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Nature of dust grains in comets

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Summary. The observed reddening in the wavelength range 0.26–2.25 μm for comae of several comets can be represented quite well with model grains having real and imaginary parts of refractive index ($m=m'-im''$) given by $m'\simeq 1.38$ and $m''\simeq 0.039$, respectively. It is also possible to explain the observations of linear polarization and geometric albedo of comet comae.

1 Introduction

The study of dust grains in comets has been an active area of investigation for quite some time. Unfortunately, the exact nature and composition of cometary grains still remain an enigma. Until recently, all the information about the grains was limited to ground-based observations (see Ney 1982; Hanner 1984). The recent space mission to Comet Halley, however, have added some important information on the nature of the grains in that comet (Anon. 1986). It is not clear whether this is a representative sample of all comets. So until more *in situ* measurements are carried out on other comets, the information about dust grains in comets has to come mainly from the ground-based observations in conjunction with theoretical models (Krishna Swamy 1986). In an earlier paper (Krishna Swamy & Shah 1987), we had analysed the reddening curves of Comet West. Unfortunately, the wavelength range of observations were limited in extent. Here we would like to consider the observations of A'Hearn *et al.* (1984b) and Feldman & A'Hearn (1985), who have derived the reddening curves from 0.26 to 2.25 μm for several comets. The wide range in wavelength region should give a better opportunity to assess the properties of the dust grains in comets.

2 Model calculations and results

2.1 REDDENING CURVE

The source of information on the possible nature of the dust grains in comets has come out of the analysis of continuum observations (See Liller 1960; Stokes 1972; Sivaraman *et al.* 1979; Bappu *et*

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al. 1980). The observations carried out on several comets show a definite trend of slight reddening with increase in wavelength in the visual and near-infrared regions. In recent years, some comets have been observed from the UV to IR wavelength regions. The UV observations have been obtained mainly with the IUE satellite (Feldman 1982). The main difficulty in extending the reddening curve into UV and IR regions is that, since the observations are performed with different instruments, different wavelength regions, etc., it is a problem to connect them with one another. Recently, A'Hearn *et al.* (1984b) have succeeded to some extent in this direction. They have combined the data obtained from the *IUE* and ground-based observations along with the IR observations of Comet Bowell to get the reddening curve for the coma in the wavelength range λ=0.26 to 2.25μm. This has been extended to two other comets, namely, comets Cernis and Stephen–Oterma (Feldman & A'Hearn 1985). As suggested by A'Hearn *et al.*, comet Bowell may be considered a prototype of a new comet approaching the Sun. For intercomparison of the various observations, they have derived a quantity $Af\varrho$, where A, f, and ϱ represent the grain albedo, filling factor of the grains within the field of view, and the linear radius of the aperture projected on to the comet, respectively. With this method of reduction, the reddening observations of the coma for the above mentioned comets show almost the same behaviour from the ultraviolet to the infrared wavelength regions.

The model calculation of the reddening curve is based on the assumption of homogeneous and smooth spherical grains so that the use of Mie theory is permissible. We will discuss the limitations of this approach later on. The scattered intensity at wavelength λ and for scattering angle θ is given by the expression

$$I(\lambda,\theta)=\frac{I_0(\lambda)}{2k^2r^2\Delta^2}\left[i_1(\lambda,\ \theta)+i_2(\lambda,\ \theta)\right], \tag{1}$$

where

$I_0(\lambda)$=the intensity of the solar radiation at 1 AU,
r=the Sun–Comet distance in AU,
Δ=the Comet–Earth distance,
ϕ=the phase angle,
θ=the scattering angle=$\pi-\phi$,
$k=2\pi/\lambda$=the propagation constant, and
$i_{1,2}$=polarized intensity scattering functions in the two orthogonal reference planes usually defined in Mie theory (see, for example, van de Hulst 1957).

Note that λ and Δ should be in the same units in order to satisfy equation (1) dimensionally. The average intensity function $i=(i_1+i_2)/2$.

The observed variation of $Af\varrho$ with λ contains the filling factor, f, which in turn depends upon the extinction efficiency of the grains. It can be shown that, for uniform size of the grains, the theoretically calculated quantity iQ_{ext}/k^2 should be proportional to the observational value of $Af\varrho$ where Q_{ext}=the extinction efficiency of a grain. Therefore, in order to predict the expected variation, we have to essentially calculate an average quantity (apart from the proportionality constant):

$$\left(\frac{Af}{Q_{\text{ext}}}\right)_{\text{obs}}\varrho=\left(\frac{1}{k^2}\right)\frac{\int_0^\infty [i_1+i_2]n(a)da}{\int_0^\infty n(a)da}, \tag{2}$$

where the left-hand side can be determined from the observations and the right-hand side from theoretical models. Note that A'Hearn *et al.* (1984b) assume $Q_{ext}=1$. It may be noted, however, that in the relevant anomalous scattering region, barring unusual resonances, Q_{ext} can be as large as 4.0. In equation (2), $n(a)$ is the size distribution function such that $n(a)\,da$ represents the number of grains of size a in the range a to $a+da$. The size distribution function $n(a)$ is still not very clearly established. It is generally assumed to be given by a power-law distribution of the type

$$n(a)da=\text{constant.}\ a^{\alpha}da \tag{3}$$

where α is a parameter and a is the grain radius lying in the range from certain minimum (a_{min}) to maximum (a_{max}) values (Finson & Probstein 1968; Oishi, Okuda & Wickramasinghe 1978; A'Hearn, Dwek& Tokunaga 1984a). This form of the size distribution function is justified in view of the fact that the recent *in situ* measurements (Anon. 1986) carried out from the *Vega* and *Giotto* spacecraft missions to Comet Halley, can be roughly fitted to a power-law distribution (see Mazets *et al.* 1986a,b; Mukai, Mukai & Kikuchi 1986). Therefore, we have performed the calculations for various values for α in equation (3) as well as for the actual size distribution function derived for Comet Halley, namely,

$$\begin{aligned} &n(a)\propto a^{-2}, && a<0.62\,\mu\text{m}\\ &n(a)\propto a^{-2.75}, && 0.62\,\mu\text{m}<a<6.2\,\mu\text{m}\\ &n(a)\propto a^{-3.4}, && a>6.2\,\mu\text{m}. \end{aligned} \tag{4}$$

The procedure for the calculation of the theoretical model requires the specification of the composition of the grains. The presently available observations indicate that the grains could be composed of silicate, carbonate minerals or be organic in character (Ney 1982; Kissel *et al.* 1986; Vanysek & Wickramasinghe 1975). Here, instead of assuming various possible types of grain materials, we will limit ourselves to that refractive index which produces a good fit to the observations. Mukai *et al.* (1986) have constructed models of cometary grains based on the size spectrum of the grains derived from *in situ* measurements in the spacecraft mission to Comet Halley (Mazets *et al.* 1986 a,b). They have given a representative set of 80 curves for phase angle (ϕ) dependence of polarization (p) at wavelength $\lambda=0.63\,\mu$m by choosing a wide range of the complex index of refraction $m=m'-m''$ such that $1.2\leqslant m'\leqslant 3.0$ and $10^{-5}\leq m''\leq 0.3$. With the strong constraint on the observed polarization given by $-10\leqslant P\leq 30$ per cent for phase angle variation from 0° to 90° and using a typical observational polarization curve for Comet comae, it has been inferred that the appropriate index of refraction of the grains should be $m'=1.39\pm0.01$ and $m''=0.035\pm0.004$. These results are much different from the usually quoted optical properties of interstellar grains composed of silicates, graphite, dirty ice, etc. Besides, the question regarding identification of the actual materials in the grains remains open. However, such optical properties of the grains can be justified in view of the fact that the grains composed of pure materials are unlikely to exist in cometary, circumstellar, molecular clouds, or in interstellar and other environments of astrophysical interest. They might be complex conglomerations of silicates, non-volatile organic refractories (yellow stuff), volatiles (such as solid H_2O, NH_3, CH_4, CO, CO_2, etc.), metal oxides, carbon, polycyclic aromatic hydrocarbons and other esoteric substances (see e.g. Greenberg 1983; Kissel *et al.* 1986) depending on the ambient physical conditions, the optical properties of the grains would be different for different objects/regions. As noted by Mathis (1985) it would be interesting to investigate the optical constants of mixtures of these substances; at the least, one can take up the case of the 'yellow stuff' produced in the laboratory. Meanwhile, for Comet Halley and other comets, we would like to adopt the above mentioned empirical optical constants (Mukai *et al.* 1986) in the present work.

The scattered intensities depend upon the shape and structure of the grains. Cometary grains could be regular and irregular in shape, fluffy or collections of small particles. However, these odd kinds of particles are not amenable to rigorous analytical treatment of electromagnetic

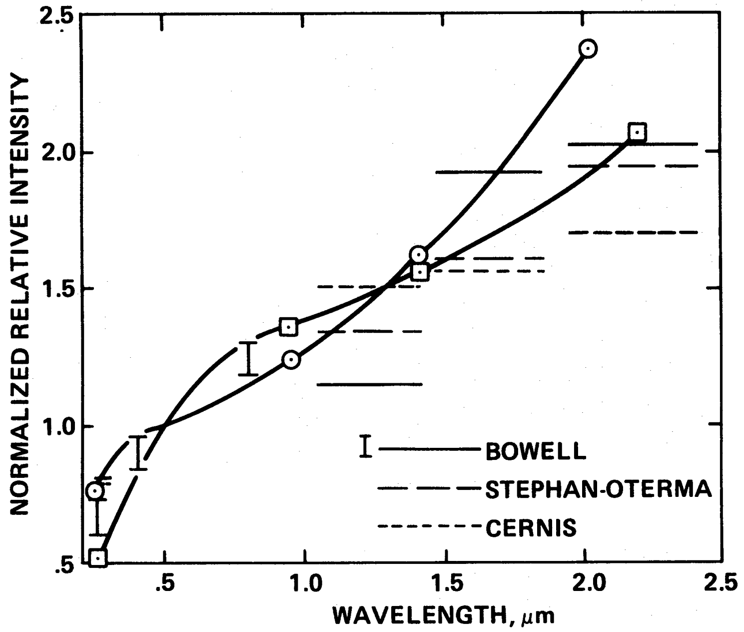

Figure 1. The observed and calculated reddening curves plotted as a function of wavelength. The curves are normalized to λ=5000Å. *Observations:* the solid, long-dashed and dashed short lines refer to Comets Bowell, Stephan–Oterma and Cernis, respectively. The three short vertical lines with bars denote the rough range in values for these wavelength regions for Comet Bowell (all taken from A'Hearn *et al.* 1984b; Feldman & A'Hearn, 1985). *Calculations:* the results are for Halley size distribution function. The solid curve with circles is for $a_{\min}=0.001\,\mu$m to $a_{\max}=20\,\mu$m and that with squares is for $a_{\min}=0.001\,\mu$m to $a_{\max}=40\,\mu$m.

scattering at the present time. Therefore, in the absence of precise knowledge as to how to do the calculations for such particles, we will restrict ourselves to the usually widely used Mie theory for spheres. The results should be interpreted with this limitation in mind.

The results of calculation on reddening are shown in Figs 1 and 2. Fig. 1 shows the result based

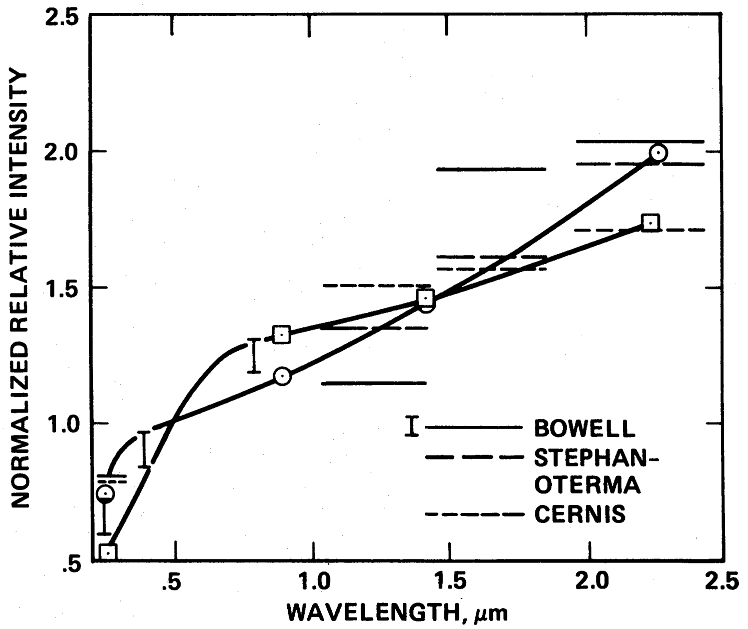

Figure 2. The observed and calculated reddening curves plotted as a function of wavelength. The curves are normalized to λ=5000Å. *Observations:* Same as Fig. 1. *Calculations:* the results are for the power-law size distribution function for $\alpha=-3.5$. The solid curve with circles is for $a_{\min}=0.001\,\mu$m to $a_{\max}=20\,\mu$m and that with squares is for $a_{\min}=0.001\,\mu$m to $a_{\max}=40\,\mu$m.

on *in situ* measurement of the size distribution of the grains obtained for Comet Halley (see equation 4), whereas in Fig 2 we have assumed a power law for the size distribution of the grains. The observations for Comets Bowell, Stephan–Oterma and Cernis, represented as continuous, long-dashed and dashed lines respectively, are those of A'Hearn *et al.* (1984b) and Feldman & A'Hearn (1985). The three lines with bars in the wavelength region around 0.3 to 1.0μm represent roughly the range in the observed values for this wavelength region for Comet Bowell. Although there is a range in the observed values for these comets, it is interesting to note that the general trend is the same from ultraviolet to infrared wavelengths. The trend of the expected variation is in reasonable agreement with the observed variation of reddening with wavelength. It is hoped that the reddening curve will be better defined based on the good and extensive observations carried out on Comet Halley. This should help further in refining the properties of the grain material.

2.2 POLARIZATION

Another set of observations which any grain model must explain is the linear polarization of light scattered by the grains. Unfortunately, at the present time, systematic polarization measurements on a single comet over extended values of heliocentric distances and/or for scattering angles from 0° to 180° are not available. The presently available observations refer to either fixed scattering angles or for fixed heliocentric distances. Such observations for several comets are

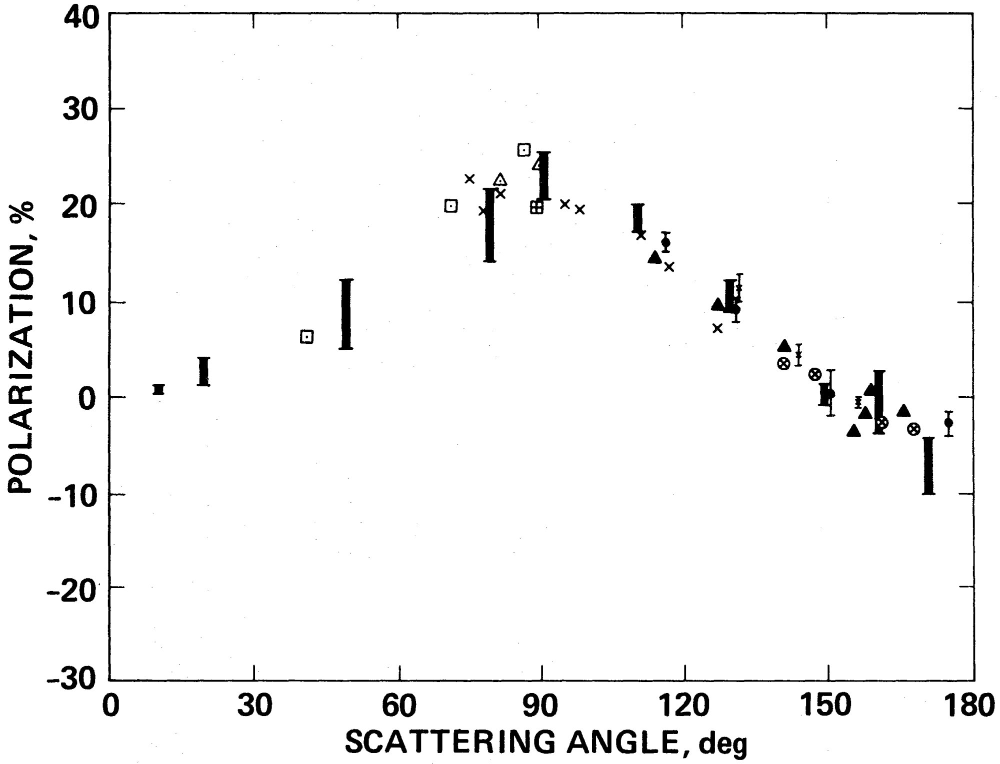

Figure 3. A plot of the observed and calculated polarization versus scattering angle. *Observations:* Comet West: (□) Michalsky (1981); (▲) Kiselev & Chernova (1978); Comet Austin: (×) Myers & Nordsieck (1984); Comet Churyumov–Gerasimenko: (⊕) Myers & Nordsieck (1984); Comet Arend–Roland: (⊞) Bappu & Sinvhal (1960); Comet Ikeya–Seki: (△) Bappu *et al.* (1967); Comet Halley: bars with circles, Mukai *et al.* (1986), bars with crosses, Bastien, Menard & Nadeau (1986). *Calculations:* The dark vertical bars show the polarization variation for wavelengths between 0.5 and 0.7μm and for the Halley size distribution function. Note that $a_{\min}$=0.001μm to $a_{\max}$=20μm.

compiled in Fig. 3. They are represented by points which clearly delineate a well defined polarization curve as a function of the scattering angle. The expected polarization for the model parameters of Fig. 1 are also shown in Fig. 3. Note that the span of variation of the calculated polarization within the wavelength range 0.4–0.7 μm is shown by vertical bars. A more precise matching of the observational and calculated values of polarization has not been attempted because of the fact that there are uncertainties in the measured polarization presently available in the literature.

2.3 ALBEDO

The albedo of the model grains should also be consistent with the observed albedo in the visual spectral region. The calculated geometric albedo, $Ap(\theta)$ (see Hanner *et al.* 1981) for the model grains of fig. 2 and for $\theta=100°$, $\lambda=0.5\,\mu$m has a value of about 0.01. This can be compared with the visual albedo 0.04 obtained from the *in situ* meaurements of Comet Halley by the *Giotto* spacecraft (Keller *et al.* 1986) and a value of about 0.05 obtained for fluffy particles based on laboratory studies (Hanner *et al.* 1981). It has been noticed earlier by several investigators that the value of $Ap(\theta)$ for the fluffy or irregular type of particles could be larger than given by the Mie calculations by a factor of about 2 to 5. This difference arises basically due to some extra effects which operate on a rough surface as compared to that of a smooth surface (Giese *et al.* 1978; Zerull *et al.* 1980). Therefore, the presently calculated value of $Ap(\theta)\simeq 0.01$ for the model grains is also consistent with these results.

3 Conclusions

It is shown that the observed reddening curve and linear polarization for several comets, as well as the visual geometric albedo, can be explained reasonably well with model grains having index of refraction specified by $m'\simeq 1.38$ and $m''\simeq 0.039$ and with the size distribution of the grains measured by space probe missions to Comet Halley. It is also interesting to note that the same value of the refractive index for the ultraviolet and visible regions, combined with the infrared properties of the Moon rock material, can explain quite well the observed infrared radiation of Comet Halley (Krishna Swamy *et al.* 1988). Therefore, the above material property for the grain is consistent with the results based on observations made in the visible and infrared spectral regions of comets.

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