COMETARY DUST AND ZODIACAL LIGHT CONNECTION

A. DOLLFUS
Observatoire de Paris
92195 Meudon
France

ABSTRACT. Photopolarimetry of P/Halley coma characterizes, in the cloud of dust grains released by the nucleus, the presence of a significant population of large flakes, made of aggregated small and very dark grains. These globules are subsequently transported toward the Sun, with some modifications in texture, and concentrate in the inner part of the Solar System. Comets appear to be the source for the fluffy grains which are observed in the zodiacal light.

DUST GRAINS IN THE COMA OF P/HALLEY

When approaching the Sun, the nucleus of a comet releases gases and grains of solid material, because the increase of radiation heating from the Sun produces an evaporation of the ice and internal fracturations or explosions. The cloud of solid grains which are liberated into space scatters the solar light and is made visible around the nucleus, being telescopically observed as the cometary coma. The smallest grains are subjected to the solar radiation pressure which produces an additional force to the gravitation, radial to the Sun, they are moved outward and produce the cometary tail. Finally, these small grains spread out in the outer part of the solar system. We consider here the grains of larger size.

It was an assignment of the spacecrafts VEGA and GIOTTO which entered into the P/Halley coma cloud to record flux, mass and size distribution of these grains, directly in the vicinity of the nucleus. The dust impact-detectors CIS, PIA, DIDSY, SP and DUCMA placed on board these spacecrafts recorded essentially very small and sub-micron size grains. Mass distribution functions were derived (Mc Donnell et al., 1987 - Mazets et al., 1987 - Krasnapolsky et al., 1987 - Simpson et al., 1987).

However, the mass distribution deduced from these measurements does not exclude the presence of larger particules either if they have not been detected by the impactors (Green et al., 1987). The analysis of the spacecrafts deceleration when passing through the coma requires a flux of impacts by large particles (Edenhofer et al., 1987). The camera of spacecraft GIOTTO experienced attitude excursions explained by discrete impacts on the craft by grains with mass of at least a μg, corresponding to several hundreds μm in size (Curdt and Keller, 1988). The spacecraft SUISI was hit twice by large particles with masses of several mg and several μg, respectively (Uesugi, 1987), and spacecraft GIOTTO was disbalanced by a powerfull impact.

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All these results suggest that the population of the solid particles which are ejected by the cometary nucleus is not limited to sub-micron or micron size grains, as was suggested by the impactors results alone, but must comprise a significant number of large pieces with sizes of at least 100 μm, or far more. In practise, the overall dust mass distribution is probably dominated by these large grains (Curdt and Keller, 1988).

The presence of large grains in the coma dust cloud is also supported by the Radar analysis. The ground-based Radar observation identified predominantly very large grains reaching the cm size range (Campbell and Harmon, 1988), and such was also the case for the comet IRAS-ARAKI-ALCOCK (Harmon et al., 1988).

CHARACTERIZATION OF THE COMA GRAINS BY TELESCOPIC PHOTOPOLARIMETRY

A way to characterize remotely some physical properties of a cloud of grains is by the technique of optical telescopic polarimetry. Polarization produces information about albedo, absorption, texture, size, aggregation and shape of grains (Dollfus, 1985 - Geake and Dollfus, 1986 - Wolff, 1981).

We implemented the method for P/Halley using the photoelectric photopolarimeter of Observatoire de Paris, between October and December 1985 at the 1 m. telescope at Meudon (France), and then in April 1986, with the 1.52 m ESO telescope at La Silla, Chile, (Dollfus and Suchail, 1987). A total of around 400 individual measurements were collected over 13 distinct nights covering a range of phase angle from 21.6° to 54.2°. The three Stokes polarization parameters Q/I, U/I and V/I were extracted with an accuracy of around 10^{-3} and nine maps of these parameters were constructed over the coma field.

Other polarimetric observations on P/Halley suitable for dust characterization were recorded by Bastien et al. (1986, 1987), Kikuchi et al. (1987), Kiselev et al. (1986), Le Borgne et al (1987), Brooke et al. (1987) and Vrba (1987). The instrument HOPE on-board spacecraft GIOTTO recorded in situ data (Levasseur-Regourd et al., 1986). All those measurements pertaining to the dust characterization have been analysed jointly in a workshop study in Paris on April 2-3, 1987, and synthetic linear polarization phase variation curves have been derived (Dollfus et al., 1988). The curves relevant to the present work are reproduced here in the Figures 1, 2 and 3.

Differences in the polarization signature are observed with the distance to the nucleus, which is also a function of time after the initial dust release into space. Figure 1 refers to the very bright envelope surrounding the nucleus in April 1986 with a radius not exceeding 100 km (Dollfus and Suchail, 1987), corresponding to a time after release of one or few minutes. Figure 2 is for the inner coma up to a distance of 1000 km (significantly more in the streamers) and corresponds to the recently ejected dust after they cleared up the bright envelope. Figure 3 corresponds to the older dust, after a travel over larger distances from the nucleus. This curve of Figure 3 pertains to a more advanced stage of cometary grains morphologic evolution after completion of the processes of modification due to evaporation of volatiles and re-shaping following immediately of the release into space.

INTERPRETATION OF THE POLARIZATION DATA

It was tempting to try an interpretation of the polarization on the basis of the optical effects by the grain population analysed by the impact detectors of the spacecrafts. Such an attempt was implemented by Mukai et al. (1987) who used the Mie theory with the grains size distribution given by the SP-2 instrument. They varied the two optical parameters n and k of the refraction index and found a reasonable fit with the curve of polarization at 0.63 μm with the precise values n=1.49±0.01 and k=0.03±0.004. But no realistic substances have such indices (Lamy et al., 1987). However, inspection of the phase dependent polarization curve of Figure 3 is immediately reminiscent of similar curves observed on other atmosphereless solar system objects, when they have their surfaces made of cohesive small grains. Such are Mercury (Dollfus and Aurière, 1974 - Gehrels et al., 1987), the lunar surface (Gehrels et al., 1964 - Dollfus and Bowell, 1971 - Dollfus and Geake, 1977), the asteroids (Zellner and Gradie, 1979 - Dollfus et al., 1989).

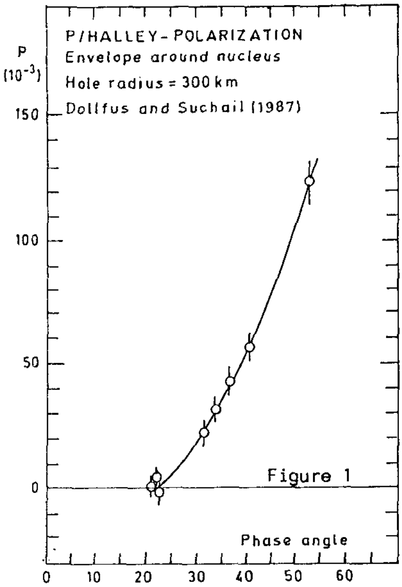

Figure 1

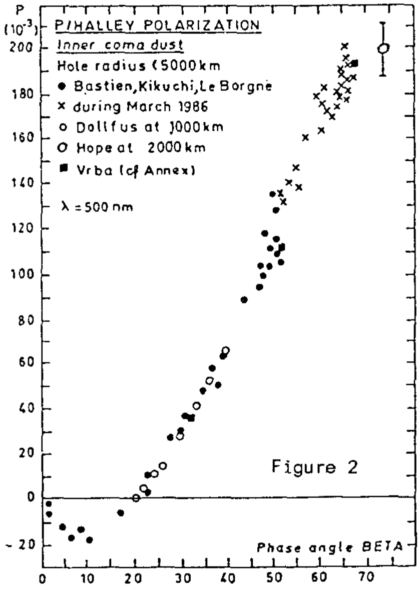

Figure 2

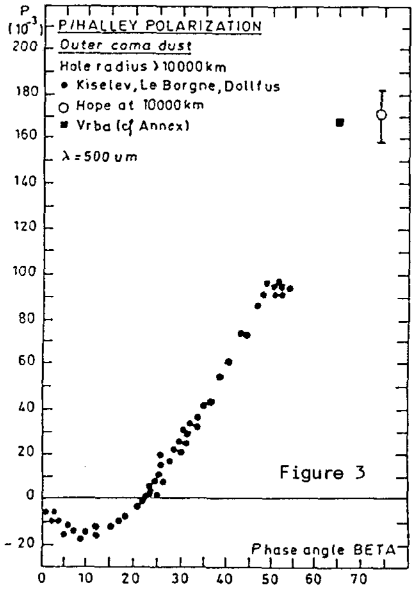

Figure 3

This similarity turns out to be an identity when we compared the coma curve with those for the darkest of these objects, which are among the C-type asteroids. The P/Halley dust grains polarization curve is exactly matched by the average of the four darkest asteroids presently analysed polarimetrically, which are 19 Fortuna, 54 Alexandra, 56 Meleta, and 84 Klio (Dollfus, 1988). The wavelength dependence fits as well. All these bodies have in common a same type of surface, which is made of a layer of grains, very dark and aggregated in a rough structure.

It is suggested that the solid particles which are responsible for the polarized light in P/Halley coma are large flakes made of aggregatred small and very dark grains.

This interpretation is entirely supported by the extensive laboratory studies on polarization by solid surfaces and samples which have been conducted at Observatoire de Meudon (Dollfus, 1971), and extended in a coordinated program involving the University of Manchester and the University of Arizona (Zellner et al., 1977a and b - Dollfus and Geake, 1977 - Geake et al., 1984 - Dollfus, 1985 - Geake and Dollfus, 1986). A large variety of terrestrial, meteoritic, lunar and artificial samples were analysed on different morphologies. Among this data, a very peculiar type of polarization behaviour emerges constantly. This typical family of curves characterizes surfaces which are made of a layer of small grains, cohesive and aggregated in complex rough structures. The polarization behaviour of P/Halley coma enters exactly into this specific category.

A limited number of polarization parameters are traditionally used to describe the phase dependence of the polarization by such solid surfaces (see ref. cited, specifically Dollfus, 1985, 1988). They are the minimum P_{min} of the degree of polarization curve, the inversion angle V_o at which the degree of polarization changes sign and the slope h of the curve after the inversion angle. For the P/Halley polarization curve, all these three parameters fit with the values for very low albedo surfaces made of aggregated small dark grains. They are exactly reproduced, in particular, on a sample of meteorites C1 Orgueil when shifted through a 50 μm mesh leaving the smaller grains. At the microscope, the Orgueil sample exhibits opaque grennish grains of irregular shape, totally wrapped with aggregated small black particles, leafly textured (Dollfus, 1988).

The information is that the optical polarization which is observed in the P/Halley coma is essentially produced by dark flakes or globules, which are made of a rough aggregation of small and very black grains. These flakes have to be large enough to integrate the effect of this texture other many asperities, which imply diameters of perhaps several hundreds of μm (Dollfus, 1988).

This result is also supported by laboratory measurements on isolated single grains. Experiments were conducted either by the technique of microwave homothetic analogs (Zerull and Giese, 1974 - Schuerman, 1980) or with laser sources (Weiss-Wrana, 1983). Compact grains, in the size range of few tens micrometers in diameter, measured by Zerull and Geise (1984), do not fit al all; this is because compact textures do not permit the multiple exchanges of light between asperities or grains at the surface needed to produce the negative part of the polarization curve. Brownlee type grains, when they are made of very small aggregated particles producing a globule of around 4 μm in diameter (Zerull et al., 1980) does not fit well; the very deep negative polarization which is observed suggests particles of too small size. But a flying ash particle, irregular in shape, with a rough dark and particulate texture, measured by Weiss-Wrana (1983), fits properly with the cometary coma results (Dollfus, 1988).

It emerges again from these laboratory simulations that the polarization of the coma in the visible light is matched by grains far larger than the wavelength, very dark, with an extremely rough surface reminiscent of aggregates of small black particles.

GRAIN FLAKES AND SMALL PARTICLES

These globules, however, have to be intermixted with the mist of small particles sensed by the impact detectors of the spacecrafts. Occasionally, at the occurrence of specific ejection events by the nucleus, the population of small particles exhibits temporarily a dominant contribution to the polarization. Such is particularly the case of large phase angles and in the IR. Events of this type occurred during the course of the observation of P/Halley in 1985-1986 and they have been discussed (Dollfus et al., 1988 - Dollfus, 1988). For other comets, an outstanding case was comet West when its nucleus broke into four pieces on March 1976, with the release of a dense cloud of grains producing a very atypic polarization behaviour (Isobe et al., 1978).

More sensitive to the effect of the small grains is the polarization in IR. Brooke et al. (1987) attempted to explain their curves of polarization at 2.2 μm by a mixture of two types of grains. There is five free parameters however and, despite this flexibility, the author considers that an additive contribution by large rough particles is needed.

It was found also that, of six other comets analysed polarimetrically with sufficient accuracy, four of them, which were Bennett, Mrkos, Austin and West before breaking, were observed at a distances to the Sun smaller than 2 AU and produced the same polarization signatures as for P/Halley, which means dominated by the effect of large dark fluffy grains. The two other comets, which are Chernykh and Ashbrook-Jackson, were observed in excess of 2 AU from the Sun, and produced a polarization behaviour which is essentially dominated by the effect of small grains (Dollfus, 1988).

GRAIN EVOLUTION IMMEDIATELY AFTER RELEASE BY THE NUCLEUS

In the close vicinity of the nucleus, a bright envelope is observed at the telescope with almost the aspect of a star image. Its radius was estimated to be around 100 Km (Dollfus and Suchail, 1987). The phase dependent polarization curve of this bright feature is reproduced Figure 1. This curve departs from the specific polarization behaviour which characterizes dark rough solid surfaces. Although the cross-over angle of 22° remains compatible, the slope h after the inversion has a value of 2.8×10^{-3}/degree and the polarization increases with phase angle more and more steeply, a trend which is not observed on the specific rough particulate solid surfaces. The suggestion is made that ice is included in the immediate process of release by the nucleus, either as isolated grains intermixted with the population of dust grains and flakes, or as a cement or a coating, and that this volatile contribution is quickly removed by evaporation (Dollfus, 1988).

After they cleared up from this bright envelope, the large dark flakes disclose temporarily a slightly different polarization signature than at a large distances to the nucleus, as shown in the figure 2 compared to figure 3. It is tempting to suggest the effect of other volatile compounds, which vaporized more slowly with time (Wallis et al., 1987). Then the grains apparently stabilize in a more final stage.

FURTHER COMETARY GRAIN EVOLUTION

After the cometary grains escape the influence of the nucleus environment, they are subjected to solar gravitation and planetary perturbations with occasional collisions. For the largest grains and the flakes, the radiation pressure and magnetic field effects are negligible, but the Poynting-Robertson drag and the corpuscular drag are cumulating their influences. Detailed analysis of all these forces were derived by Gustafson and al. (1987 a, b). There is a decrease of the excentricity and of the semi-major axis, producing a spiral motion toward the Sun, and a concentration of the largest interplanetary grains in the ecliptic plane toward the Sun, which is made visible as the zodiacal light.

However, modification processes in the physical properties of the grains are at work during their travel into the solar system. Catastrophic collisions occur (Leinert, 1985 - Grun et al., 1985). Energetic ions and electrons accumulate damages (Strazulla et al., 1985 - Sandford, 1986). Aggregated grains in flake-like particles are slowly loosing their outer mantle, assumed to be organic, and the structures become denser and more compact (Fechtig and Mukai, 1985). In addition, there is a contribution to the interplanetary dust population by the solid particles ejected during collisions in the asteroidal belt, which supply compact grains.

The end-state of this double origin and evolution processes is an heterogenous population. The shape of the micro-craters at the surface of the lunar rocks indicates at least three types of particles, of respective densities 8 (irons), 3 (silicates) and 1 (aggregated flakes) gr/cm^3 (Fechtig, 1982 - Fechtig and Mukai, 1985).

ZODIACAL CLOUD CONNECTION

The next step of this evolution is a concentration in the inner zodiacal cloud. Photometry and polarimetry of the zodiacal light enable again, like for the cometary coma, to retrieve physical properties about the cloud itself (Weinberg, 1985 - Frey et al., 1974 - Leinert, 1975 - Leinert et al., 1981 - Levasseur-Regourd and Dumont, 1980 - Dumont, 1983 - Dumont and Levasseur-Regourd, 1985 - Giese et al., 1986), and about the individual grain properties.

Photopolarimetry indicates, in the zodiacal cloud, rather large, fluffy, low albedo grains (Giese et al., 1978 - Greenberg and Gustafson, 1981 - Weiss-Wrana, 1983 - Lumme and Bowell, 1985). The detailed analysis suggests an increase of albedo toward the Sun and a correlated decrease of the degree of polarization maximum (Dumont and Levasseur-Regourd, 1985 - Lumme and Bowell, 1985), in agreement with the in-situ measurements by the spacecraft Helios (Leinert et al., 1981). This fluffy structure of the zodiacal grains is reminiscent of the interplanetary "Brownlee particles" collected in the upper atmosphere. A link is suggested with our identification of flake-like clumps of dark particles in the cometary coma.

There is indication that the zodiacal grains are not identical to the cometary coma grains, however, being probably more compact and of less dark albedo. But the aggregated structure is essentially preserved. Meteoroid impacts at the surface of asteroids are not producing ejectas of this kind, and the processes at work in the interplanetary space may apparently not suffice to produce a large quantity of fluffy structures.

Our polarimetric analysis of P/Halley coma indicates that cometary nuclei are able to release into space a large amount of aggregated flake-like features. Comets appear to be the source, for the fluffy grains which are observed in the zodiacal cloud.

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