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Experimental characterization of the opposition surge in fine-grained water–ice and high albedo ice analogs

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ABSTRACT

We measured the bidirectional reflectance in the VIS–NIR spectral range of different surfaces prepared from small-grained spherical water–ice particles over a wide range of incidence and emission geometries, including opposition. We show that coherent backscattering is dominating the opposition effect on fresh sample material, but its contribution decreases when particles become more irregularly shaped and the bulk porosity increases. Strong temporal evolution of the photometric properties of icy samples, caused by particle sintering and resulting in a decrease of backscattering, is shown. The sintering of the ice particles is documented using cryo-SEM micrographs of fresh and evolved samples. To complement the photometric characterization of ices, multiple high albedo laboratory analogs were investigated to study the effects of shape, grain size distribution, wavelength and surface roughness. In addition to the main backscattering peak, the phase curves also display the effect of glory in the case of surfaces of granular surfaces formed by either spherical ice or glass particles. We show that the angular position of the glory can be used to determine accurately the average size of the particles. Reflectance data are fitted by the Hapke photometric model, the Minnaert model and three morphological models. The resulting parameters can be used to reproduce our data and compare them to the results of other laboratory experiments and astronomical observations.

1. Introduction

The reflectivity of a granular surface depends on numerous parameters such as the chemical composition, the internal structure of the grains, the particle size distribution, porosity and surface topography. The direction of the incident light and the direction of observation also have a strong influence on the measured reflectivity. Brightness variations of a surface caused by changing illumination and observation geometries are commonly characterized by phase curves where the phase angle, α, is the angle between the illumination and observation directions as seen from the surface.

A ubiquitous and particularly interesting phenomenon observed in measured phase curves is the so-called “opposition effect”, a sharp, nonlinear surge in brightness when the directions of illumination and observation become nearly parallel (i.e. the phase angle goes to 0°). It is an omnipresent feature that has been observed on many kinds of objects including planetary and terrestrial terrains, planetary rings, asteroids, as well as laboratory samples (see e.g. Helfenstein et al., 1997 or Déau et al., 2013).

The opposition effect was first described by Seelinger (1884) and Müller (1885), who analyzed brightness measurements of the rings of Saturn. More recent reviews of the opposition effect in the Solar System and its mechanisms can be found in Rosenbush et al. (2002) and Belskaya et al. (2008). According to a generally accepted view, this peak can be caused by two different mechanisms: Shadow Hiding Opposition Effect (SHOE, e.g. Seelinger, 1887; Hapke, 1986) and Coherent Backscattering Opposition Effect (CBOE, e.g. Wolf and Maret, 1985; Tsang and Ishimaru, 1985; Muinonen et al., 2012). When particles are much larger than the wavelength of the light, an illuminated surface is partially covered by shadows when observed at larger phase angles, whereas at opposition the entire surface observed is illuminated and shadows disappear, which noticeably increases its brightness (Hapke, 2002). When the particles are in the same range of size as the wavelength, the grains cannot create a well-defined

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shadow, because of the wave-nature of light. At this scale, the CBOE dominates the opposition effect (Liang and Mishchenko, 1997). CBOE occurs as well on complex shaped large grains, because microscopic grain-surface irregularities, voids and inclusions are of much smaller scale than the dimension of the entire particle and therefore allow multiple scattering (Shkuratov and Helfenstein, 2001; Hapke, 2002). CBOE can be understood as a constructive interference of two rays, coming from the same direction, but undergoing the same scattering path between particles in the opposite direction. At exactly zero phase angle they would be in phase and interfere constructively. This is independent of spatial proximity between the two rays, but only because they had the same origin (Akkermans et al., 1986). The angular half-width of the CBOE is always much narrower than the one of SHOE, e.g. in case of the lunar regolith $\sim 2°$ versus $\sim 8°$ (Hapke et al., 1998). Contrary to the SHOE, the angular width and the amplitude of CBOE should positively correlate to the wavelength in case of visible light and particles sizes in the micrometer-range (Van Albada et al., 1990; Mishchenko, 1992; Hapke et al., 1998, 2012; Hapke, 2002). Discussion about correlations between sample material properties and the opposition effect can be found in Shkuratov et al. (2002) or Muinonen et al. (2002).

The "normal reflectance" of planetary surfaces, which can be mapped by laser altimeters, as a side product of the determination of the surface topography (Gardner, 1982; Thomas et al., 2007) is strongly influenced by both the SHOE and CBOE. The intensity of the opposition peak is therefore a crucial parameter for dimensioning these instruments. A good understanding of the physical and compositional parameters that control the opposition effect is also required to interpret the spatial variations of the reflectance observed at the surface. The characterization of the opposition effect in icy surfaces is particularly relevant for the preparation of the GAnymede Laser Altimeter (GALA; Hussmann et al., 2013) experiment on-board ESA's upcoming JUICE mission (Grasset et al., 2012) to be launched in 2022 toward the jovian system.

Another interesting optical scattering phenomenon discussed in the present work is the glory. It is often seen from airplanes as a concentric rainbow-like feature around the plane's shadow cast on a cloud layer (see Laven, 2005a). It has also been already observed in the laboratory on bidirectional reflectance measurements of samples consisting of glass beads (Shkuratov et al., 2002; Hapke et al., 2009). Recently, evidence for glory on venusian cloud tops was obtained by the Venus Monitoring Camera (VMC) of ESA's Venus Express mission. Useful information on the composition and particle size of the clouds could be derived from this observation (Markiewicz et al., 2014). To our knowledge, there is no report in the literature of the observation of glory on icy surfaces, although Hapke (1993) notes that glory can contribute to the opposition effect if samples are composed of spherical particles. Glory originates from the interaction of light rays propagating along different optical paths inside transparent spherical.

Although Mie theory (Mie, 1908) can simulate glories accurately, it offers no precise explanation for their formation. Laven (2005b) used simulations with the Debye series to suggest that glories are a result of two-ray interference between two surface waves with a phase difference. The glory effect depends on the particle size parameter, i.e. the ratio of the scattering particle size and the wavelength. For visible light, it is restricted to particle diameters between 8 and 50 μm (Laven, 2005a). Furthermore, broad size distributions ($\sigma > 2\ \mu$m) have the effect of smearing the primary peak and vanishing secondary maxima. There is no simple formula for the relationship between particle size and angular separation of the first maximum. Mayer et al. (2004) determined water cloud droplet sizes and distribution from remote sensing observations made by the Compact Airborne Spectrographic Imager (CASI) by fitting numerical models to their data. They proved that the technique was reliable for deriving the effective radius and the width of the size distribution, but not its exact shape.

Contrary to the opposition effect, the glory effect is a phenomenon purely originating from the single particle scattering phase function and restricted to spherical particles. The parallel observation of the glory and CBOE on a sample indicates that, at distinct phase angles, the single scattering mechanism dominates over the multiple scattering (scattering between particles), which is necessary for coherent backscattering.

There is little laboratory data available on the photometry of different types of icy surfaces and especially in opposition geometry, whereas numerous observations of icy surfaces in the outer Solar System have already been obtained (e.g. Kaasalainen et al., 2001; Rosenbush et al., 2002; Verbiscer et al., 2013). In a previous work, we characterized micrometer-sized spherical water–ice particles (Gundlach et al., 2011; Gundlach and Blum, 2015) and measured their phase curves at phase angles between 5° and 130° (Jost et al., 2013). These particles are thought to be representative analogs for some icy surfaces in the outer Solar System. To be able to measure such samples at low phase angles, the PHIRE-2 goniometer (Pommerol et al., 2011) of the University of Bern has been modified. A system with a beam splitter was constructed to observe at geometries where the detecting unit was vignetting the incoming light in the previous setup.

Several goniometers have been built in the past decades or are presently under construction, to measure bidirectional reflectance. For example the long-arm goniometer at JPL in Pasadena (Nelson et al., 2000), the spectro-goniometer in Grenoble (Brissault et al., 2004), PHIRE-1 in Bern (Gunderson et al., 2006), the Bloomsburg University Goniometer (BUG; Shepard and Helfenstein, 2007), ISEP in Toulouse (Souchon et al., 2011), and unnamed instruments in Helsinki (Kaasalainen et al., 2002; Näränen et al., 2004) and Kharkov (Shkuratov et al., 2002; Psarev et al., 2007).

All of them have certain advantages and drawbacks in terms of maximum/minimum phase angle, temperature range, spectral range and resolution, angular resolution or acquisition speed, as it is not possible to optimize all these parameters in one single experiment.

There are only a few studies of high albedo laboratory analogs in opposition geometry or at low phase angles. A very extensive study of structural analogs for planetary regoliths was performed by Shkuratov et al. (2002), including magnesium oxide, aluminum oxide, glass beads, hollow glass spheres, silica and terrestrial snow. The authors investigated effects of albedo, bulk compression, particle size, wavelength and particle shape on the opposition effect and degree of polarization. Hapke et al. (2009) characterized soda–lime glass microspheres at BUG and JPL. Nelson et al. (2000) and Kaasalainen (2003) investigated aluminum oxide particles. Deb et al. (2011) also measured aluminum oxide but at large phase angles.

In this work, we present a variety of bidirectional reflectance measurements on high albedo materials, including spherical ice particles, with different surface preparations. Reflectance was measured over a range of large phase angle including the opposition geometry. We demonstrate how particle size, macroscopic roughness, and wavelength influence the bidirectional reflectance properties. We further characterize the temporal evolution of fine-grained ice particles as a follow-up work of Jost et al. (2013) and prove the sintering hypothesis postulated therein by imaging samples composed of micrometer-sized water ice particles with a cryogenic scanning electron microscope. Furthermore we present a method to characterize the particle sizes directly from the measured phase curves.