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Light scattering by agglomerates: Interconnecting size and absorption effects (PROGRA^2 experiment)

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ABSTRACT

Linear polarization of the scattered light by clouds of dust particles and by very large agglomerates deposited on a surface are studied with the PROGRA^2 experiment. A first series of measurements use bare silica spheres and black-coated spheres to compare the phase curves obtained by different sizes of agglomerates with varying albedos. The refractive indices are evaluated by comparison with numerical simulations. Then, the maximum polarization, P_{max}, on the phase curves for irregular particles is studied as a function of the size of the grains (equivalent diameters from submicron-sized to hundreds of micrometres) and of the agglomerates (from micrometres to centimetres). A minimum value of P_{max} is obtained for silica (about 5% for lifted agglomerates and 3% for layers of particles with a grain size of about 50 μm) and amorphous carbon (about 40% for lifted agglomerates and layers with a grain size of about 0.2 μm). For smaller grain sizes, P_{max} increases when the grain size decreases. For larger grain sizes, P_{max} increases when the grain size increases. Differences between transparent and absorbing materials are underlined. Such studies may be used to interpret remote observations of light scattering by dust particles in cometary comae and Titan's atmosphere.

1. Introduction

1.1. Context

Clouds of solid particles are found in different regions of the solar system, e.g. cometary comae and tails, interplanetary dust cloud as well as atmospheres of planets and Titan [1–4]. Loosely packed solid particles are also found in lunar and asteroidal regoliths; they correspond to fragmentary debris produced by meteoritic impacts [5,6].

Physical properties of the particles are derived from a few in-situ measurements, by cometary, interplanetary and atmospheric probes, with recent results obtained by e.g. Deep Impact [7] and Huygens mission [5]. Also, unique results may be derived from unique sample return missions, such as Stardust, which has allowed dust samples from comet 81P/Wild 2 to be analyzed in Earth laboratories [8]. To infer the properties of a larger set of objects, remote observations are mandatory. Amongst them, observations of the solar light scattered by dust can provide clues to the physical properties (e.g. size distribution, porosity, albedo of the dust particles), as long as they are correlated with numerical and laboratory

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simulations [4,9–12]. Of special interest is the fact that decent laboratory analogues can now be obtained, both for cometary dust and for Titan tholins [13,14].

In the present paper, the word 'grain' is used for an individual entity as visible on a SEM or TEM image; the word 'aggregate' is used for bonded grains (e.g. sintered grains). We use the word 'agglomerate' for grains and/or aggregates staying in a small limited volume when lifted simultaneously during our light scattering measurements and 'huge agglomerates' for particles made by random ballistic deposition (see Section 2.2). An aggregate is difficult to destroy just by handling; agglomerates are fragile and can be easily destroyed; new agglomerates are created at each parabola when the particles are lifted or when 'air' is injected. The word 'particle' is more general and can be used for an individual grain or aggregate as well as for an agglomerate of grains.

1.2. Linear polarization

The linear polarization value depends on the phase angle, the wavelength and the physical properties of the particles. The total intensity, I, and the degree of linear polarization, P, of the scattered light are defined by:

$$I = I_{\perp} + I_{\parallel} \tag{1}$$

$$P = (I_{\perp} - I_{\parallel})/(I_{\perp} + I_{\parallel}) \tag{2}$$

where $I_{\perp}$ and $I_{\parallel}$ are the polarized intensities, respectively, perpendicular and parallel to the scattering plane. As a dimensionless ratio, P does not need any normalization. On the opposite, the intensity needs to be normalized as a function of the number of scattering particles in an experiment.

The linear polarization phase curves observed for solar system dust are typical of the interaction of light with irregular particles. They present a shallow negative branch at phase angles smaller than about 20° and a bell-shaped positive branch at larger phase angles. The main parameters that characterize the phase curves are the minimum polarization and the corresponding phase angle ($P_{\min}$ and $\alpha_{\min}$), the phase angle at inversion (α_0) and the slope at this point (h), the maximum polarization and the corresponding phase angle ($P_{\max}$, $\alpha_{\max}$).

1.3. Laboratory measurements

Light scattering by clouds of particles and, more specifically, the linear polarization of the scattered light can be studied using different levitation techniques such as a steady-state gas flow or jet streams [15–17]. These techniques are suitable for submicron-sized or micron-sized particles but not for large particles (hundreds of microns). The PROGRA^2-vis instrument ('vis' for visual) is dedicated to light scattering measurements on clouds of particles in microgravity conditions for any kind of particles without discrimination by weight or composition [18]. The particles can also be lifted by an air-draught under Earth gravity conditions when they are fluffy or smaller than a few micrometres. The lifted particles may be agglomerates of grains [19,20]. The second instrument PROGRA^2-surf ('surf' for surface) is used to study of the light scattered by grains deposited on layers on the ground, e.g. regolith analogues [21].

In the present paper, we first shortly describe the instruments and samples. Then results are presented for micron-sized spheres (bare or coated with an absorbing material). Comparison of results obtained for the same constituent grains in small lifted agglomerates (SL) with sizes smaller than 10 μm, in large lifted agglomerates (LL) with sizes between 20 and 500 μm and in huge deposited agglomerates (HD) with diameters between 1 and 2 cm and thickness of about 0.3 cm are made with transparent and absorbing materials, as well mixtures of both. In the next part, results for irregular particles are presented. The maximum polarization for particles made of transparent and absorbing materials is studied as a function of the particles sizes. Finally some astronomical applications are presented.

2. PROGRA^2 experiment

A database for the experiment with a description of the instruments and results is now available on the web www.icare.univ-lille1.fr/progra2.

2.1. Instruments

Two instruments are used: (i) PROGRA^2-vis (Fig. 1a) for lifted particles in the visible domain and (ii) PROGRA^2-surf (Fig. 1b) for samples deposited on a horizontal surface. More details on the instruments can be found in [22,23]. Detailed optical sketches are provided for both instruments in Fig. 2a and b. The light sources in the two cases are randomly polarized lasers at 543.5 and 632.8 nm. The diameter of the beam is about 3 mm. The particles to be lifted during the measurements are enclosed in a vial. Two cameras (resolution 10 μm/pixel for the 'vis' instrument) measure the two polarized intensities of the scattered light after separation by a beam-splitter cube. The signals are digitized in real time on 10 bits. The cameras record 12.5 images by second. To increase the dynamics, exposure times are between 1/50 s and