Light scattering by cometary dust

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Observations of sunlight scattered by cometary dust particles provide clues to their properties. Interpretation of the variations of its linear polarization, through laboratory and numerical simulations, suggests that dust particles might be built of both very fluffy aggregates and more compact grains, with significant amount of rather transparent silicates and absorbing materials.

INTRODUCTION

Cometary dust

Dust particles, which may consist in compact grains as well as in aggregates, are everywhere in the Solar System, on cometary nuclei, in cometary comae, tails and trails, as well as in the interplanetary dust cloud, in planetary atmospheres, on asteroidal surfaces, on trans-neptunian objects, and on the surfaces of planets and moons. While a limited amount of information on cometary dust is available from a few in-situ missions (i.e. Giotto, Vega, Deep-Space 1, Deep Impact) and one sample return mission (Stardust), clues to the bulk properties of the dust mainly stem from remote observations, i.e. spectroscopy that provides information on the composition and study of the characteristics of the solar scattered light that provides information on the bulk properties (e.g. morphology, structure, size distribution, and tentatively albedo). This latter approach, reviewed in [1], may provide evidence on the physical processes that allowed the formation and evolution of the dust.

Relevance of polarization measurements

Solar light scattered by low-density particulate media, e.g. cometary comae and dust tails, is partially linearly polarized. The degree of linear polarization, thereafter called P, is the ratio of the difference to the sum of the polarized brightness components respectively perpendicular and parallel to the scattering plane. It is a very convenient quantity, since it is normalized and depends neither on the distances to the Sun (while the brightness does not follow a R^{-2} law with solar distance R) and to the observer, nor on the dust spatial density. It only varies with the phase angle α (or scattering angle) and the wavelength λ of the observations, and with the properties of the scattering medium. It thus reveals changes in dust properties from changes in polarization in different regions of the coma observed at the same time for identical α and λ, as well as different classes of comets from their polarization properties, even while they are studied at different distances to the Sun and to the observer. It may nevertheless be added that observations of the light scattered by comets requires some attention, since comets are usually faint extended objects and since dust observations have to be done through narrow filters to avoid depolarization from cometary gaseous emissions.

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MAIN TRENDS IN COMETARY OBSERVATIONS

Changes within cometary comae

The variation of the linear polarization of the dust inside comet 1P/Halley coma had been monitored from the OPE experiment on board the Giotto spacecraft, as shown in Fig 1 [2]. In addition, the average dust geometric albedo and density of the particles have been estimated to be about respectively 0.04 and 100 kg m^{-3} in the inner coma [3]. Since then, polarization images have been obtained from remote observations of various comets [see e.g. 4-6]. Significant variations are pointed out, especially for active comets, with often two types of features: i) a circum-nucleus halo with a lower polarization, ii) fan-shaped features with a higher polarization corresponding to some jet-like features. Also, radial averages of the polarization reach an asymptote for increasing nucleus distance, leading to the determination of whole coma polarization from polarimetric images.

Phase angle dependence

The dependence (for a fixed wavelength) of the whole coma polarization upon the phase angle, $P_{\lambda}(\alpha)$, is monitored through the changing geometry for an Earth-based observer. It provides smooth polarization phase curves (see e.g. Fig. 2), with a shallow negative branch near the backscattering region, an inversion region near 20° and a wide positive branch. Such curves are typical of scattering by irregular particles with sizes greater than the observational wavelength, i.e. a few μm. Data suggest the existence of at least two classes of comets, corresponding to different properties of the dust particles: comets with a low maximum in polarization (in the 0.10 to 0.15 range), comets with a high maximum in polarization (in the 0.25 to 0.30 range), and comet C/1999 O1 Hale-Bopp, the polarization of which was the highest ever measured [7]. The maximum in polarization is high whenever a silicate emission feature is detected near 11 μm and may increase after an outburst.

Wavelength dependence

The dependence (for a fixed phase angle greater than about 30°) of the whole coma polarization upon the wavelength, $P_{\alpha}(\lambda)$, presents a quasi-linear trend, at least in the visible domain [5,8]. Some exceptions have been noticed in the innermost coma of comet 1P/Halley (see Fig. 1) and during some disruption events. They reveal drastic changes in the physical properties of the dust freshly ejected, possibly from the subsurface of the nucleus.

LABORATORY AND NUMERICAL SIMULATIONS

Constraints on the properties of the dust are provided by the above-mentioned phase and wavelength dependences. However, some empirical laws, documented for light scattering by surfaces (e.g. albedo - slope at inversion relation), are not necessarily acceptable for optically thin dust clouds; besides the uniqueness of the results through straightforward Mie theory is hardly proven for light scattering by irregular particles with a size parameter above 1. Interpretation of the observed variations of the polarization thus stems from simulations with so-called analogue particles, generally considered to correspond to a realistic composition and morphology of the cometary dust.

Laboratory simulations have been initiated in the sixties, with purpose-built particles for microwave experiments. More recently, measurements in jet streams and steady-state gas flow, which provide the whole Mueller matrix at 632.8 nm and are most appropriate for particles below 1 μm, have been successfully performed [9]. We have, since the mid-nineties, developed the PROGRA² experiment, which provides brightness and polarization measurements on dust samples at 543.5 and 632.8 nm for phase angles in the 6° to 165° range, as reviewed in detail in [10]. Measurements are feasible on low-density clouds of particles of about 1 μm or much more enclosed in a vial; small or fluffy particles are lifted in N_2 draught, while the larger or more compact particles are levitating in microgravity conditions during parabolic flight campaigns, in order to avoid sedimentation and orientation of the dust. A wide variety of samples are used, including series with one parameter changing (e.g. size of the grains, particles size, structure, absorption) and specific cometary analogues. As far as cometary measurements are concerned, excellent matches have been obtained with porous aggregates of sub-μm (MgSiO + FeSiO + C) grains and compact Mg-silicates [e.g. 11].

Numerical simulations have been initiated, after the comet Halley return, of spheres with realistic sizes distribution or more irregular grains. More recently, numerous simulations have been developed with porous aggregates of grains, using DDA, T-Matrix or Ray-tracing codes [e.g. 12,13]. We have initiated simulations for spheroids of astronomical silicates and more absorbing organics and fractal aggregates thereof (BCCA & BPCA, 256 grains) leading to a limited number of free parameters (slope *s* of the size distribution a^s, minimal and maximal equivalent radius *a*, silicates/organics ratio) [14]. For comet Hale-Bopp and a fit in two colours, both compact and fluffy particles are required, *s* is about -3, *a* is in the 0.1-20 μm range and there are 40 to 65 % silicates in mass and 60 to 35% in organics. As illustrated on Fig. 2, there is an excellent agreement between the fits and the observational data in other colours [15,16].

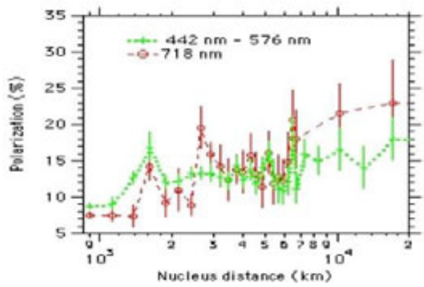

Figure 1. Changes in polarization with nucleus distance along Giotto trajectory within Halley coma, at 73° phase angle.

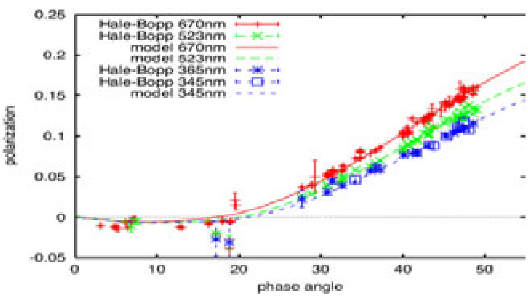

Figure 2. $P_\lambda(\alpha)$ data for Hale-Bopp, compared fits (from blue and red data) with compact grains and fluffy aggregates [15].

The similarities found between the conclusions of such simulations and the ground truth provided by Stardust samples [17] demonstrates the relevance of light-scattering observations.

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