THE DUST IN THE COMA OF COMET HALLEY

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ABSTRACT. The interstellar dust model of comets is numerically worked out to satisfy several basic constraints provided by observations of comet Halley and to derive the porosity of coma dust. The observational constraints are: (1) the strengths of the 3.4 μm and 9.7 μm emission bands; (2) the relative amount of silicates to organic materials; (3) the mass distribution of the dust. The results indicate that coma dust has a porosity in the range $0.93 < P < 0.975$. Preliminary calculations concerning the observed linear polarization of comet Halley are presented.

1 Introduction

The purpose of this work is to provide evidence for the model of comets by Greenberg (1985) by showing that interpretation of ground based and spacecraft observations of the coma of comet Halley may be successfully performed on the basis of this model. We present here the main ideas of recent work (Greenberg and Hage 1990; see this paper for details) and some new, preliminary results concerning the interpretation of the observed linear polarization of light scattered by the coma of comet Halley.

In terms of the present model, the dust in the coma consists of porous aggregates (figure 1a) consisting of interstellar core-mantle particles (figure 1b). Comets are assumed to be aggregates of particles as shown in figure 1c. The porosity, P, of the aggregates is defined as the relative amount of volume filled by vacuum inside the aggregate. The comet model predicts $0.6 < P < 0.83$ for comet nuclei and $0.9 < P < 0.975$ for coma dust.

2 Method

Basically, we want to show that on the basis of the present comet model, it is possible to explain the observed strengths of the 3.4 μm (Danks *et al.* 1987) and 9.7 μm (Hanner *et al.* 1987) emission bands of the coma of comet Halley, in terms of: (1) the mass ratio of silicates to organic materials as measured *in situ* (Kissel and Krueger 1987) and (2) the mass distributions of the dust, which were also measured *in situ* (McDonnell *et al.* 1989, Mazets *et al.* 1987). The shape of the 9.7 μm feature will not be considered here, although it may also be explained. The above is accomplished by going through the following scheme:

(1) Assume the porosity of the coma dust is unknown and use it as a free parameter.

(2) Calculate the thermal flux from the coma as a function of the dust porosity using: (a) the observed mass distributions; (b) the observed mass ratio in the dust of silicates:organics=2:1; (c) the interstellar dust model of comets to provide the morphology and specific chemical composition of the dust.

The model calculations to determine the thermal emission of the coma dust particles with their complicated shapes, as a function of their porosity, size and distance to the sun are described fully in Hage and Greenberg (1990) and in Greenberg and Hage (1990).

(3) Equate, if possible, the calculated results with observed values, at the wavelengths of 9.7 and 3.4 μm. If the observed values are matched, then not only are spacecraft and ground based observations tied together, but a (representative mean) value for the dust porosity is also found.

We note here that we do not calculate the continuum radiation from the coma at

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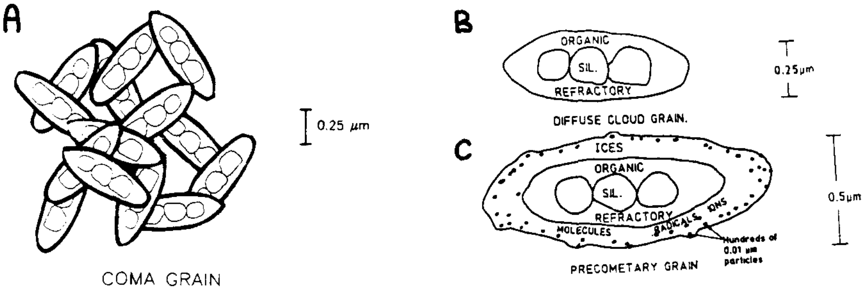

Figure 1. *(a) Schematic drawing of a coma grain according to the interstellar dust model. (b) Schematic of an interstellar dust grain which contains a core of silicates and a mantle of organic refractory material. (c) An interstellar grain after accretion of gases on its surface. These grains make up a comet.*

arbitrary wavelengths, but only the amount of emission *above the continuum* in the observed 3.4 and 9.7 μm emission bands. This restriction makes an accurate model calculation possible in spite of the fact that the mass distributions are unknown for the larger particles, because it can be shown that the contribution to the emission *above the continuum* from the large particles is negligible.

3 Results and Discussion

We have listed in table 1 the coma dust porosities which are required to match the calculated and observed emissions, on the basis of the assumptions listed in section 2. For example, the first line shows that, using a mass distribution measured by the Vega1 spacecraft to match the observed strengths of the 9.7 and 3.4 μm bands observed on March 6.85, 1986, (the 3.4 μm band strength was inferred from other observations), porosities of 0.80 and 0.90 are required, respectively. From Table 1 we can conclude that the strengths of the 3.4 and 9.7 μm bands can indeed be reproduced and that the required porosities are all rather high. The results for the 3.4 and 9.7 μm bands are slightly discrepant, but this is not surprising in view of the uncertainties in the observational data.

We summarise the conclusions from Greenberg and Hage (1990), which were based on a broader discussion: a high coma dust porosity of $0.93 \leq P \leq 0.975$ is a likely possibility which is consistent with (a) the direct results of this work, (b) comet densities as deduced independently by other workers (Sagdeev *et al.* 1988, Sekanina and Yeomans 1985) and (c) observed meteor densities (Verniani 1973). Furthermore, there are two additioanl features in the present model of comets which are *critical* in producing the observed 9.7 *μm* and 3.4 *μm* coma dust emissions: (1) The presence of organic refractory material. Without this component, it would in some cases be impossible to reproduce the amount of excess 3.4 and 9.7 *μm* emissions, because the coma dust would not become hot enough. (2) The presence of particles with a size similar to interstellar dust grains as basic units of the aggregates. If the mean size of the aggregate units were much larger than the size of interstellar dust grains, it would again be impossible to reproduce the amount of excess emission, because the aggregates would then neither become hot enough nor emit the emission features well.

4 The Linear Polarization of Comet Halley

Having arrived at the above results, an immediate question arises: is the observed degree of linear polarization of scattered radiation (as a function of phase angle) from the coma of comet Halley (Dollfus *et al.* 1988) also explicable in terms of very porous aggregates of interstellar dust? The main feature of the observed polarization is its negative branch at low phase angles. Ideally, a model of the dust should reproduce the following: (1) the amount of minimum polarization; (2) the phase angle at which the minimum occurs; (3) the phase angle at which the polarization goes from negative to positive values; (4) the slope of the polarization curve for larger phase angles; and (5) the wavelength dependence of these

Spacecraft	date	$P(9.7)$	$P(3.4)$
Vega1	March 6.85	0.80	0.90
Vega2	March 12.8	0.90	0.96
Giotto	March 12.8	0.97	0.98
Giotto	March 13.75	0.84	0.95

Table 1. *Required porosities of the coma dust. $P(9.7)$ is the porosity required to match the strength of the 9.7 μm emission band, and $P(3.4)$ is the result for the 3.4 μm band. The date refers to the time of the infrared observations from Earth.*

particle number	x	y	z
1	5	1	1
2	3	4	1
3	5	5	1
4	1	1	2
5	3	2	2
6	1	3	2
7	2	5	2
8	4	2	3
9	4	4	3
10	2	5	3
11	4	2	4
12	2	4	4
13	5	1	5
14	1	2	5
15	1	5	5

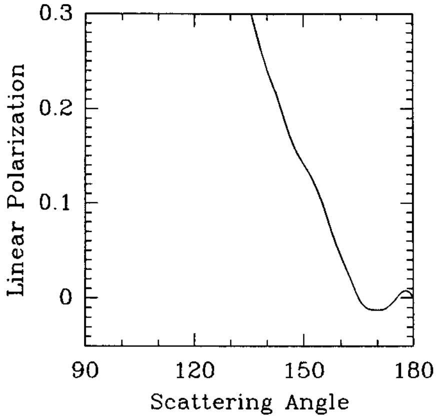

Table 2 *(Left). Positions of the inclusions in the model aggregate in rectangular cartesian coordinates.* **Figure 2** *(Right). Linear polarization as a function of scattering angle produced by the model.*

quantities.

It seems very likely that the same physical mechanism which produces negative polarization for two dipoles (Muinonen 1990) could work also for porous aggregates of interstellar dust. The main question is: what are the physical properties an aggregate should have in order to produce the observed polarization behaviour? For example, what should be its size and porosity; what should be the refractive index and size of the inclusions? Furthermore, are these requirements consistent with the assumptions of the present comet model?

We have started preliminary calculations to investigate the polarization produced by porous aggregates of interstellar dust. We use a numerical method (Hage and Greenberg 1990) which has been experimentally verified for porous particles (Hage, Greenberg and Wang 1990). The first step in these calculations is to build a model to represent the most important features of a porous aggregate. As one of the first attempts we have built a model representative of 15 interstellar dust grains. The model consists of 15 identical cubes with a size parameter of about 1.2, which are randomly distributed in a 5 × 5 × 5 cubic lattice, simulating a structure with a porosity of $P = 1 - 15/125 = 0.88$ (see table 2). The refractive index was chosen as $m = 1.6$ and the scattering was averaged over 225 orientations of the model with respect to the scattering plane (furthermore $k = 0.9396$ and $\epsilon = 10^{-5}$; these parameters are defined in Hage and Greenberg 1990). The resulting linear polarization is shown in figure 2 as a function of the scattering angle (which corresponds to 180°−phase angle).

Figure 2 shows that the model does indeed produce negative linear polarization at low phase angles. One notes that the calculated curve does not reproduce the observed polarization curve exactly, but this is not to be expected, one reason being that the observed polarization is produced by a large range of particles with different sizes.

The convergence of the results in figure 2 is not yet rigorously established. The reason is that the polarization at high scattering angles turned out to be highly variable as a function of scatterer orientation, so that averaging over very many orientations is required to acquire a reliable mean. A problem associated with these numerical calculations is that they take a considerable amount of computer time, even on a supercomputer. We are still in the process of solving this problem. We believe, however, that the negative branch of the polarization in figure 2 is real, because: (1) Other calculations with different parameters consistently show the negative polarization; (2) we understand the physical mechanism producing negative polarization. However, the numerical values of the polarization presented in figure 2 are expected to have a non-negligible error at scattering angles close to 180°.

Our present conclusions are, based on computations similar to those described above: (1) a high porosity is necessary to obtain the negative polarization, consistent with the results derived in section 3; (2) the particles in the aggregate must have a size parameter $x > 1$ (for moderate refractive indices), otherwise there is no negative polarization. This is consistent with the physical mechanism producing the negative polarization, which is a second order effect. If the constituent particles are too small, they do not scatter enough radiation to produce a second order effect. This also leads to the prediction that the negative polarization should vanish in observations further toward the infrared. (3) Maximum polarization should occur at 90 degrees phase angle.

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