Cosmic dust optical properties: numerical simulations and future laboratory measurements in microgravity

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Abstract

Understanding the properties of particle aggregation and resulting aggregates under microgravity conditions leads to better insights on the formation of the early Solar System planetesimal. Simulating such conditions is the main objective of Interactions in Cosmic and Atmospheric Particle System (ICAPS), a multi-users facility currently under phase B at ESA for the International Space Station (ISS). First results of light scattering simulations by core-mantle aggregates of grains with organics and icy mantles are presented to show the evolution of polarization with aggregation. The Light Scattering Unit (LSU) is both a polarization diagnostic tool for ICAPS, and an experiment that will allow the interpretation of the available light scattering dust observations in terms of physical properties of the scattering media. This presentation updates the current approach of the calibration procedures and the innovative experimental setup (providing a phase angle exploration from about $2^\circ$ to $175^\circ$ together with a wavelength exploration from 0.4 to 0.8 micrometers). We also assess the possibility for the determination of the entire Stokes vector of the light scattered by the aggregates.

Key words: polarization, light scattering, cosmic dust, microgravity experiment.

1 Introduction

In the proto-solar nebula, solid submicron sized grains from interstellar origin slowly merged to form solid particles, small bodies and planets \cite{Greenberg1997}. In the Solar System, cosmic dust can be found in dust clouds and cometary comae, or can form regolith on asteroidal surfaces and aerosols in planetary atmospheres. Physical characteristics about these particles come from in situ studies by space missions such as Stardust, see e.g. \cite{Levasseur-Regourd2007}.
Tuzzolino et al. (2004), and collection of Interplanetary Dust Particles (IDPs) collected in the earth atmosphere, see Zolenski et al. (1994); Jessberger et al. (2001). Nevertheless, most of the available data regarding the physical properties of the particles (size, morphology, albedo etc.) are deduced from remote observations of the light scattered by the dust.

1.1 Observations of scattered light

The complete description of scattered light is given by a four elements vector, also called Stokes vector, the coefficients of which are $I, Q, U,$ and $V,$ respectively the total intensity of the light, the difference of parallel ($I_\parallel$) and perpendicular ($I_\perp$) polarized intensity with respect to the scattering plane, the difference of the intensities of linearly polarized light at $+45^\circ$ and $-45^\circ$ and finally the difference between left and right polarized intensity (e.g. Hapke, 1993). Observations of the linear polarization degree, $P,$ defined as:

$$P = \frac{I_\perp - I_\parallel}{I_\perp + I_\parallel} = \frac{-Q}{I}$$

are of special interest. Being a dimensionless number and the incident solar light being unpolarized, $P$ does not require any calibration with the distances between the scatterer and the source or observer, but only varies with the phase angle $\alpha,$ the wavelength $\lambda$ and the dust physical properties.

Current polarimetric observations show that most of the dust clouds, cometary comae and asteroidal regoliths in the Solar System present similar linear polarization phase curves. They all have a bell-like shape with a small negative branch (electric field parallel to the scattering plane) for small phase angles, an inversion angle around $20^\circ$ and a large positive branch with a maximum value in the $[80^\circ, 120^\circ]$ phase angle range (Hanner, 2003; Levasseur-Regourd, 2004b). The global shape of these curves is most probably related to the interaction of light with irregular particles of size larger than the wavelength (e.g. Bohren and Huffman, 1983; Mishchenko et al., 1999).

Analysis of recent observations have shown a quasi-linear dependence of the polarization with respect to the wavelength in the visible domain. The gradient is positive for cometary comae, and negative for S-type asteroids. In both cases, the slope increases with larger phase angles between the inversion and the maximum region (Levasseur-Regourd and Hadamcik, 2003).
1.2 Light scattering measurements on aggregates

The IDPs constituted by aggregates of submicron grains are generally expected to be from cometary origin (Rietmeijer, 2002). Such particles exhibit very low densities as reviewed by Rietmeijer (1998), in agreement with the density of about $100 \text{ kg.m}^{-3}$ obtained from the Giotto probe for Halley’s comet (Fulle et al., 2000). The aggregation of interstellar grains into very fluffy particles was suggested by Greenberg and Hage (1990) to explain the formation of cometary grains and cometary nuclei.

Experiments on light scattering by particles have been developed by laboratory to reproduce the intensity and polarimetric curves observed in the Solar System. A couple of experiments have been performed with slowly falling particles, including dust from meteorites, thus validating the experimental approach and presenting relevant results regarding the polarization phase curve (West et al., 1997; Muñoz et al., 2000; Hadamcik et al., 2003). Other relevant experiments made use of the similarity principle and microwave techniques with bigger particles (Gustafson and Kolokolova, 1999). Even if interesting results have been obtained, ground-based experiments cannot entirely reproduce the space environment in which dust particle aggregation processes took place and we need other approaches to improve our knowledge of the dust particle properties.

In the next part, we will describe results obtained through a numerical simulation of cometary dust particles. Light scattering codes are efficient and can be used for an increasing number of particle types. However the computer time required for such applications is still very high. Moreover the approximations used in the algorithms should be checked with well controlled laboratory measurements.

Microgravity experiments allow us to create experimental conditions closer to the space environment in which cometary and interplanetary dust lie. Therefore particle aggregation can be reproduced free from gravitational forces. The drawback of working under space conditions is that the experiments have serious constrains in terms of size, mass and time of duration. More precisely, the light scattering measurements that will be performed with ICAPS, a multi-users microgravity facility for the ISS, will be further detailed in the last part of the paper.
2 Core-mantle model for cometary dust particles

2.1 Description of the model

The description of light scattering by irregular particles with size close to the incident wavelength involves numerical tools and approximations, such as the Discrete Dipole Approximation (DDA) [Draine and Flatau, 2000], or the T-matrix [Mishchenko et al., 1999]. These tools have already been used for the description of cometary particle properties using aggregates of spheres, showing the apparition of a negative branch and a maximum in polarization at 90° for porous aggregates of few tens of submicron spheres, see e.g. Xing and Hanner (1997); Petrova et al. (2000).

One commonly accepted model used to explain the astronomical observations and physical properties of pre-cometary grains, or proto-solar grains, is the core-mantle model presented by Greenberg and Hage (1990). The interstellar grains are elongated and constituted of a core of interstellar silicates, a layer of organic refractory material and an outer layer of volatile ices with water ice as the main component.

As a first step, we use spherical grains, with two concentric spherical layers: a silicate core with refractive index \( m = 1.62 + 0.003i \) [Dorschner et al., 1995], a first layer of organic material with \( m = 1.88 + 0.1i \) [Greenberg and Li, 1996] and a second layer of water ice, the refractive index of which might be assumed to be \( m = 1.31 \) [Warren, 1984]. All the indices are given in the optical domain. The mean size parameter of the grains, \( X = \frac{2\pi r_{\text{grains}}}{\lambda} \), is around 2, at \( \lambda = 0.5 \mu m \), as deduced from Li and Greenberg (1997).

2.2 First results

We used the DDA code to calculate the light scattered by such grains aggregated by a typical fractal process: Ballistic Cluster-Cluster Aggregation (BCCA), described by Meakin (1983). When each grain has a size parameter of 2, typical features of the polarization and intensity curves observed in the Solar System begin to appear. Fig. 1 shows the evolution of the polarization phase curve expected during the aggregation process by comparing in Fig. 1a the polarization phase curve for a single two-layered sphere (\( X = 2 \)), and in Fig. 1b the curve for a BCCA aggregate of 64 spheres (\( X = 1.8 \) to 2). The negative branch appears below 20° phase angle and the large positive branch has a maximum around 80°. Moreover, calculations made for aggregates of spheroidal grains show the same tendencies, the gradient of the polarization degree with the size parameter being in this case less steep than in the case
of spheres.

Fig. 1. Variation of polarization phase curve with the aggregation: Fig. 1a, Mie theory for a two-layered sphere: silicates-organics-ice (X=2); Fig. 1b, DDA calculations for a BCCA aggregate of 64 such two-layered spheres (X=1.8; X=1.9; X=2).

Our model size, composition and optical indices, even with the high simplicity of a spherical hypothesis, produce curves presenting features observed for dust in the Solar System. However, the validity of any numerical approach needs to be confirmed experimentally by carefully controlling each parameter involved in the model.

3 ICAPS light scattering description

The above mentioned process of BCCA has already been monitored during microgravity experiments attempting to simulate the original seedling of planets, producing open structures of particles with a fractal dimension around 2 (Blum et al., 2000). In order to understand the properties of particle aggregation and resulting aggregates under low-pressure and microgravity conditions, measurements are performed during microgravity flights on a cloud of particles, to analyze their polarization properties and to provide a link between the polarization observations and their physical properties. Reconstructing such realistic conditions is the main objective of Interactions in Cosmic and Atmospheric Particle System (ICAPS), a multi-users facility currently under phase B at ESA for the ISS.

3.1 Precursor Experiments

Precursor experiments have already been performed. First the PRopriétés Optiques des GRains Astronomiques et Atmosphériques (PROGRA²) experiment has shown the feasibility of light scattering measurements under microgravity conditions during parabolic flights. It also allowed the creation
of a polarization database for more than 100 samples including compact as well as fluffy particles (Worms et al., 1999; Hadamcik et al., 2002). Second, the COsmic Dust AGgregates - Sounding Rocket Experiment (CODAG-SRE) has demonstrated the feasibility of simultaneous measurements of the polarization degree and total intensity at different phase angles. The onset of particle aggregation has been monitored, up to aggregates of a few tens of grains (Levasseur-Regourd et al., 2001). New concepts have been developed, which are to be validated and will provide new scientific results during the ICAPS Precursor Experiment (IPE) due to fly on board the ISS in the near future.

3.2 Scientific objectives of ICAPS

The main scientific objectives of the ICAPS experiment are amongst other ones (Blum et al., 1999):

(1) to simulate the aggregation processes of submicron and micron spheres of several absorbent and nonabsorbent materials under presumed protosolar nebula conditions,
(2) to produce large aggregates of such spheres whose properties are comparable to the ones of cosmic dust and asteroidal regolith,
(3) to relate the light scattering measurements with the physical properties of the aggregates and regolith simulant formed in the chamber,
(4) Finally the scattering measurements shall also validate the approximations used on light scattering codes and models.

The ICAPS light scattering device will be able to probe the polarization degree and total intensity for small phase angle (as small as $2^\circ$) and give information related to the formation of large (> 1 cm) aggregates. The use of three different wavelengths well distributed in the visible will allow the monitoring of the linear dependence of the polarization with the wavelength. Finally, the four Stokes parameters ($I, Q, U, V$) of the scattered light should be retrieved for one phase angle, giving twice as much information as would be obtained using a single separating prism. Of particular interest will be the detection of the circular polarization degree for comparison with the astronomical observations and ground-based experiments (Hovenier et al., 2003).

3.3 Description of the instrument

In order to investigate the evolution in shapes and characteristics of the aggregates formed in the dust chamber (Fig. 2), the particles will be illuminated by laser diodes and flash lamps and observed through cameras, microscopes.
and a new light scattering device upgraded from the CODAG-LSU. Angular light scattering measurements are usually performed by nephelometers, in which a collimated light source illuminates a sample and a detector collects the scattered light at a given phase angle \(\text{e.g., Bohren and Huffman, 1983}\). The sample inside the chamber will be illuminated at three wavelengths (408, 635 and 830 nm) with a high frequency switch (about 100 Hz). The unpolarized state of the solar light cannot be reproduced satisfactorily by a laser diode. However since we will retrieve the linear polarization degree, the polarization of the incident light on the particles will be previously circularized by a Fresnel prism (equivalent to an achromatic quarter-wave plate) in order to give the same intensity to the perpendicular and the parallel linear components of the light.

![Diagram](image1.png)

Fig. 2. Instrumental concept: left, low pressure chamber with dust particles sequentially illuminated by 3 laser diodes; \(I\) and \(P\) analyzed at 24 phase angles to retrieve phase curve; right, detail of one analyzer constituted of a Foster prism with 2 lenses and diaphragms.

The two perpendicular components of the light scattered by the particles are then separated using a Foster prism. Each intensity is measured with a very sensitive photodiode for at least 24 phase angles at three different wavelengths (see Fig. 2). The specificity of the experiment relies on simultaneous measurements of the polarization for each phase angle with an array of fixed analyzers, in a small and compact configuration. The unscattered and forward scattered light will be absorbed by a light trap to prevent stray light from coming back into the chamber.

To ensure a proper calibration of the instrument, each analyzer has to be checked separately. Tests will be carried out with opal glasses and lambertian surfaces with a well known scattering function. A further test using silica spheres on microgravity (parabolic flight) will provide the definite calibration test and validate the experiment concept with the Mie theory. Fig. 3 shows the curve that would be retrieved by the light scattering unit at 650 nm for spheres of 0.5 \(\mu m\) radius.
4 Preliminary results on the instrument capabilities

4.1 Validation of the optical principles

The breadboard activities of the ICAPS optical concept validated and characterized critical optical elements. The Fresnel and Foster prisms have been studied and proved to be sufficiently achromatic for the purpose of the experiment. Precision of circularization for the Fresnel prism is about 1% and the separation precision of the Foster prism for each ray of light is better than \( \frac{1}{1000} \). Absorption of each of those two elements is lower than 10%. The photodiodes have a high enough sensitivity to detect \( 3.10^{-11} W \) which is the lowest expected intensity on the detectors based on the physical parameters (Haudbourg, 2000).

4.2 First steps towards Stokes polarimetry

In order to measure the four Stokes parameters with limited volume, weight and power consumption, a Liquid Crystal Variable Retarder (LCVR) aligned with a Foster prism can be used as shown in Fig. 4. Calculations show that with an alignment angle of $\frac{\pi}{8}$ between the LCVR and the Foster prism, the Stokes parameters of the light and the measured intensities on the detectors \( D, I_n \), are related with the formulae:

\[
\begin{align*}
I &= I_1 + I_2 = I_3 + I_4 = I_5 + I_6 \\
Q &= I_1 - I_2 \\
U &= I_5 - I_6 \\
V &= \sqrt{2} \times (I_5 + I_1 - 2I_3) = \sqrt{2} \times (2I_4 - I_2 - I_6)
\end{align*}
\]
First tests performed in 2004 have validated the principle of Stokes vector measurements. Theoretical studies have shown that constraints of $\pm 0.5^\circ$ in optical alignment, $\pm 0.7^\circ$C in temperature and $\pm 4.2 \times 10^{-3}$ V in voltage are sufficient to reach a precision of 1% for the measurement of Stokes parameters, a precision comparable to the one of Solar System observations.

5 Conclusions and perspectives

Numerical simulations based on the core-mantles model give first results comparable with polarization phase curves observed in the Solar System: negative branch below 20$^\circ$ and large positive branch with a maximum around 80$^\circ$. The ICAPS microgravity experiments will allow us to validate the numerical studies with new optical instruments. On one side, information will be retrieved regarding the evolution of polarization with particles aggregation under proto-solar conditions, on the other side wavelength dependence of the polarization will be monitored and finally the four Stokes parameters of the scattered light should be measured. First results on cometary studies will be obtained with IPE due to fly on board the ISS in the near future.

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