude dust clouds is too red to be scattered light, and thus may be similar to the extended red emission (ERE) seen in reflection nebula by Witt & Schild (1988). The ERE is an extension of the 3 μm emission from thermally pulsing grains seen by Sellgren (1984).

2. OBSERVATIONS

Wright *et al.* (1991) measured the average spectrum of the Milky Way in the 1-90 cm^{-1} range and gave two fits to the continuum emission. One fit assumed two temperatures of dust with ν^2 emissivity laws:

$$g(\nu) \approx 0.00022(\nu/30\ \mathrm{cm}^{-1})^2[B_\nu(20.4) + 6.7B_\nu(4.77)] + S(\nu) \tag{1}$$

where $S(\nu)$ models the synchrotron emission. This should not be taken as proving the existence of dust with $T = 5$ K, since an alternate fit with a single dust temperature is almost as good:

$$g(\nu) \approx 0.00016(\nu/30\ \mathrm{cm}^{-1})^{1.65} B_\nu(23.3) + S(\nu) \tag{2}$$

This form also matches observations of external galaxies by Carico *et al.* (1992).

The cold component in Eq(1) contributes only $\tau_c T_c^6/\tau_w T_w^6 = 6.7(4.77/20.4)^6 = 0.1\%$ of the total power radiated by the warm dust. This very small fraction guarantees that the optical emission without IRAS 100 μm emission seen by Paley *et al.* is due to small transiently heated grains instead of large cold grains, since any component contributing only 0.1% of the high latitude optical cirrus would not be detectable by any observations made to date. This small fraction of the total power in the cold component also means that the large spherical grains proposed by Rowan-Robinson only require 12% of the cosmic carbon abundance.

3. THEORY

The ISM can be considered to contain a very dilute gas of dust grains, with density n, and polarizability $\alpha(\omega)$ (Purcell 1969). The dielectric constant of this medium is given by

$$\epsilon(\omega) = 1 + 4\pi n\alpha \tag{3}$$

The propagating waves have an E-field that follows

$$E = E_o \exp(i(\omega/c)x\sqrt{\epsilon} - i\omega t) \tag{4}$$

The absorption coefficient of the medium is

$$\kappa = 4\pi n\omega \mathrm{Im}(\alpha(\omega))/c = n\sigma_{\mathrm{ext}} \tag{5}$$

so

$$\sigma_{\rm ext} = 4\pi\omega {\rm Im}(\alpha(\omega))/c \tag{6}$$

Now for a small spherical grain

$$\alpha = \frac{a^3(\epsilon_m - 1)}{(\epsilon_m + 2)} \tag{7}$$

(where ϵ_m is the dielectric constant of the grain material) which yields the standard Mie theory small sphere result.

The impulse response function for the electric dipole of the grain, when exposed to $E = \delta(t)$, is

$$d(t) = \frac{1}{2\pi}\int \alpha(\omega)e^{-i\omega t}d\omega \tag{8}$$

but $d(t) = 0$ for $t < 0$ by causality. This shows that α has no poles in the upper half plane ${\rm Im}(\omega) > 0$. Thus the value of the integral

$$\oint \frac{\alpha(\omega)d\omega}{\omega - iy} = 2\pi i\alpha(iy) \tag{9}$$

for all $y > 0$ and is 0 for all $y < 0$. The principal value of the integral with $y = 0$ is

$$\int \frac{\alpha(\omega)d\omega}{\omega} = i\pi\alpha(0) \tag{10}$$

This gives the Kramers-Kronig relation between the DC polarizability and the integral of the absorption coefficient:

$$\alpha_{DC} = \frac{1}{\pi}\int {\rm Im}(\alpha)d\omega/\omega = \frac{c}{2\pi^2}\int_0^\infty \sigma_{\rm abs}d\omega/\omega^2 = \frac{1}{4\pi^3}\int_0^\infty \sigma_{\rm abs}d\lambda \tag{11}$$

There is one further limitation on the polarizability α and hence the cross-section σ. Since the response $d(t)$ to a real electric field $E(t)$ must be real, one derives that $\alpha(-\omega) = \alpha(\omega)^*$. This in turn implies that σ is an even function of ω. Thus

$$\sigma(\omega) = A + B\omega^2 + C\omega^4 + ..., \tag{12}$$

and, unless $\alpha_{DC} = \infty$, we know from the Kramers-Kronig relation that $A = 0$. However, the Stone-Weierstrass approximation theorem guarantees that any continuous function can be approximated to any desired precision by a polynomial, and thus one can always approximate any $\sigma(\omega)$ as a series in ω^2. Still, one should clearly favor functional forms for σ that are manifestly functions of ω^2, such as the $\sigma_o/(1+(\omega_o/\omega)^2)$ appropriate for constant conductivity needles.

In order to have a large long wavelength absorption cross-section per unit mass of dust, one clearly needs to maximize α/V. Since $\alpha \propto L^3$, where L is the maximum dimension of the dust grain, α/V is maximized for grains with one long axis and two small axes: needles. In general for a fractal dimension D the volume is $V \propto (l_o)^3(L/l_o)^D$, where l_o is the size of the building block

or monomer, so $\alpha/V \propto (L/l_o)^{D-3}$. Figure 1 shows α/V for the DLA and CL fractal grains considered by Wright (1989).

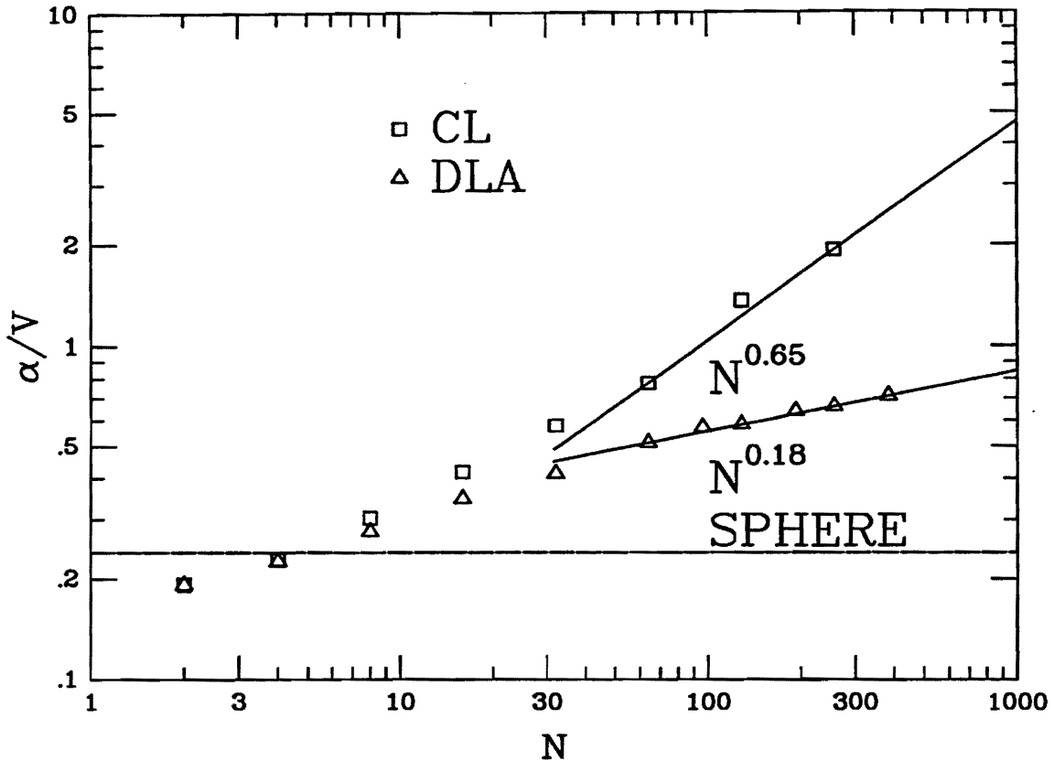

Fig. 1. Polarizability per volume *vs* number of subunits

4. THERMAL FLUCTUATIONS

Purcell (1976) found that for small interstellar grains the cooling time is about $400/T$ seconds. For small enough grains this is longer than the mean time between absorption of optical photons from the interstellar radiation field (ISRF). However, the cooling time depends on both the grain material and shape. Figure 2 shows the cooling times for graphite spheres, CL fractals and needles. Since graphite is such a good conductor, the graphite sphere behaves like a mirrored ball, reflecting all the IR radiation that hits it. This high reflectivity gives a low emissivity, and a long cooling time. On the other hand the fractal and needle have very short cooling times.

The ISRF can be reasonably well approximated by

$$I_\nu = 10^{-16} f_\nu (30766 B_\nu(2213) + 578 B_\nu(5280) + 1.14 B_\nu(24091)) \qquad (13)$$

where f_ν is 1 for $\lambda > 4000\mathring{A}$ and 0.56 for shorter wavelengths, with an expected sharp drop to zero shortward of 911 Å. In this ISRF the dust grains in Figure 2 have equilibrium temperatures shown by the dots on the cooling time curves.

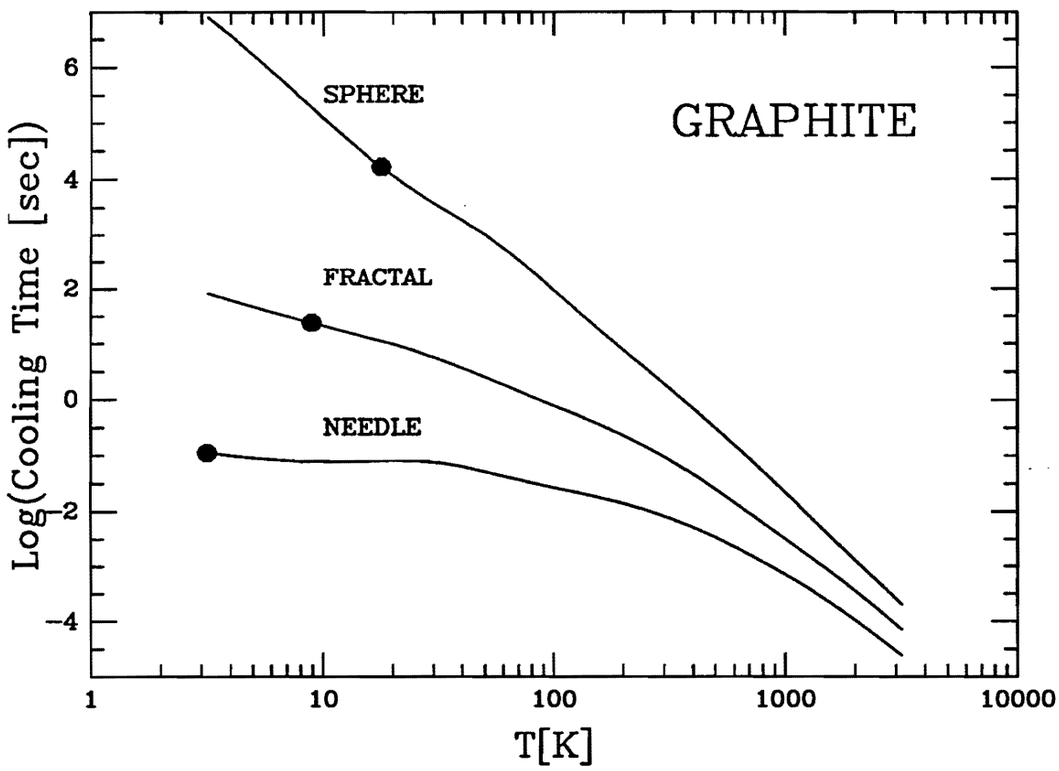

Fig. 2. Cooling time *vs* temperature for graphite grains

Because fractals and needles have such short cooling times, they will be far out of thermal equilibrium even for rather large masses. Figure 3 shows thermal time histories for a graphite sphere with a 100 Å radius, and a fractal and needle with the same mass as the sphere. Clearly the sphere is close to equilibrium, while the fractal shows large temperature swings, and the needle is entirely in the single photon limit. This means that the IR emission from fractals and needles is not determined by their equilibrium temperature, but rather by their enthalpy $U(T)$, their mass spectrum, and their absorption efficiency σ_ν.

The spectrum of the IR emission from thermally pulsing dust grains can be calculated using the method of Guhathakurta & Draine (1989). Figure 4 shows the *COBE* spectrum of the galaxy with the emission from a population of thermally pulsing DLA fractal grains made out of amorphous carbon, with equal total dust mass in logarithmic mass bins from 8,000 to 500,000 carbon atoms. The curve has been normalized so that it does not exceed the *COBE* spectrum at any wavelength. Extending the mass spectrum to smaller masses would clearly improve the fit at short wavelengths, and thus a population of thermally pulsing fractal grains can explain almost all of the IR spectrum of the galaxy. On the other hand, large fractal or needle-shaped grains can contribute at most a small fraction of the bolometric IR emission of the galaxy because their equilibrium temperatures are so low, and the *COBE* spectrum has such a small long wavelength excess.

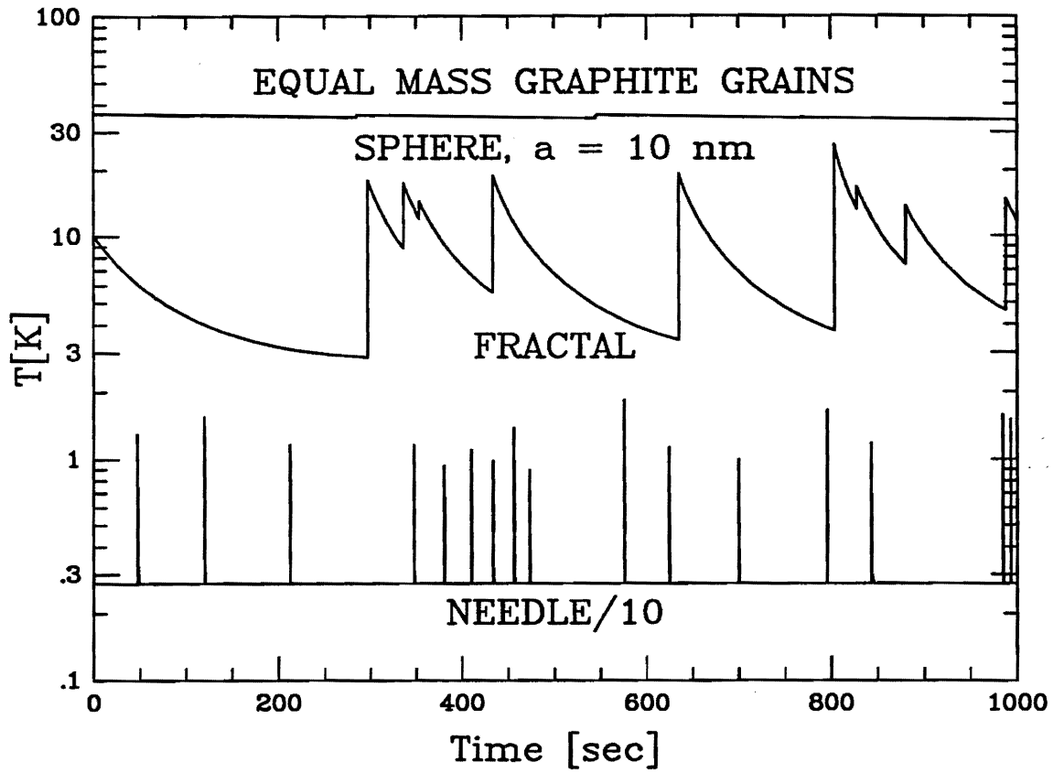

Fig. 3. Thermal time histories for graphite grains

5. CONCLUSIONS

Cold dust radiates only a small fraction (0.1 to 3%) of the total bolometric emission of IR dust. If the dust is cold because of a small optical σ/m then the mass fraction in the cold dust can still be substantial, as in the case of the 30 μm carbon spheres proposed by Rowan-Robinson (1992). In the case of fractal grains their low equilibrium temperature is caused by an increased sub-mm σ/m instead of a reduced optical σ/m. Thus if the fractal grains are in thermal equilibrium their mass fraction is limited to a few percent of the total dust mass. But thermally pulsing fractals with a suitable mass spectrum can produce close to 100% of the bolometric IR emission, and could thus make up close to 100% of the IS dust by mass. If so, the mass spectrum of the dust would have to vary from cloud to cloud to explain the results of Paley *et al.* (1991), and the high mass fraction would have to increase with galactocentric radius to explain the DIRBE results on the variation of the 240 μm to 100 μm color temperature that were presented at this conference by Sodroski *et al.* In this picture, most of the dust in the ISM is cold most of the time, but almost all of the IR emission is produced during brief warm intervals following the absorption of an optical photon.

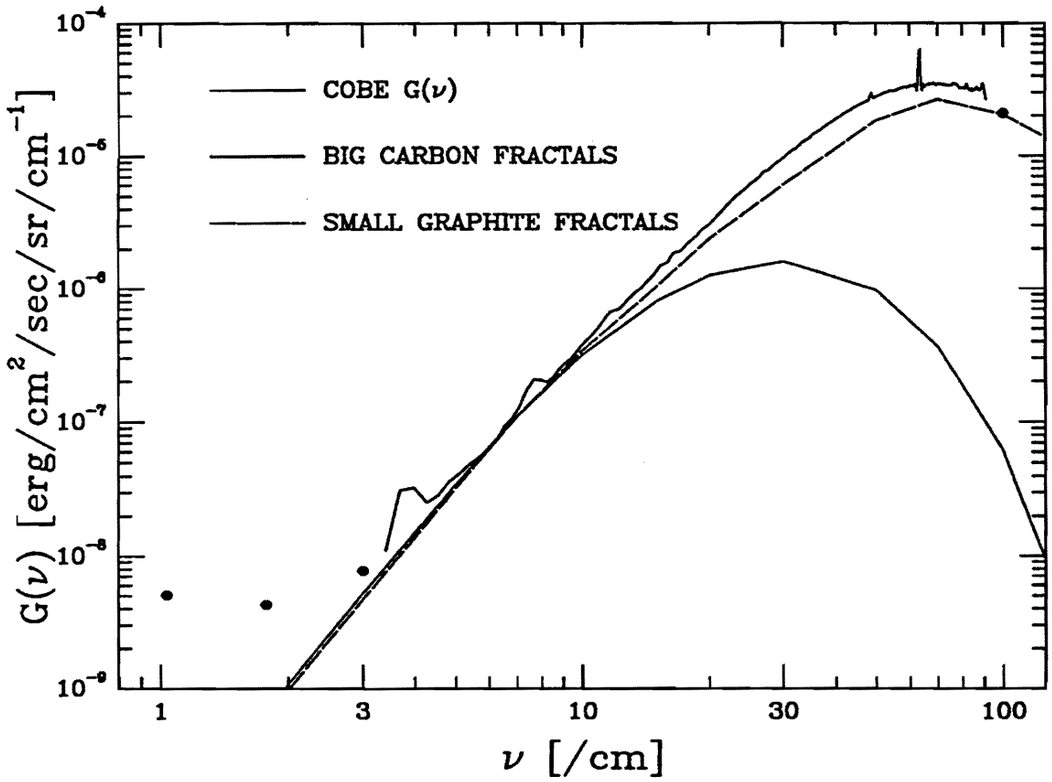

Fig. 4. Spectra of the galaxy and fractal dust

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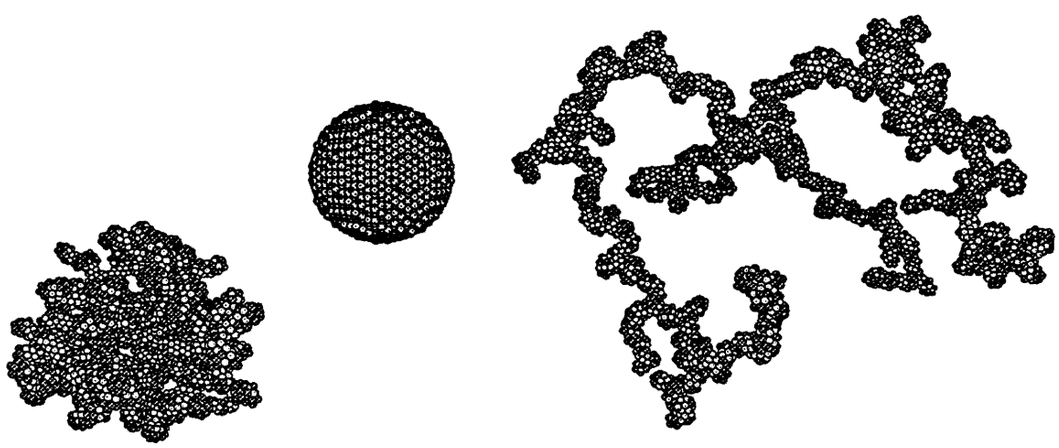

Fig. 5. Equal mass sphere (center), N = 1024 DLA fractal (left), & CL fractal (right).