The Scattering Properties of Cometary Dust

Martha S. Hanner,[1]

[1] *Jet Propulsion Laboratory, California Institute of Technology,*
Pasadena, CA 91109 USA

Abstract

Comet dust consists of silicate and carbonaceous material, mixed on a submicron scale. In comparing comets, there is a correlation of stronger polarization, redder polarization color, higher albedo, stronger infrared silicate emission, and higher infrared color temperature. Aggregate particles having constituent grain size parameters $X \geq 1.5$ show promise in matching the observed scattering properties. An enhancement in the abundance of small silicate grains with $X \sim 1.5 - 2$ may cause the higher polarization and stronger silicate emission in comets such as Hale-Bopp.

1 Introduction

Comets formed as icy planetesimals in the outer solar nebula where the temperatures were low enough so that pre-existing interstellar grains could have been incorporated essentially intact. Thus, we expect comet dust to be a mix of interstellar dust and solar nebula condensates. Radial gradients in temperature and composition and the extent of mixing within the solar nebula should be evident today as differences in the dust properties among comets. Thus, a major goal of cometary dust studies is to look for trends in dust properties among comets that might correlate with their place of origin.

While in situ measurements from the comet Hally space probes and the analysis of interplanetary dust particles (IDPs) captured in the Earth's atmosphere provide basic information about the physical properties of cometary dust, interpretation of remote sensing data is the only means for understanding the differences among comets and comparing cometary dust with interstellar dust.

Cometary dust is a heterogeneous mixture of primarily silicates, iron oxides, and carbonaceous material; these components are usually mixed even on a submicron scale [6]. Dust particle sizes range from nanometers to centimeters. The dust mass distribution measured during the Giotto Halley flyby indicates that the mass is concentrated in the large (mm-cm) particles, while the cross section (thus observable scattering properties) is dominated by 0.1-10 μm particles [9]. Interplanetary dust particles of likely cometary origin are typically irregular porous aggregates of sub-micron to micron sized silicate grains embedded in a carbon-rich matrix [1].

These particles are very different from the small, homogeneous symmetrical particles that are easy to model. First of all, these particles are not spheres. While some optical properties of small compact particles can be approximated by spherical particles, the polarization in particular is strongly dependent on particle shape. The modeling also requires treatment of inhomogeneous particles, either explicitly in a code such as DDA or by means of effective medium theory. Moreover, appropriate grain sizes have to be used. The optically dominant particles in many active comets have size parameters, X, in the range 1-10 at visual wavelengths.

2 Dust scattering properties

Optical and infrared observations of the dust coma of active comets yield the following average scattering properties for the ensemble of dust particles [12]. The average geometric albedo at $\lambda 0.5\mu m$ is 3-5%. The scattering function is fairly flat from $90° - 150°$ scattering angle, then rises by a factor of 2 from $150° - 180°$. The color of the scattered light is neutral to slightly red. Polarization maximum of 10-25% occurs near 90°, with negative polarization at scattering angles $160° - 180°$ [8]. Polarization is higher at longer wavelengths (red polarimetric color). In the infrared, the color temperature of the Planck function fitted to the 3-18 μm thermal emission is higher than the equilibrium blackbody temperature. In some (but not all) comets, there is an emission feature at 8-12.5 μm due to small, optically thin silicate grains [5].

These scattering properties are in qualitative agreement with the dust physical properties described above. The low average albedo indicates that silicates are well mixed with absorbing material. (Only a small fraction of finely dispersed absorbing material is required to decrease the albedo of a silicate particle.) The red color indicates that the particles are not Rayleigh scatterers; the coloring agent is most likely a hydrocarbon material. The relatively low maximum polarization implies a particle size parameter ≥ 1.5 [15]. The presence of silicate emission requires that the silicate particles be micron-sized or smaller and not so embedded in absorbing material that the feature contrast is masked. A color temperature above the equilibrium blackbody temperature requires particles that can absorb more efficiently at visual wavelengths than they radiate in the infrared; this requirement can be met by absorbing grains that are micron-sized or smaller. Larger particles can have elevated temperatures only if they are very porous and the constituent grains are micron-sized or smaller [2,4,14]. A high 3-5 μm thermal flux is a particularly sensitive indicator of hot sub-micron sized absorbing grains (grain radius $a \leq 0.5\mu m$) [5].

Many of the larger cometary particles may be rather porous aggregates of small grains, as we see in the porous aggregate subclass of IDPs. The degree of porosity makes a critical difference in the optical properties. For a very porous aggregate, the light interacts primarily with the individual structural units. Thus, the scattering properties of such aggregates, particularly the polarization, are determined to a large extent by the scattering properties of the constituent grains [13,4]. Understanding the relative influence of the constituent grains versus the overall particle structure, as a function of the porosity, is an important modeling goal. Note that the constituent grains have typical sizes of 0.1-1 μm, so they cannot be modelled as Rayleigh scatterers.

Polarization is difficult to interpret, because it depends on particle size, shape, and composition. In order to separate the effects of these parameters, it is useful to look at the correlations among observable quantities. Table 1 compares the average observed properties in the inner coma of Hale-Bopp with similar measurements of comet P/Halley. There is a clear correlation of higher polarization, redder polarimetric color, higher albedo, stronger silicate feature, higher infrared color temperature, and enhanced 3–5 μm thermal emission. Other comets show similar trends.

Comets tend to form two groups with differing maximum polarizaion, P_{max} [8]. The comets with higher $P_{max} \sim 25\%$ generally exhibit a strong scattered light continuum and a conspicuous silicate feature. When a silicate feature is absent, P_{max} is typically $\sim 10 - 15\%$ at $\lambda \sim 0.5\mu m$. Negative polarization of a few percent is present at scattering angles $\geq 160°$ in all comets.

Several studies of scattering properties for particle sizes $a \sim \lambda$ have yielded results relevant to the problem of polarization in comets. For regular, but non-speherical shapes, with $X \sim 2.5 - 6$, P_{max} is higher for absorbing particles than for silicate particles. As X increases from 2.5 to 5, P_{max} decreases for silicate particles, but increases for carbon particles [15]. Thus, higher P_{max} would imply more absorbing grains relative to silicate grains in the coma, in contradiction to the observed correlation between P_{max} and silicate emission. If $X \leq 2$, then a decrease in particle size would

Table 1: Correlations among cometary dust scattering properties

Hale-Bopp versus Halley		Possible explanations
Polarization	higher	more small grains, X ≤ 2 more absorbing grains $a \sim \lambda$
Polarimetric color	redder	more small grains, X ≤ 2 more silicate grains, $a \sim \lambda$
Albedo	higher	more small grains, $a \sim 0.2\mu$m more "clean" silicates
Continuum	stronger	more small grains more "clean" silicates higher dust/gas ratio
Silicate feature	stronger	more small silicate grains, $a \leq 1\mu$m higher silicate/carbon abundance warmer silicates
Color temperature	higher	more small absorbing grains, $a \leq 1\mu$m
3–5 μm flux	higher	more small absorbing grains, $a \leq 0.5\mu$m

produce an increase in polarization for both silicate and absorbing grains, consistent with both the higher silicate feature and higher 3-5 μm flux. Thus an increased abundance of particles with radius 0.1-0.2 μm within a broad size distribution may explain the scattering properties in the comets with higher P_{max}. A low $P_{max} \sim 10\%$ and the presence of negative polarization seem to require primarily silicate particles, despite the lack of a silicate feature in comets with low P_{max}, and this remains a puzzle. A shape distribution of silicate spheroids with $X = 3.4$ can produce negative polarization at $160° - 180°$ and positive polarization at smaller scattering angles [10].

Aggregate particles with constituent silicate grains of size $X \sim 1.65$ exhibit a polarization phase curve similar to that of comets, including negative polarization at small phase; however, the shape of the polarization curve depends strongly on constituent grain size [11]. Mixed aggregates of silicate and carbonaceous grains with $X = 2.6$ also show the approximate shape of the cometary polarization [14]. Laboratory scattering measurements, scaled to the microwave domain, are a powerful tool for investigating the polarization properties of irregular aggregates, including particle size and shape and wavelength dependence [3]. Grain mantles, specifically organic refractory mantles on silicate grains, may play an important role [7].

3 Conclusions

Observed scattering properties are qualitatively consistent with what we know about the composition, size, and aggregate structure of cometary dust. However, the polarization, particularly the stability of the negative polarization branch and the low P_{max} in comets lacking a silicate feature, is not yet fully explained. Continued laboratory measurements and numerical modeling are needed, in particular 1) scattering by aggregates with constituent grain sizes, $X \geq 1.5$ and 2) effect of the way silicate and absorbing material are mixed; e.g., finely dispersed, or silicate cores with organic refractory mantles, or a mix of silicate and absorbing constituent grains in aggregates.

Acknowledgments

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with the National Aeronautics and Space Administration.

References

[1] J.P. Bradley, H.J. Humecki, and M.S. Germani, "Combined infrared and analytical electron microscope studies of interplanetary dust particles", Astrophys. J. **394**, 643–651 (1992).

[2] J.M. Greenberg and J.I. Hage, "From interstellar dust to comets: a unification of observational constraints", Astrophys. J., **361**, 260–274 (1990).

[3] B.A.S. Gustafson and L. Kolokolova, "A systematic study of light scattering by aggregate particles using the microwave analog technique: angular and wavelength dependence of intensity and polarization", JGR, **104** 31711 (1999).

[4] J.I. Hage and J.M. Greenberg, "A model for the optical properties of porous grains", Astrophys. J., **361**, 251–259 (1990).

[5] M.S. Hanner, R.D. Gehrz, D.E. Harker, T.L. Hayward, D.K. Lynch, C.C. Mason, R.W. Russell, D.M. Williams, D.H. Wooden, and C.E. Woodward, "Thermal emission from the dust coma of comet Hale-Bopp and the composition of the silicate grains", Earth, Moon and Planets, **79**, 247–264 (1999).

[6] E. Jessberger, "Rocky cometary particulates: their elemental, isotopic, and mineralogical ingredients," Space Science Rev. **90**, 91–97 (1999).

[7] L. Kolokolova, K. Jockers, B.A.S. Gustafson, G. Lichtenberg, "Colors and polarization as indicators of comet dust properties", JGR **106**, 10113–10128 (2001).

[8] A.C. Levasseur-Regourd, E. Hadamcik, and J.B. Renard, "Evidence for two classes of comets from their polarimetric properties at large phase angles", Astron. Astrophys **313**, 327–333 (1996).

[9] J.A.M. McDonnell, P.L. Lamy, and G.S. Pankiewicz. "Physical properties of cometary dust", in *Comets in the Post Halley Era*, ed. R. L. Newburn, M. Neugebauer, and J. Rahe, Kluwer Dordrecht, pp. 1043–1073 (1991).

[10] M.I. Mishchenko, "Light scattering for size-shape distributions of randomly oriented axially symmetric particles of a size comparable to a wavelength", Appl. Opt., **32**, 4652–4666 (1993).

[11] E.V. Petrova, K. Jockers, and N.N. Kiselev, "Light scattering by aggregates with sizes comparable to the wavelength: an application to cometary dust", Icarus, **148**, 526–536 (2000).

[12] Z. Sekanina, M.S. Hanner, E.K.Jessberger, and M.N. Fomenkova, "Cometary Dust", in *Interplanetary Dust*, ed. E. Grun, B.A.S. Gustafson, S. Dermott, and H. Fechtig (Springer, 2001).

[13] R.A. West, "Optical properties of aggregate particles whose outer diameter is comparable to the wavelength", App. Opt., **30**, 5316–5324 (1991).

[14] Z. Xing and M.S. Hanner, "Light scattering by aggregate particles", Astron. Astrophys **324**, 805–820 (1997).

[15] P.A. Yanamandra-Fisher and M.S. Hanner, "Optical properties of nonspherical particles of size comparable to the wavelength of light: application to comet dust", Icarus **138**, 107–128 (1999).