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Light scattered by Solar System bodies and the aggregate model of dust particles

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Introduction The phenomenon of electromagnetic scattering is widely utilized in remote-sensing characterization of various objects. However, such different celestial bodies like comets and asteroids show qualitatively similar linear polarization phase curves with the negative branch within a backscattering angle range [1-4]. In the case of atmosphereless celestial bodies, it can be accompanied by a backscattering enhancement of brightness. During the last decade, aggregate structures have been actively invoked to explain the observed polarization of cometary dust [5-13]. The analysis of the light scattering mechanisms acting in an ensemble of particles shows that the negative polarization is produced not only by the constructive interference of multiply scattered waves, but also by the near-field effects working in a wide angular range [14,15]. It was also shown that in the backscattering region the polarization for rather large ensembles of particles weakly depends on the number of these particles [14]. This result prompted us to use a unified approach - the aggregate model - to explain the observed polarization phase curves of both comets and regolith surfaces.

Modeling results and their discussion The light scattering models of randomly oriented aggregates consisting of spheres in contact were calculated for a wide range of each parameter (refractive index, size, and number of constituent particles (CPs), structure and porosity of the cluster) [14] with the superposition T-matrix method [16].

The analysis of the influence of different scattering processes on the polarization phase curve shows that its bell-like shape and a small negative branch evidence that the sizes of CPs in the cometary or regolith particles (or the details on their surfaces) must be smaller than the wavelength (the size parameter 0.75$< x <$1.75). The smallest x providing the negative branch in modeling can serve for estimating the sizes of CPs in the cometary dust particles. Then, for comet Hale-Bopp, the CP radius $\approx$0.26 μm, while for comet Halley, where the negative branch was certainly measured at the same wavelength, the CPs must be larger or/and the structures must be more compact.

The behavior of the polarization phase function (in dependence on the growth of the CP number) compared to the measured curves shows that the sizes of the scattering ensembles in cometary dust must be larger than the wavelength. However, the negative branch becomes less sensitive to the increase of the CP number, if the latter reaches the value, at which the cluster becomes comparable to the wavelength. This is explained by the fact that the wave interference, determining the scattering properties near opposition, is effective within the area comparable to the wavelength in size. Then, the appearance of the negative branch depends weakly on the sizes of the scattering ensemble as a whole, if it is larger than the wavelength and rather compact. The existence of the CPs of the "appropriate" size (depending on the refractive index and the cluster porosity) in the aggregates representing both the cometary dust and the regolith seems to be the only condition for producing the negative branch of polarization. Moreover, the internal structure of the cluster is of minor importance, because the external layer works as an amplitude-phase inhomogeneity for the incident wave.

The increasing of the polarization maximum for smaller CP sizes, which is typically obtained for aggregates, is in good agreement with the strengthening of the positive branch of polarization with wavelength observed for comets in the visible. For the Moon and bright asteroids, the spectral behavior of positive polarization is opposite, which may be caused by the increase of the multiple-scattering contribution in the layer and by the more effective suppressing of polarization in the long-wavelength range (due to the refractive index decrease). The quantitative modeling of the spectral dependence of polarization for large aggregates meets serious computation difficulties, which do not allow, e.g., the spectral stability of the negative branch observed in the visible range for comets to be simulated. However, the latter phenomenon can be caused by irregular shapes of CPs, or by their polydispersity, or by complex structure of aggregates, because the smoothing of the CP properties is highly effective at low phase angles. The differences in the shape of the negative branch of polarization observed for asteroids of different types can be explained by the fact that differences in the composition and structure of the regolith particles are less for the asteroids within a given type than for the asteroids of different types or for comets. The parallel appearance of the opposition effects in polarization and in intensity is not always obtained in modeling, since these effects are determined by two mechanisms (not counting the shadow hiding) working differently. Depending on the effectiveness of each mechanism in a given cluster, the both opposition features are pronounced in the same degree, or one of them is more noticeable. In many experiments, the both effects were measured simultaneously; however, there are also different examples [e.g.,17,18].

The influence of the refractive index on polarization is more noticeable for aggregates of larger CPs. The actual dependence of polarization on the refractive index is difficult to estimate, since the effects of the real and imaginary parts are opposite. Examining the polarimetric data together with the data on color, which is more efficiently affected by the imaginary part, might improve the situation. However, to model the color of aggregates is impossible now, because the ensembles accessible for modeling are still too small (the size parameter $<$10), and the size distribution is too narrow. The largest aggregates built for the present study are still blue (if no spectral gradient of the refractive index is applied), while the cometary dust is red in general.

Conclusions The aggregate model of particles was used here to explain the polarization phase curves observed for both comets and regolith surfaces. The modeling confirmed that the cometary dust particles are larger than the wavelength. However, the grains composing the particles of the cometary dust or regolith (or the details of their surfaces) are less than 0.3-0.5 μm in size. It was shown that the appearance of the negative branch and its shape essentially depend on the sizes of the scattering elements and on the structure of the particle ensemble (mainly on its surface structure), but not much on the size of the aggregate as a whole. It is worth stressing that a more complete correct interpretation of the observational data can be made only if the optical characteristics of aggregates comparable to the wavelength are simulated in a wide spectral range (which still meets serious difficulties of both theoretical and technical character). Besides, the particles forming the aggregate must be irregular in shape and heterogeneous in size and, most likely, in composition, or the complex structures, such as "aggregates in the aggregate", should be used. In its turn, the extending of the set of the model parameters makes a unique result more unachievable. To overcome these difficulties, the spectral range of observations must be extended and the data of other types of measurements must be also used for a joint interpretation.

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