LABORATORY STUDIES OF ICY REGOLITHS IN RELATION TO OBSERVATIONS OF MINOR BODIES IN THE OUTER SOLAR SYSTEM

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Abstract. Observing the properties of solar light scattered by TNOs is (up to now) the only way to obtain information on the physical properties of their surfaces. As such observations, performed near backscattering, become available, it is important to stress the significance of the phase angle and wavelength dependences of the linear polarization of the scattered light. At small phase angles, a narrow spike in brightness and a significantly negative polarization could be typical of icy regoliths, actually expected to be formed by alteration of icy bodies surfaces. Accurate experimental simulations of icy aggregates and regoliths formation that should take place with the ICAPS facility on board the ISS are presented, with emphasis on light scattering measurements providing a link between remote observations of TNOs and physical properties of their surfaces.

1. Introduction

The approach that is being used to derive the physical properties of dust surfaces and clouds in the solar system from their scattering properties may be used for Centaurs and Trans Neptunian Objects (TNOs). Although photometric and polarimetric observations require long observing times and are necessarily performed on a narrow range of phase angles near backscattering, they are the only ways to obtain information on the surface and sub-surface physical properties (without in-situ missions), and thus on the physical processes that shaped the evolution of these objects.

The surfaces of large asteroids are covered with regolith, a dusty and unconsolidated material produced by meteoritic bombardment (see e.g., Clark et al., 2003). The surfaces of smaller asteroids are also dusty, as demonstrated by the NEAR mission to 433 Eros (Veverka et al., 2001). The smallest planetesimals are likely to present dusty surfaces formed by mutual collisions of growing dust aggregates, with sticking of dust particles through low speed impact (see e.g., Weidenschilling and Cuzzi, 1993; Dominik and Tielens, 1997). Finally, dust is also found in cometary comae and tails, in planetary atmospheres and rings, and in the thin interplanetary dust cloud.

The light scattered by these low concentration dusty media is mostly linearly polarized (see e.g., Hapke, 1993), and defined by its brightness and degree of polarization, hereafter called polarization P. The brightness varies with the distance

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to the Sun and to the observer, with the rotational state of the minor body, with the dust concentration, as well as with the phase angle α, the wavelength λ and the dust physical properties. The polarization, which is a ratio, only varies with α, λ and the dust properties. It can thus be used to compare data obtained at different times and on different objects, without making disputable assumptions.

The phase and wavelength dependences of the polarization, defined by $P_\lambda(\alpha)$ and $P_\alpha(\lambda)$, are well documented for quite a few objects (see Levasseur-Regourd and Hadamcik, 2003, and references within). Cosmic dust phase curves are fairly smooth, with a slight negative branch (electric field vector parallel to the scattering plane) at small phase angles and a wide positive branch (electric field vector perpendicular to the scattering plane) with a maximum near 90°. Such curves are typical of scattering by irregular particles with a size larger than the wavelength. Some specific parameters, such as the slope at inversion, may be used to characterize the physical properties of the scattering medium (e.g., the albedo).

Significant results on the wavelength dependence have been obtained for comets and near Earth asteroids. In the near minimum region, the absolute value of P seems to increase with the wavelength for S-type asteroids (Muinonen et al., 2003), while it could decrease for a bright comet such as C/1995 O1 Hale-Bopp. Above 35°, P seems to increase linearly with the wavelength for cometary dust and to decrease linearly for S-type asteroids (Levasseur-Regourd and Hadamcik, 2003). The latter variation may correspond to different morphologies of the scattering dust particles (fluffy aggregates, compact particles).

The next part of this paper discusses the light scattering properties of dusty objects near backscattering, with emphasis on the results already obtained on TNOs. Taking into account the fact that measurements on realistic particles are needed to interpret without any ambiguity the remote observations, the laboratory simulations that have already been performed, and that should be performed in the coming decade, are then presented.

2. Light Scattering Properties of TNOs

The near-backscattering region is characterized by an opposition effect, which corresponds to an increase of the brightness towards small phase angles. The effect could originate in a mutual shadowing mechanism and/or in a coherent backscattering mechanism (see e.g., Muinonen et al., 2003). The coherent backscattering mechanism could explain the narrow opposition spike and the asymmetry of the negative polarization branch, as noticed for icy satellites near backscattering (see e.g., Rosenbush et al., 2002).

The scattering properties of TNOs are starting to be assessed. The opposition surge seems to be quite linear, at least in the 0.3° to 2° or 4° range (see e.g., Schaefer and Rabinowitz, 2002; Rousselot et al., 2003), although an extremely narrow spike below 0.3° cannot be ruled out. Most promising preliminary results on an accurate determination of the polarization of Ixion 2001 KX_{76} by Bagnulo et al. (Boehnardt, this volume) indicate a significantly negative polarization below 1.4°. These results seem to agree with the possible existence of a layer of icy regolith on the surface of these objects.

It may indeed be anticipated that various processes have been taking place on the surfaces: polymerization of organic-rich ices by cosmic irradiation, collision with other minor bodies and solid particles (with possibly subsequent accretion of icy grains), and resurfacing of the icy surface (which depends upon the orbit).

Numerical and/or experimental simulations are still required to derive the physical properties of the scattering media from the observable quantities. Light scattering numerical simulations are difficult for irregular particles with a size greater than the wavelength, for which Mie computations on spheroidal particles are not valid. Approximations are required, and the uniqueness of the solution remains disputable. The situation is even worse in the case of regoliths, for which multiple scattering cannot be ruled out, especially for high albedo surfaces.

On the other hand, experimental simulations need experimental techniques that avoid the sedimentation in layers of the dust particles. Microwave analogue techniques have been successfully used by Gustafson and Kolokolova (1999), although they require some artificially built particles and thus an assumption on the shape and morphology of the scattering medium. Moreover, it is of major importance to reproduce the agglomeration/fragmentation processes that have shaped small bodies made up of ices and dust particles.

3. Measurements on Realistic Particles

We have, since the mid-nineties, developed a programme with nephelometer type instruments avoiding the sedimentation of dust particles under microgravity conditions (Levasseur-Regourd et al., 1998). Whenever the microgravity duration is long enough, conditions representative of the proto-solar nebula and outer solar system environment may be reproduced, to allow the progressive formation of aggregates and of porous regoliths. A modular approach has been used with experiments operating on a regular basis during parabolic flight campaigns ($PROGRA^2$, CODAG-LSU) and with an experiment operating during a rocket flight (CODAG-SRE). A new experiment, so-called ICAPS (Interactions in Cosmic and Atmospheric Particles Systems) should take place on board the International Space Station, with a precursor flight, so-called ICAPS-MSG (Microgravity Science Glovebox) in the near future.

The $PROGRA^2$ experiments measure, through images of the polarized components of the brightness, the polarization of the dust enclosed in a vial at a given phase angle. They have demonstrated the feasibility of polarization measurements under microgravity conditions and provided a very important database on natural and industrial particles, as well as on particles of meteoritic origin (see e.g., Worms et al., 1999). Some of the results suggest that the scattering particles observed in the outer cometary comae are mostly highly porous aggregates of submicron grains (Hadamcik et al., 2002).

The CODAG experiments make use of a LSU (Light Scattering Unit), with a ring of analysers uniformly distributed around a low-pressure chamber in which the enclosed particles are aggregating (Levasseur-Regourd et al., 1999). They have demonstrated the feasibility of monitoring the brightness and polarization phase curves of micron-sized dust particles and of the fractal aggregates they may form under low velocity conditions. Both series of experiments indicate that the polarization method is reliable and sensitive enough to estimate various particles properties in planetary sciences (Pentillä et al., 2003).

4. Future Prospects

ICAPS is a physics facility for the International Space Station. It has been preselected by ESA in 1999, following the studies of a topical team on pre-planetary dust agglomeration. The phase A was approved in 2001 and the phase B in 2002. It is now anticipated to integrate ICAPS and IMPF (International Microgravity Plasma Facility) in the same rack on board the Columbus laboratory. Some of the scientific objectives are as follows: to investigate the agglomeration processes at the early stage of planetary formation (from micron-sized particles to macroscopic dusty bodies), to interpret the light scattering remote observations in terms of physical properties of dust particles, aggregates or regoliths, to validate some light scattering codes, to understand how particles interact with the Earth atmosphere, and to monitor ice condensation and evaporation on particles and regoliths.

The ICAPS-MSG precursor flight should take place in 2006. As far as the light scattering is concerned, this experiment will use a ring of analysers to monitor the brightness and polarization phase curves, from near backscattering (tentatively 2°) to near forward scattering, and in three colours (from about 500 nm to about 1000 nm). Two sets of micron-sized particles (with different albedos) will be injected to allow the formation of bi-disperse particles.

The light scattering observations performed on-board ICAPS will be of interest to interpret observations of Centaurs and TNOs, since measurements will be performed close to backscattering, and since special emphasis will be given to regolith and icy particles formation. In the present instrumental concept (Figure 1), two low-pressure chambers surrounded by their diagnostic tools, including the light scattering unit, are to be used.

The objectives of experiments on ice-coated aggregating particles forming icy regoliths have been discussed in the frame of an ESA topical team on icy particles and regoliths (Ehrenfreund et al., 2003). The low-pressure chambers will reach temperatures of about −50 °C, and possibly even lower temperatures in a later phase of development. Besides, it is anticipated that one of the chambers will

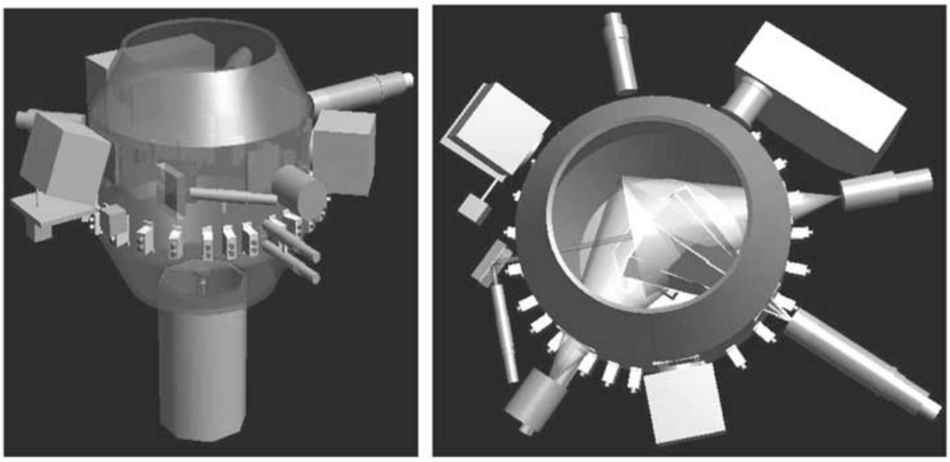

Figure 1. Schematic views of one of the experimental chambers in the ICAPS/IMPF laboratory, with diagnostic tools including the Light Scattering Unit (courtesy by Kayser-Threde GmbH and Nubila S.a.s.).

allow the formation of centimetre-sized aggregates on which low velocity impacts can take place. Such impacts have already been tested in microgravity conditions (Colwell, 2003), and should lead to the formation of a medium representative of regolith on minor bodies.

5. Conclusion

From the observations already performed with very large telescopes, and from the laboratory experiments now developed under microgravity conditions, it can be expected that the physical properties of the surfaces of quite a few of these objects will be fairly assessed in the coming decade, and that a significant diversity will be noticed. Such information will be of major importance to understanding the various mechanism of evolution, and to improve the strategy of their detection and observation. It will also provide, before the first landing on a comet nucleus takes place with the Rosetta mission (with a likely landing on comet 67P/Churyumov-Gerasimenko nucleus by 2013), unique information on fresh bare comet nuclei.

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