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The reflectance and negative polarization of light scattered from snow surfaces with different grain size in backward direction

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ABSTRACT

The scattered light from particulate surfaces is useful for the verification of light scattering theory and the remote sensing applications. We present the photometric and polarimetric measurement results of natural snow surfaces with different grain size in the backward direction in field and in the laboratory. The snow grains are assumed that they exhibit both nonsphericity of shape and small-scale surface irregularities. All the samples display the prominent phenomena of brightness opposition surge and negative polarization; both of them are in dependence on the phase angle. There are clear effects of snow grain size on the photopolarimetric measurement results: the snow surfaces with small diameter show brighter reflectance than those of larger diameter, because of the amount of contaminants there is an exception of snow samples consist of small grain in the visible wavelengths; the absolute values of negative polarization increase with a decrease in grain size (corresponding to packing density), and the effect of snow grain size on negative polarization is quite significant in this study. The relation between snow grain size and negative polarization at near-backscattering geometries can be explained by the coherent backscattering mechanism. These results are useful to better understand the scattering property of high-albedo particulate surface with large particles.

1. Introduction

Light scattering may provide a rapid, noninvasive means of interpreting the particulate system. Such a methodology is of particular importance for the applications of remote sensing in geophysics and planetary astrophysics in the Solar System, each application has the same basic stages which were summarized by Mishchenko et al. [1]. Snow, as a typical particulate surface, covers a large portion of terrestrial surface during the winter. Therefore snow fields have significant effects on the planetary albedo and climate [2,3]. Snow grain size is the primary parameter controlling broadband [4], and affects our ability to accurately map snow cover [5]. The knowledge of scattering properties of snow surface is fundamental for accurate inversion technique that can retrieve quantitative estimates of snow properties (e.g. grain size) from remote sensing data. However, for a long time remote sensing studies had relied on the measurements of only the scattered intensity and its spectral dependence, the numerous model inversion and validation experiments of snow properties based on spectral reflectance have been reported and summarized by mangy researchers [2–17].

For particulate system, as a result of persistent research efforts (see Refs. [1,18,19] and references therein), it is clear that polarimetric characteristics of the scattered radiation contain much accurate and specific information about such important properties of particles as their size,

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morphology. The most remarkable observation phenomenon is the negative branch of polarization in the backscattering direction, which is widely presented in the literature [20–27]. Although, in many cases, but not always, the negative branch of polarization is accompanied by a nonlinear increase of brightness [28–30], the backscatter photometric and polarimetric effects of particulate surfaces in the backward direction are important for the development of remote-sensing researches for atmosphereless celestial bodies.

Among the mechanisms proposed for explaining the phenomenon of the brightness opposition spike and negative polarization of high-albedo particulate surfaces at the backscattering direction, the best proved is the coherent backscattering mechanism (also known as weak localization [31]). The coherent backscattering mechanism, which has been put forward by Mishchenko in the general formulation [32], gains widespread attention from many scientists to explain both phenomenon, which have been observed for a class of high-albedo Solar System objects [1,31,33–35] and identified in laboratory measurements for particulate media [36].

It is clear that light scattering media composed of irregular, nonspherical and internally inhomogeneous particles are of a common occurrence. The application of standard theoretical study of the scattering properties to such media encounters a number of difficulties. Fortunately, the T-matrix method and the discrete-dipole approximation (DDA) have been proposed by Waterman [37], and Purcell and Pennypacker [38], respectively, both of them can be used as powerful tools to compute light scattering by non-spherical particles even though the T-matrix method is limit to simple geometries [39–48]. Moreover, the simulations for some realistic values of refractive indices corresponding to water ice, silicates and so on are effectively carried out with the help of the T-matrix method and DDA. However, our ability to model scattering by individual particles and many geophysical scattering media composed of densely packed particles, whose size are much larger than the incident wavelength, is also limited [49,50].

In recent years, scientists have paid more attention to investigate the scattering characteristics of densely packed particles groups, in which the particles are randomly distributed and wavelength-sized. Their numerical data coupled with the results of unique observations at near-backscattering geometries demonstrate that the brighness and polarization opposition effects detected simultaneously for high-albedo solar system objects are caused by the effect of coherent backscattering [51–58]. These results are particularly valuable for the interpretation of remote-sensing observations such as the observations of high-albedo solar system objects. However, for particulate surfaces, such as snow surfaces whose grain size is much larger than the incident wavelength, the investigation relate both reflectance and polarization to surface properties characterization in the backward direction is also insufficient.

In this paper we measure and analysis the reflectance-phase spectral curves and polarization-phase spectral curves of snow surfaces with different grain size near backscattering geometries in the field and laboratory. The original intent of those measurements is to investigate the general scattering characteristics, and in particular, the backscattering characteristics of surfaces are composed of different snow grain size. Nevertheless, we find the relation between the negative polarization of natural snow surfaces and snow property (corresponding to grain size in this paper) can be explained based on the coherent backscattering mechanism. Below, we report our measurements with a brief analysis and discuss the results of the photopolarimetric data from snow surfaces. The targets, instruments and campaigns are given in Section 2, the result of reflectance and polarization from snow surfaces with different grain size in the backward direction are shown in Section 3, and we present the discussions and conclusions of this study in Section 4.

2. Targets and measurements

2.1. Samples

The choice of snow is dictated by the requirement that it is a typical particulate surface with high-albedo and widely distributed on the land surface. The measurements are composed of two parts in Northeast China, one is in the laboratory, and the other is in field whose site located at 43°55′12″N, 125°23′32″E. The information of measurement data, location, snow type, temperature, grain size, incident light source, incident angles and contaminant concentrations are available in Table 1. During the field measurements progress, all these samples were taken from the surface layer which is not much deeper than 3 cm near the measurement site, after sieved with a series of sieves we accumulated them to a depth of 30 cm which is equal to the depth of snow with different grain size in the laboratory. We denoted the snow samples as S1, S2, S3 and S4 corresponding to the measurement date at 25-2-2012, 26-1-2013, 27-1-2013 and 2-2-2013 in Table 1, respectively.

For all the snow samples measured in the laboratory, we sieved them with two 900 μm and 450 μm sieves, and a 300 μm sieve, producing five different size ranges: 900 μm, 450–900 μm, 450 μm, 300–450 μm and smaller than 300 μm. For the samples measured in field, they were collected through the identical way for samples measured in the laboratory; the distributions of snow grain size were shown in Table 1. Fig. 1 presents the snow samples S2 with grain size equal to 900 μm and 450 μm. They were separated using two 900 μm and 450 μm sieves, to clearly display the snow samples we filled them in white plastic bowl. During the winter in 2012, the outside temperature was −17 °C and the temperature in laboratory was −5 °C; in 2013, the outside temperature of all three measurements was about −18 °C, −16.5 °C and 14.5 °C (see Table 1). Comparing with Salminen's results [59] we approximately defined all the samples as dry snow, and established the metamorphism of snow can be negligible because Colbeck [60] concluded that the crystal growth rate was very low when the temperature was lower than −16 °C. We also weighted the contaminants in snow samples using an electronic scale with an accuracy of 0.0001 g