Phase-angle variations in absorption bands as a manifestation of the coherent-backscattering effect

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We have found systematic variations in the depth of the absorption bands in the spectra of Saturn's icy satellites and showed that these variations likely resulted from the coherent-backscattering effect (CBE). Our computer modeling of the CBE reproduces the observed spectral variations and also shows that they are strongly affected by the size and packing of particles. The variations in the absorption bands produced by the CBE not only allow us to improve interpretation of the spectra but also provide a promising approach to study size and packing of the regolith and dust particles.

INTRODUCTION

The coherent-backscattering effect (CBE) results from the interference of the light that experiences multiple scattering in the medium and has the same but opposite optical path, i.e., was scattered by the same particles but in the opposite order. The most well known manifestation of the CBE is a steep brightness spike observed at small phase angles for numerous dusty environments, including planetary rings and icy cosmic bodies. Since the CBE spike is formed by multiply scattered light, it is more pronounced if more opportunities for multiple scattering occur, e.g., in the case of less absorbing particles. Strong dependence of the CBE on absorption was confirmed by numerous theoretical and laboratory simulations (see, e.g., [1-5]). Since the steepness of the CBE spike depends on the absorption, it should be different for the wavelengths within and outside of the absorption bands. As a result, the depth of the absorption bands should be different at different phase angles. We study this effect observationally and theoretically and provide recommendations for its application.

MANIFESTATION OF COHERENT BACKSCATTERING EFFECT IN THE SPECTRA OF ICY BODIES

The coherent-backscattering effect is especially pronounced for high albedo bodies such as Saturn's rings [6], icy satellites of the outer planets [7-10], Kuiper-belt objects (KBOs) [11], and E-type asteroids [12]. As it was mentioned above, it manifests itself in a steep photometric spike at the phase angles smaller than 3°. It is more pronounced for the high-albedo bodies and the steepness of the spike increases with increasing albedo [7]. Thus, one can expect that, at the wavelengths where the body is brighter, the CBE spike is steeper than at the wavelength where the body is darker. The different steepness affects the difference between the brightness of the object within and outside the absorption bands and, thus, results in a different depth of the bands at different phase angles. Such an effect has been already noticed for Saturn's rings [13]; however, [13] could not provide any explanation of this effect

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and neglected it in the interpretation of the data. The effect of CBE on the photometric data taken in different spectral bands was discussed in [8] for satellites of Uranus; however, [8] did not have the data within absorption bands and the effect of the CBE on the spectra was not analyzed there.

Cassini VIMS spectra of icy satellites of Saturn

A great opportunity to study spectral variations with phase angle appeared when the data for icy satellites of Saturn were taken by the instrument VIMS (Visual and Infrared Mapping Spectrometer, see [14]). VIMS provided the spectra in a broad range of wavelengths, including the near infrared where the deep water ice absorption bands are located. Due to the high spatial resolution provided by VIMS, the spectra for the same surface features can be selected, thus eliminating an effect of rotational variations of albedo. Besides, VIMS data have been analyzed to check the phase dependence of brightness, and a strong opposition spike whose steepness and width are consistent with the CBE was found [10]. Here we focus on the data for the leading hemisphere of Rhea as they are characterized by the best signal-to-noise ratio. The expected effect of changing the depth of the absorption bands with the phase angle is clearly seen in the spectra of Rhea (Fig. 1). For example, the difference in the depth for the 2 μm ice band is 12% for the phase angles 0.05° and 1.5° with the accuracy of the measurements about 1%.

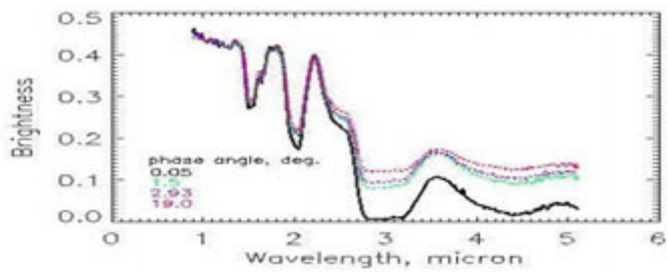

Figure 1. Spectra for Rhea taken at several phase angles (indicated in the plot) at a similar orbital longitude. The spectra were shifted to match the continuum at the short wavelengths. The units of brightness are the ratio of the measured intensity to the solar flux at the heliocentric distance of Saturn. For a grayscale image, the absorption bands for smaller phase angles are deeper.

Computer simulations of the CBE effects in the spectra

To check if CBE can be responsible for the observed phase angle variations in the spectra of Rhea, we modeled the spectra using the approach to CBE developed in [15-16]. At this approach the CBE is considered as the weak localization of the electromagnetic waves scattered by a layer of discrete random medium. A solution of the weak localization problem was presented in [16]; it is based on a transformation of an exact system of integral equations into a system of linear algebraic equations which can be solved readily. Comparisons of the theoretical results with benchmark numerical data for a medium composed of non-absorbing Rayleigh scatterers as well as with experimental data for a medium composed of wavelength-sized particles have shown that this approximation can be expected to give a good accuracy.

Using this technique we simulated the spectra for semi-infinite layer of water ice spheres of different size and packing [17]. We considered three packing factors ξ = 0.05, 0.1, and 0.2

(that corresponds to the porosity 95%, 90%, and 80%), and two particle radii, r=0.25 and 0.5 μm, that can be typical for the icy satellites of Saturn [18]. The optical constants of water ice were taken from [19]. The results (Fig. 2) show that the theoretical modeling produces the same tendencies that were observed for Rhea: the depth of the band gets smaller with increasing phase angle and the faster change in the depth happens at smaller phase angles. The rate of the change and the shape of the bands are strongly affected by the particle size and packing. The trend most close to the observational data (compare the vertical separation between the spectra in Figs. 1 and 2) is demonstrated by particles of r=0.5 μm and ξ = 0.2.

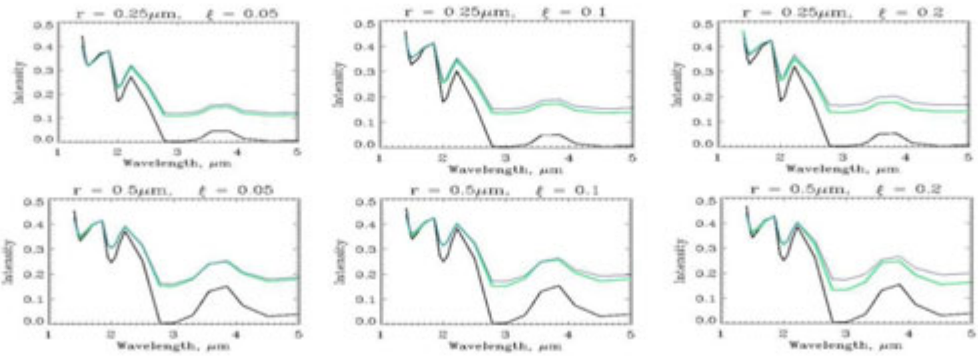

Figure 2. Computer modeling of Rhea's spectra. The radius of particles and their packing are indicated on the top of each figure. The results are for the phase angle 0.05° (the deepest absorption band), 1.5° (next deepest band) and 19° (the most shallow absorption band). As in Fig. 1, the spectra were shifted to match at the shortest wavelength.

CONCLUSIONS

Coherent backscattering affects not only the photometric (and polarimetric) characteristics of high-albedo objects, but also their spectra at small phase angles. The depth of the absorption bands and their shape are different at different phase angles, reflecting the dependence of the steepness of the CBE photometric spike on the absorption of the material.

The phase angle dependence of the spectra should be a common phenomenon for high-albedo cosmic bodies: planetary rings, satellites of the outer planets, KBOs, E-type asteroids, etc., and should be a part of any interpretation of their spectra. Neglecting the phase angle variations of the absorption bands at a comparative analysis of spectral data obtained at different phase angles can result in misinterpretation of the spectra, leading to erroneous conclusions about compositional and particle size differences of icy bodies. Particularly, ignoring this effect provides misleading conclusions regarding composition and relative abundance of water ice on the surface of the bodies.

Studies of the spectral manifestations of CBE not only improve our understanding of the formation of absorption bands, but also can be used as a new remote sensing technique for the characterization of surfaces and dust particles. The advantage of this method is that it does not require a detailed phase angle trend and, thus, does not need multiple observations. The spectra at 2–3 phase angles are sufficient so that the future modeling allows extracting information about the size and packing of regolith or ring particles. We can say that the role of the range of phase angles is replaced here by the role of the range of wavelengths. This makes the method especially convenient at studies of very distant objects, e.g. KBOs, whose phase angle changes slowly and within a very narrow range.

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