3.4 OPTICAL PROPERTIES OF COMETARY DUST

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Optical features of comets suggest that the dust in the coma is composed of a micron size core and a mantle formed by an aggregate of submicron grains.

1. Introduction

Photometric observations of Comets Kohoutek (1973f) and Bradfield (1974b) over wide wavelength ranges (Ney, 1974a,b; Noguchi et al, 1974; Iijima et al, 1975) and polarization measurements of Kohoutek in the near infrared (Noguchi et al., 1974) and in the optical range (Tanabe, 1974) show the following features.

(1) The spectrum longward of 2.2 μm is Planckian plus an enhancement at about 10 μm. The Planckian part gives a rather high temperature, suggesting higher absorption in the optical range than in the infrared range.

(2) The spectrum shortward of 2 μm is similar to the solar spectrum, and the scattering coefficient depends only weakly on the phase angle in the range $55^\circ - 93^\circ$.

(3) The degrees of polarization at phase angles of about 90° are 12 - 25% with the electric vector nearly perpendicular to the ecliptic plane and apparently show a slow increase with wavelength.

These features may be accounted for in terms of micron size grains with a mantle of aggregate structure. If submicron grains are responsible (O'Dell, 1971), an unrealistic wavelength dependence of the refractive index would have to be assumed. The present analysis imposes a rather stringent condition on the optical properties of cometary materials in the coma; for example, the crystalline formaldehyde polymers recently proposed by Vanýsek and Wickramasinghe (1975) would have to have a large absorption efficiency in the optical range, although they look transparent. In the present work we attempt to derive quantities which are free from the column density of coma materials and can be directly compared with optical parameters. Quantitative comparison is made with the Mie theory, whereas only qualitative properties are discussed for effects of the surface roughness, leaving details for a separate paper.

2. Thermal Emission

The infrared emission longward of 2.2 μm is considered to be the thermal emission from cometary dust heated by the solar radiation. The grain temperature T at the heliocentric distance r in AU is given by

$$\langle Q_A \rangle_s \, F/r^2 = 4G \, \langle Q_A \rangle_g \, \sigma \, T^4, \qquad (1)$$

where F is the solar flux at 1 AU, σ the Stefan-Boltzmann constant, G the geometrical factor representing a deviation from the uniform sphere. The absorption efficiencies Q_A are averaged over the solar spectrum and the emission spectrum on the left and right hand sides, respectively. The grain temperatures are obtained at several heliocentric distances by fitting the observed emission spectrum to the Planckian distribution (Ney, 1974a,b).

From the observed values of the grain temperature we obtain

$$R \equiv G\langle Q_A \rangle_g / \langle Q_A \rangle_s = F/4\sigma T^4 r^2, \qquad (2)$$

as shown in Figure 1. The value of R decreases from 0.6 to 0.3 as the grain temperature increases from 350 K to 950 K.

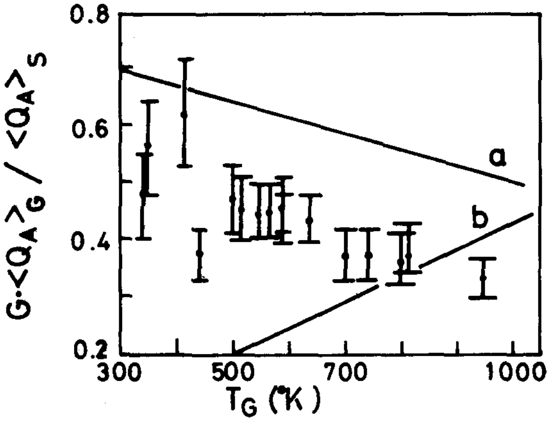

Fig.1. Ratio of the absorption efficiencies obtained from Equation (2). The solid line: (a) Mie theory for kx>1, a = 1.6 μm, but the absolute value is reduced by a factor 3; (b) Mie theory for kx<<1, k = 1.4, a = 0.16 μm.

Since the emission spectrum can be approximately simulated by the Planckian distribution over the above temperature range, the wavelength dependence of Q_A is very weak in the infrared range concerned.

The Mie theory applied to the spherical grain of radius a predicts that the absorption efficiency is nearly proportional to kx for kx < 1, where the index of refraction is m = n - ik and x = 2πa/λ, λ being the wavelength, passes a maximum at about kx = 1, and decreases slowly as x increases. The wavelength independence results if the grain size is so large that kx > 1. Large grains are also favoured to account for the wavelength independence of the scattering efficiency. Small grains of constant k show a temperature dependence opposite to that observed, as shown in Figure 1, whereas $k \propto \lambda^{1/2}$ simulating small metallic grains gives a too low R because of a high infrared reflectance.

If $kx \gtrsim 1$ is taken for granted for $\lambda = 2 - 8$ µm beyond which emission bands affect the spectrum, the grain size is given as

$$a = x\lambda/2\pi \gtrsim \lambda/2\pi k \simeq 1.3/k \ \mu\text{m}. \tag{3}$$

Namely, cometary dust is of micron size or larger. This is in contrast to the conclusion reached by O'Dell (1971) who has argued for submicron grains based mainly on the effect of radiation pressure.

A difficulty arises if $kx \gtrsim 1$ is assumed. The value of $\langle Q_A \rangle_g / \langle Q_A \rangle_s$ greater than unity is obtained from the Mie theory, whereas the value of R observed is appreciably smaller than unity. The discrepancy could be accounted for by the geometrical factor G. The value of G can be smaller than unity if the area facing the earth is smaller than that facing the sun. This would require the alignment of nonspherical grains. However, the direction of alignment is expected to be opposite, since solar wind protons tend to align the long axis parallel to the solar wind direction. The small value of R may result from a deviation from the Mie theory due to the surface roughness.

The surface roughness is characterized by two parameters, the rms vertical deviation from the average surface, σ, and the mean correlation distance of roughness, α (Beckmann, 1963). If σ is not too small compared with λ and α, the reflectance is smaller than that expected from the Fresnel reflection because of multiple reflection in pores (Houchens and Hering, 1967). This increases the absorption efficiency in the optical range but by a factor smaller than two, since Q_A is already as large as unity. If the rough surface is formed by a mantle as an aggregate of submicron grains with a small index of refraction, the mantle is highly transparent for infrared radiation, and the absorption efficiency is therefore essentially equal to that of the core. The core radius as small as or smaller than 2/3 of the mantle radius could account for a small absorption efficiency in the infrared range in comparison with that in the optical range. The aggregate structure of the mantle results in a small bulk density, which is in favour of the dominant effect of radiation pressure (O'Dell, 1971).

3. Scattering

The scattering efficiencies at $\lambda = 1.2$ µm and at phase angles θ, $Q_S(\lambda, \theta)$, are shown relative to the absorption efficiency $Q_A(\lambda)/4\pi$ in Figure 2. The results at other wavelengths are similar. The phase angle dependence can be fitted to the Mie theory only for $x \gtrsim 10$ as indicated by theoretical curves in Figure 2, whereas the spectrum of scattered light is similar to the solar spectrum if $kx > 3$.

The theoretical curve for $x = 10$ is close to that of the Fresnel reflection. If the surface roughness is taken into account, the observed behaviour could be reproduced for smaller values of x.

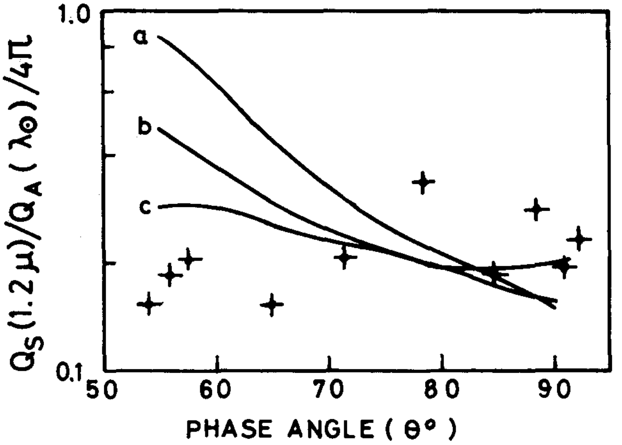

Fig.2. Phase angle dependence of the scattering efficiency. Crosses represent observed results for $\lambda = 1.2$ µm based on Ney (1974b). Solid curves represent results of the Mie theory with $m = 1.7 - 1.0i$. a: $x = 2.5$, b: $x = 5.0$, c: $x = 10$.

The absolute intensity of scattered light requires a rather large value of the refractive index; since the real part cannot be too large, the imaginary part has to be as large as or larger than 0.6 for the smooth surface. The aggregate structure would increase the reflectance and, consequently a little smaller value of k may be permissible.

4. Polarization

If the grain is of micron size, its optical properties are approximately accounted for in terms of the Fresnel reflection. Then the polarization at the phase angle 90° may be as large as 60% (Matsumoto, 1973). The degree of polarization is reduced if diffuse scattering is taken into account. For $\sigma \ll \lambda$, the wavelength dependence of polarization is appreciable, whereas only a weak dependence has been observed in the range 0.5 - 1.7 µm. The observed polarization is reproduced for $\sigma \simeq 0.8$ µm, if reference is made to an experiment (Torrance et al, 1966).

Finally, we remark that the grain model proposed here is favourable to account for zodiacal light, in particular the spectrum similar to the solar spectrum in the optical and near infrared ranges (Hayakawa et al.; 1970, Nishimura, 1973; Matsumoto, 1973). It may, however, be almost needless to mention that this does not necessarily rule out the existence of submicron grains since their contribution to brightness is of minor importance.

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