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THERMAL PROPERTIES OF HETEROGENEOUS GRAINS

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Cometary dust is neither spherical nor homogeneous, yet these are the assumptions used to model the thermal, optical, and dynamical properties of cometary dust. To better understand the effects of heterogeneity on the thermal and optical properties of dust grains, the effective dielectric constant for an admixture of magnetite and a silicate were calculated using two different effective medium theories: the Maxwell-Garnett theory and the Bruggeman theory. Conceptually, the Maxwell Garnett (hereafter MG) theory describes the effective dielectric constant of a matrix material into which is embedded a large number of very small inclusions of a second material. The Bruggeman theory describes the dielectric constant of a well-mixed aggregate of two or more types of materials. Both theories assume that the individual particles are much smaller than the wavelength of the incident radiation.

The complex index of refraction (which is used as an input to Mie scattering calculations) for a heterogeneous grain using the MG theory is very similar to the complex index of refraction of the matrix material, even for large volume fractions of the inclusion. This is shown in Figure 1, where the real and imaginary parts of the complex index of refraction are plotted as a function of wavelength for magnetite, a silicate (*astronomical silicate*, Draine and Lee, 1984) and a 50-50 mix of these two minerals using the MG theory (both astronomical silicate and magnetite as the matrix material) and the Bruggeman theory. The Bruggeman theory retains the spectral features of both minerals. The thermal spectrum of a particle smaller than the wavelength of the incident radiation will show features similar to those seen in the imaginary component of the complex index of refraction.

The equilibrium grain temperature for spherical particles ranging in size from .001μm to 100μm in radius at 1 astronomical unit from the sun was calculated for a range of particles which differ only in the volume fraction of astronomical silicate and magnetite (Figure 2). For the MG theory, magnetite is assumed to be the matrix. For most grains, the equilibrium grain temperature of a heterogeneous grain is intermediate between the grain temperatures of the homogeneous grains; however, the temperature is not equivalent to a volume-weighted average of the homogenous grain temperatures. There are large differences between the equilibrium grain temperatures for the small grains using the two effective medium theories. For large grains, the equilibrium grain temperature of all grains shown in the figure approach that of a blackbody (indicated in Figure 2).

The shape of the curves in Figure 2 is easily understood. For the smallest grains, the absorptivity in the visible and emissivity in the IR are constant with size, hence the lack of change in the equilibrium temperature. The IR emissivity is relatively small, yielding the high temperature (pure astronomical silicate is transparent in the visible and near-IR, causing the equilibrium grain temperature to be smaller for the smallest grains). As the grain size increases, the optical absorptivity first increases slightly, then reaches a constant

value. This causes the slight increase in the temperature around 0.1μm. The IR emissivity increases for larger grain radii, causing a rapid decrease in the equilibrium temperature. As the size increases further, the IR emissivity and the optical absorptivity asymptotically approach a constant value, causing the equilibrium grain temperature to slowly increase with size.

The spectrum of heterogeneous grains in the thermal IR depends on the radius, the volume fractions of the materials, and the theory used. Figure 3 shows the thermal emission from 1μm and 10μm grains at 1 AU for homogeneous grains of magnetite and astronomical silicate and for a 50-50 admixture of these minerals using both the MG theory and the Bruggeman theory.

For the 1 μm grains (Figure 3a and 3b), the spectral features observed are those seen in their respective imaginary index of refraction (Figure 1). Differences in the integrated emissivities are partly due to differences in the equilibrium grain temperature of each grain at 1 AU – ranging from 306 K for magnetite to 340 K for the 50-50 mixture calculated with the Bruggeman theory – and partly due to the total energy absorbed (and hence re-emitted) by the grain. For example, even though magnetite and astronomical silicate have nearly equivalent equilibrium grain temperatures (306 K and 307 K, respectively), astronomical silicate absorbs, and hence re-emits, much less energy than the grain of magnetite. The spectral features of the heterogenous grains show the effect of the mixing theory used. For the MG theory, the spectral features are due primarily to the matrix material. For the Bruggeman theory, the spectral features of both materials are observed. In Figure 3b, this latter effect is seen as a strong absorption feature at 7.4μm and a strong emission feature at 10 μm superposed on the near-blackbody spectrum of pure magnetite.

The spectrum of a 10μm grain is very different than that of a 1μm grain (Figures 3c and 3d). At 10 μm, the emissivitiy of the grain is almost constant as a function of wavelength; hence, the spectrum is close to that of a blackbody, regardless of the composition. The small differences in the spectra of the 10μm grains are due to differences in equilibrium grain temperatures and to differences in the composition. For larger grains, this latter effect becomes even less important.

The observational consequences of these results are the following. 1) the thermal spectrum seen in most comets is due primarily to large grains. The composition and sizes of these grains is almost impossible to determine. 2) The presence of the 10μm silicate feature indicates the existence of small grains ($< 1\mu$m). 3) The degree of heterogeneity of these grains can be determined somewhat by looking at the relative intensity and slope of the thermal emission from about 4 to 8μm.

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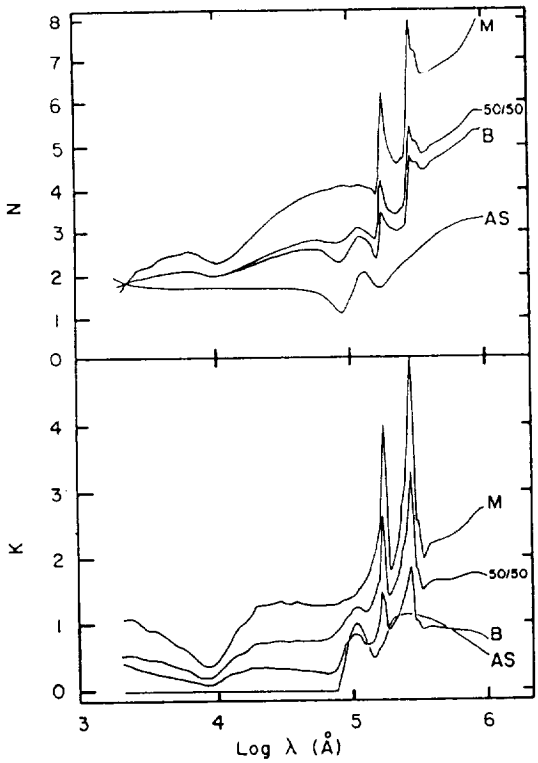

Figure 1

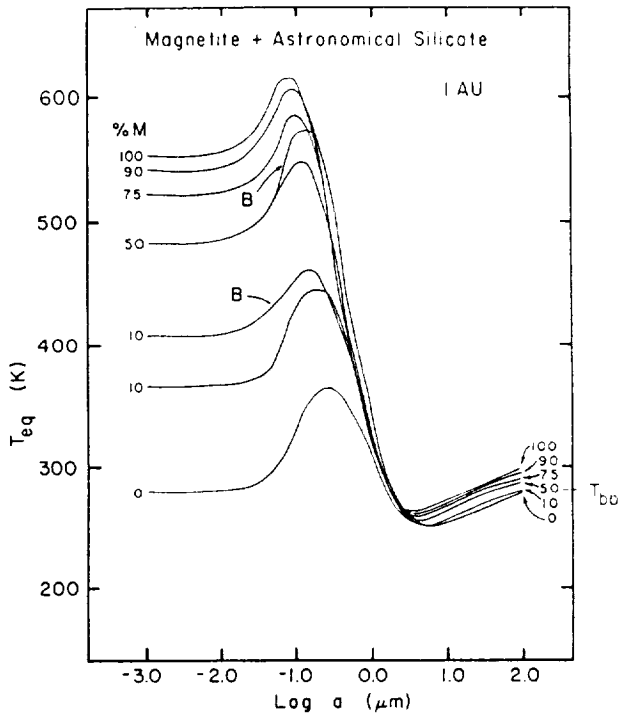

Figure 2

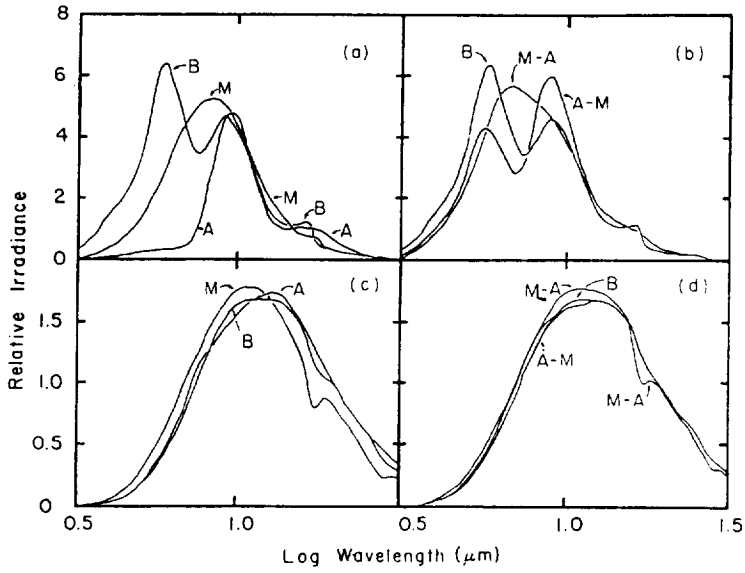

Figure 3