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Modeling variations in near-infrared spectra caused by the coherent backscattering effect

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ABSTRACT

We study a new optical effect, a spectral manifestation of coherent backscattering, which reveals itself as systematic variations in the depth of absorption bands with changing phase angle. We used Cassini VIMS near-infrared spectra of Saturn's icy satellite Rhea in order to identify and characterize the spectral change with phase angle, focusing on the change in the depth of water–ice absorption bands. To model realistic characteristics of the surfaces of icy satellites, which are most likely covered by micron-sized densely packed particles, we perform simulations using a theoretical approach based on direct computer solutions of the macroscopic Maxwell equations. Our results show that this approach can reproduce the observed phase-angle variations in the depth of the absorption bands. The modeled changes in the absorption bands are strongly affected by physical properties of the regolith, especially by the size and packing density of the ice particles. Thus, the phase-angle spectral variations demonstrate a promising remote-sensing capability for studying properties of the surfaces of icy bodies and other objects that exhibit a strong coherent backscattering effect.

1. Introduction

Photometric and polarimetric manifestations of the coherent backscattering effect (CBE) have repeatedly been observed for some Solar-system objects, including E-asteroids, KBOs, and icy outer planet satellites, and provided useful information about their surfaces [1]. The essence of CB is that light incident on a particulate surface experiences multiple scattering accompanied by constructive interference of the light resulting from different scatterings paths. The possible relevance of this mechanism to the photometric opposition effect was mentioned first by Kuga and Ishimaru [2] and then by Shkuratov [3], Muinonen [4], and Hapke [5], while Mishchenko and Dlugach [6–8] were the first to analyze relevant astronomical observations on the basis of a microphysical theory of CB. This research showed that conditions for such constructive interference are especially favorable in the backscattering direction, i.e., at small phase angles. The result is a narrow spike of brightness at a small (usually less than 3°) phase angle, which peaks at exactly the backscattering direction.

Due to the strong dependence of multiple scattering on absorptivity of the material, the CBE is more pronounced in the case of transparent materials (e.g., pure ice) than in the case of absorbing materials. The earliest observational data that revealed this effect pertained to such bright objects as Saturn's rings [9], high-albedo E-type asteroids [10], and the Jovian icy satellite Europa [11]. The known manifestations of the CBE in brightness (the spike at small

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phase angles) and polarization (a narrow negative-polarization feature with a minimum around 1–3° called the polarization opposition effect [8,12]) have been used to retrieve the properties of scattering media in numerous astronomical, geophysical, and physical applications (see, e.g., the reviews [1,13–17] and references therein).

Owing to the strong dependence of the phase-angle change of brightness on absorption, there should be different steepnesses of the opposition spike inside and outside absorption bands, thereby producing different depths of the absorption bands at different phase angles. The dependence of the depth and shape of absorption bands on the observational geometry was noticed previously (see, e.g., Refs. [18–20]). However, no explanation of the observed effect was provided. Moreover, some observers believed that this was an artefact and ignored this effect altogether. Neglecting this effect in analyses of spectral data can be a serious flaw potentially resulting in a misinterpretation of the spectra, leading to erroneous conclusions about compositional and particle-size differences between icy bodies observed at different phase angles.

A systematic study of the phase-angle dependence of the absorption bands has become possible recently due to a substantial amount of spectral data collected with the Visual and Infrared Mapping Spectrometer (VIMS) onboard the Cassini spacecraft. The VIMS experiment [21] consists of two imaging spectrometers that observe the same field of view in two spectral ranges. The imaging spectrometer VIMS-V covers the 0.3–1.05 μm spectral range in 96 channels and has a spectral resolution of $\Delta\lambda = 7.3$ nm/band and spatial resolutions of 0.5 (nominal) or 0.166 (high resolution) mrad/pixel. The VIMS-IR channel covers the 0.88–5.1 μm range in 256 bands, and has a spectral resolution of $\Delta\lambda \approx 16$ nm/band and spatial resolutions of 0.5 (nominal) or 0.25×0.5 (high resolution) mrad/pixel [22]. VIMS data for icy satellites of Saturn cover a broad range of phase angles and are characterized by a high spatial resolution during close encounters; many observations were also performed while Cassini was still far from the Saturn system.

In this paper we limit our analysis to one Saturnian satellite, Rhea, characterized by a high albedo of 0.81 at wavelengths 0.6–0.7 μm [23]. This albedo provides for a high signal-to-noise ratio for the VIMS data. Also, it indicates the domination of ice on Rhea's surface, thereby simplifying computer modeling. The purpose of this paper is to model Rhea's spectra using the theoretical approach for densely packed media developed in Ref. [12] and see if it can reproduce the observed effect of phase-angle changes in absorption bands and can be used for analyses of remote-sensing observations of icy surfaces of Solar-system bodies.

2. VIMS data for icy satellites of Saturn

A strong CBE in the near-infrared has been recently confirmed for Saturnian satellites Enceladus, Tethys, Dione, Rhea, and Iapetus [23,24]. From these publications one can see that the slope of the brightness spike produced by the CBE is different at different wavelengths: it is much steeper outside absorption bands (wavelengths 0.9, 0.96, and 2.23 μm) than inside the water–ice absorption bands (wavelengths 1.52, 2.02, and 3.6 μm).This implies a strong dependence of the CBE on the absorption mentioned in Section 1. Since a strong dependence on absorption results in different slopes of the brightness phase-angle dependence, the spectra, especially their absorption bands, should look differently at different phase angles. This is exactly what we found when plotting the spectra of icy satellites of Saturn at different phase angles. Fig. 1 shows typical near-infrared spectra of the Saturnian satellite Rhea. All the spectra were obtained for the leading hemisphere of Rhea. The relative point-to-point errors are less than 1%, although over long time intervals (weeks and longer) the errors may reach 2–3%. The dependence on the phase angle implied by the CBE studies is clearly seen here: the depth of the absorption bands becomes systematically smaller as the phase angle increases. In the following section we will model this effect and explore how it depends on the characteristics of the icy regolith. Specifically, we will study the deepest absorption band at 2.8 μm. To simplify the description of the absorption band variations, we will shift the spectra so that they match at the wavelength 3.6 μm as shown in the inset in Fig. 1.

3. Modeling of the CBE for spectra of icy bodies

The CBE is the result of constructive interference of light multiply scattered along conjugate optical paths, i.e., pairs

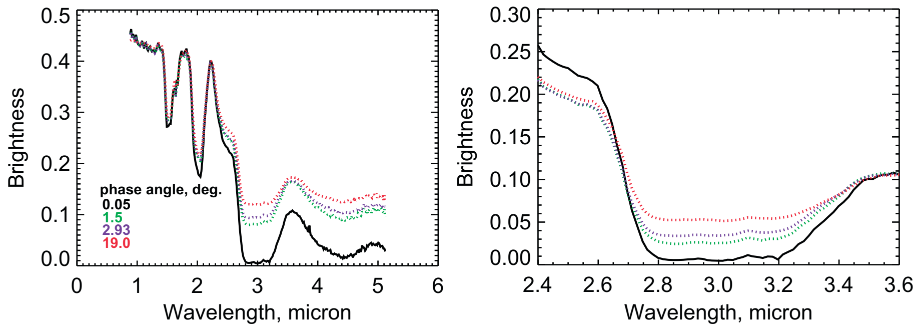

Fig. 1. Near-infrared VIMS spectra of Rhea at several phase angles. inset shows the band modeled in this paper. The spectra were shifted to match at the wavelength 1.0 μm for the whole spectrum (left-hand figure) and at the wavelength 3.6 μm for the inset.