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Laboratory measurements of single light scattering by ensembles of randomly oriented small irregular particles in air. A review

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ABSTRACT

In this paper we present an overview of light scattering experiments devoted to measure one or more elements of the scattering matrix as functions of the scattering angle of ensembles of randomly oriented small irregular particles in air. A summary of the most important findings in light scattering experiments on ensembles of randomly oriented particles in air is given. The particles of interest are relevant for studies of atmospheres of planets and satellites and also for other astronomical bodies and environments. Some applications of light scattering experiments are also presented.

1. Introduction

The study of light scattering by small irregular particles has been and still is a subject of great interest in many different scientific disciplines for many years. Prof. van de Hulst published in 1957 his well-known book *Light Scattering by Small Particles* [1]. By that time it was already clear that many atmospheric and cosmic dust particles present nonspherical shapes. More recent books on light scattering by small particles have been published by Kerker [2], Bohren and Huffman [3], Mishchenko et al. [4,5], and Hovenier et al. [6].

Light scattering is one of the most powerful techniques for determining physical characteristics of small particles such as size, shape, and refractive index. Light scattering by small particles can be either computed or measured in the laboratory. In the case of homogeneous spherical particles, their scattering behavior can be easily computed from Lorenz–Mie theory by using one of the available computer codes (e.g. [3,5,7], see also www.scattport.org). However, in the majority of cases of interest the assumption of spherical particles is highly unrealistic. We can find examples of such nonspherical particles in many different environments like mineral and soot aerosols, volcanic ashes, snow or ice crystals in the Earth atmosphere as well as planetary, interplanetary and cometary dust grains, planetary ring particles, dust around stars, and in other astrophysical environments. Some biological microorganisms also present irregular shapes and the knowledge of their scattering behavior is relevant in medical studies. In Fig. 1, we present some examples of such irregular small particles. Nowadays, computational characterization of small irregular particles from the observed scattered light remains an extremely difficult task due to the complicated morphology of these particles. Thus, controlled laboratory experiments of light scattering by irregular small particles, remain an indispensable tool to study the scattering behavior of nonspherical particles.

Since the first light scattering experiments one of the main goals has been to study possible correlations/differences between the scattering behavior of randomly oriented irregular and spherical particles. As shown in Section 2, one of the clearest effects of nonsphericity is that the 4×4 scattering matrix has in general six instead of four different non-vanishing elements. In this

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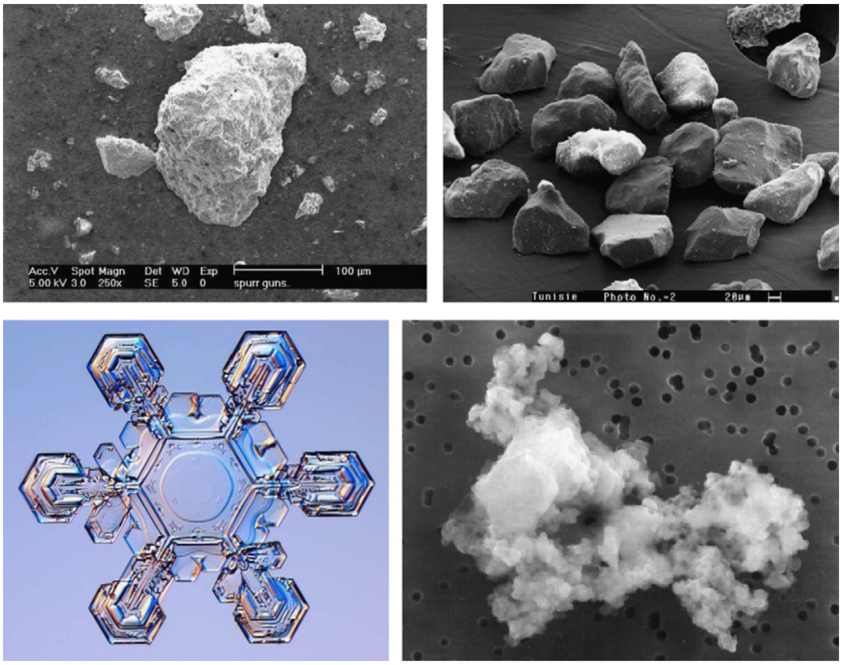

Fig. 1. Scanning electronic microscope, SEM, images of volcanic ash from Mount Spurr volcano (top left panel) [78], desert dust from Niger (top right panel) [126], and an interplanetary dust particle collected at high altitude in the atmosphere of the Earth (bottom right panel). Courtesy: NASA/JSC/CDLF. The white bars at the bottom right corner of each SEM image denotes 100, 20, and 1 µm, respectively. In the bottom left panel we present a picture of a snow crystal that fell to Earth in North Ontario, Alaska from *SnowCrystals.com* http://www.its.caltech.edu/~atomic/snowcrystals/.

review paper we focus on laboratory measurements of one or more elements of the scattering matrix as functions of the scattering angle of ensembles of randomly oriented small irregular particles in air. Some other types of light scattering experiments are only mentioned, but with references to papers for more detailed information. In Section 3, we present a historical overview of that type of light scattering experiments. A summary of the most important findings in light scattering experiments on ensembles of randomly oriented small particles in air is given in Section 4. Although we pay special attention to measurements on samples relevant for studies of astronomical bodies and environments as well as the atmosphere of the Earth, the results presented in this paper may also be useful, e.g. in the fields of chemistry or biology, but also for industrial applications like in the paper and paint industry. We refer to Black et al. [8] for a review on laser-based techniques for industrial applications and to Jones [9] for an extensive review on light scattering experiments with combustion applications. A review on experimental techniques for biophysical and biomedical applications is given by Hoekstra and Sloot [10]. Some applications of light scattering experiments are presented in Section 5.

2. The scattering matrix

The flux and state of linear and circular polarization of a quasi-monochromatic beam of light can be described by means of the so-called flux vector whose elements are Stokes parameters, I, Q, U, V [1,6]. If such a beam of light is scattered by an ensemble of arbitrary particles separated by distances much larger than their linear dimensions and in the absence of multiple scattering, the flux vectors of the incident beam and scattered beam are, for each scattering direction, related by the so-called 4×4 scattering matrix [1,6]. In general it has 16 independent elements that are dimensionless, and depend on the number and physical properties of the particles (size, shape, structure, and refractive index), the orientation of the particles, the wavelength of the incident radiation, and the directions of incidence and scattering. For randomly oriented particles, all scattering planes are equivalent. Thus, the scattering direction is fully described by the scattering angle θ, i.e. the angle between the directions of propagation of the incident and the scattered beams.

When particles and their mirror particles are present in equal numbers in the ensemble of randomly oriented particles, the scattering matrix has the simple form (see, e.g. [1,6]):

$$\begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{12} & F_{22} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{34} & F_{44} \end{pmatrix}. \quad (1)$$

Further, for homogeneous spherical particles the scattering matrix has only four independent elements that are not identically equal to zero, i.e. it has the form:

$$\begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{12} & F_{11} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{34} & F_{33} \end{pmatrix}. \quad (2)$$