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Reflectance of micron-sized dust particles retrieved with the Umov law

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ABSTRACT

The maximum positive polarization P_{max} that initially unpolarized light acquires when scattered from a particulate surface inversely correlates with its geometric albedo A. In the literature, this phenomenon is known as the Umov law. We investigate the Umov law in application to single-scattering submicron and micron-sized agglomerated debris particles, model particles that have highly irregular morphology. We find that if the complex refractive index m is constrained to $\mathrm{Re}(m)=1.4$–1.7 and $\mathrm{Im}(m)=0$–0.15, model particles of a given size distribution have a linear inverse correlation between $\log(P_{max})$ and $\log(A)$. This correlation resembles what is measured in particulate surfaces, suggesting a similar mechanism governing the Umov law in both systems. We parameterize the dependence of $\log(A)$ on $\log(P_{max})$ of single-scattering particles and analyze the airborne polarimetric measurements of atmospheric aerosols reported by Dolgos & Martins in [1]. We conclude that $P_{max} \approx 50\%$ measured by Dolgos & Martins corresponds to very dark aerosols having geometric albedo $A=0.019 \pm 0.005$.

1. Introduction

One of the most challenging tasks in remote sensing is determining the number density of particles in a optically thin cloud. While the intensity of the signal is approximately proportional to this number, it is necessary to know the light-scattering phase functions of the individual particles to extract their numbers; e.g., the measured flux from a small population of large dust particles may be the same as that of a large population of small dust particles. In practice, poorly known light-scattering properties make it necessary to consider numerous assumptions of their values in order to extract information about the population. Unfortunately, light-scattering properties are highly sensitive to the various physical and chemical properties of dust particles. For instance, their efficiencies may differ by more than an order of magnitude for particles with different chemical composition or obeying different size distribution (e.g., [2]). This places high uncertainty on retrievals of number densities of dust particles forming an optically thin cloud. In this short report we present a simple approach for reliable estimation of scattering by submicron- and micron-sized dust particles that is based on measurements of the degree of linear polarization of sunlight scattered from these particles. The approach is a consequence of the so-called *Umov law* or *Umov effect*, which was developed for a dense particulate surface (e.g., [3–7]). In the present work, we investigate its use in application to small single-scattering particles.

2. Brief introduction into the Umov effect

The Umov effect is named after the Russian scientist Nikolay Umov, who first noticed an inverse correlation between strength of polarization of the sunlight scattered by an object and its brightness [8]. In the original work, Umov described such a correlation qualitatively. A quantitative investigation of this phenomenon was initiated only about a half century later (see Section 1 of [9] for a brief historical review). Current knowledge of the Umov effect has been contributed by many authors (e.g., [3–7] and others). Their efforts revealed that the inverse correlation appears in the most unambiguous form between the maximum of positive polarization P_{max} and the geometric albedo A of a particulate surface.

When initially unpolarized sunlight is scattered by a particulate surface, it acquires partial linear polarization that is characterized with the degree of linear polarization P:

$$P = (I_{\perp} - I_{\parallel})/(I_{\perp} + I_{\parallel}). \quad (1)$$

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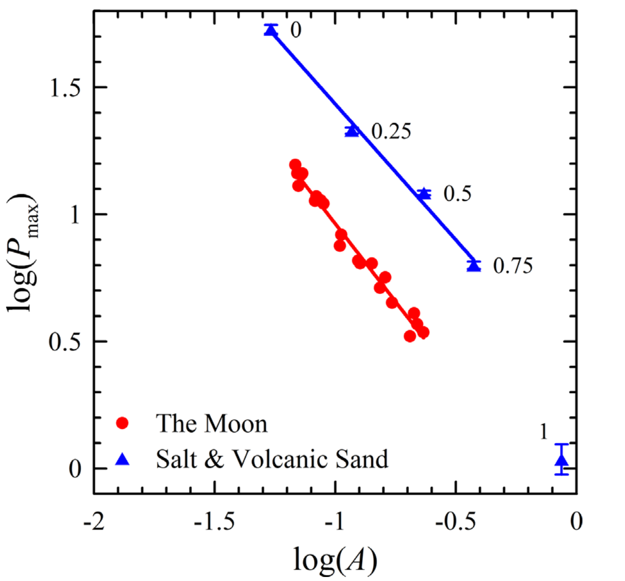

Fig. 1. The Umov effect of the lunar regolith (data adapted from [5]) and in a mixture of bright salt and dark volcanic sand (data from [7]) in red light. Symbols corresponding to the mixture are labeled with the volume ratio of salt. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Here, $I_\perp$ and $I_\parallel$ denote the intensity of two components of the scattered sunlight that are polarized perpendicularly and within the scattering plane, respectively. The degree of linear polarization P is a function of the scattering angle θ. Although angular profiles of polarization differ in various particulate surfaces, nearly all of them reveal two common features. Namely, near the exact backscattering regime, $\theta \geq 150°$, the polarization P takes on predominantly negative values, implying $I_\perp < I_\parallel$ (e.g., [10,11]). At smaller scattering angles, the polarization is essentially positive, i.e., $I_\perp > I_\parallel$ (e.g., [7,12,13]). In the vast majority of cases, the positive linear polarization reaches its maximum value P_{max} over the range of the scattering angle θ=70–110° (e.g., [14–17]).

Unlike P_{max} occurring at side-scattering angles, the geometric albedo A formally is defined at exact backscattering (θ=180°). This regime, however, is often difficult to measure in practice, due especially to obscuration of the light source by the detector (radiometer). In such cases, the reflectance often is measured at the maximum affordable scattering angle; for instance, at $\theta \approx$ 173–177° [5,7,18]. The geometric albedo A is a relative characteristic that refers to the ratio of reflectance of a target surface over what is a fully reflecting Lambertian surface with the same area.

Investigation of various samples having quite different origin reveals almost a linear dependence of the logarithm of P_{max} on the logarithm of A. To demonstrate this, we reproduce in Fig. 1 the astronomical observations of 22 different sites on the Moon in red light (λ=0.65 μm) (data are adapted from [5]) and laboratory optical measurements of a mixture of bright salt (NaCl) and dark volcanic sand in red light (λ=0.63 μm) at five volume ratios (data from [7]). In the latter case, the symbols are numbered in accordance with the relative volume of the bright component of the mixture. We refer the reader to the original publications for more details on the measurements/observations technique and description of the laboratory samples/lunar sites. As one can see in Fig. 1, both datasets reveal a linear dependence of log(P_{max}) on log (A) over a wide range of geometric albedo A, except for the case of pure salt.

The diagrams shown in Fig. 1 are useful when the projected area of a particulate surface of interest is unknown. This occurs, for instance, when the angular resolution of the optical system is insufficient to measure the projected area of the target. In such a case, the reflectance can be inferred from the polarimetric observations with help of the corresponding Umov-law diagrams. Clearly, an extension of the given technique for the case of submicron and micron-sized dust particles is of high practical interest because, in typical circumstances, their projected area cannot be measured with an optical system.

The Umov effect for small, single-scattering particles has been considered previously in [9]. There was found that dielectric submicron and micron-sized particles generally reveal an inverse correlation between their maximum of positive polarization P_{max} and the geometric albedo A. However, unlike what is shown in Fig. 1 for particulate surfaces, the log-log diagrams for single dust particles were found to be non-linear. Parameterization of such diagrams is difficult to accomplish in practice, resulting in a serious obstacle for their practical use. In the present work we incorporate into the analysis significantly more modeling results as compared to the previous study [9]. This allows for us to consider a wider range of refractive index m, with Re(m)=1.4–1.7 and Im (m)=0–1, which are representative of various terrestrial and cosmic species (e.g., [19–24]). This extended computational dataset makes it possible to conduct a more systematic study of the Umov effect in small particles.

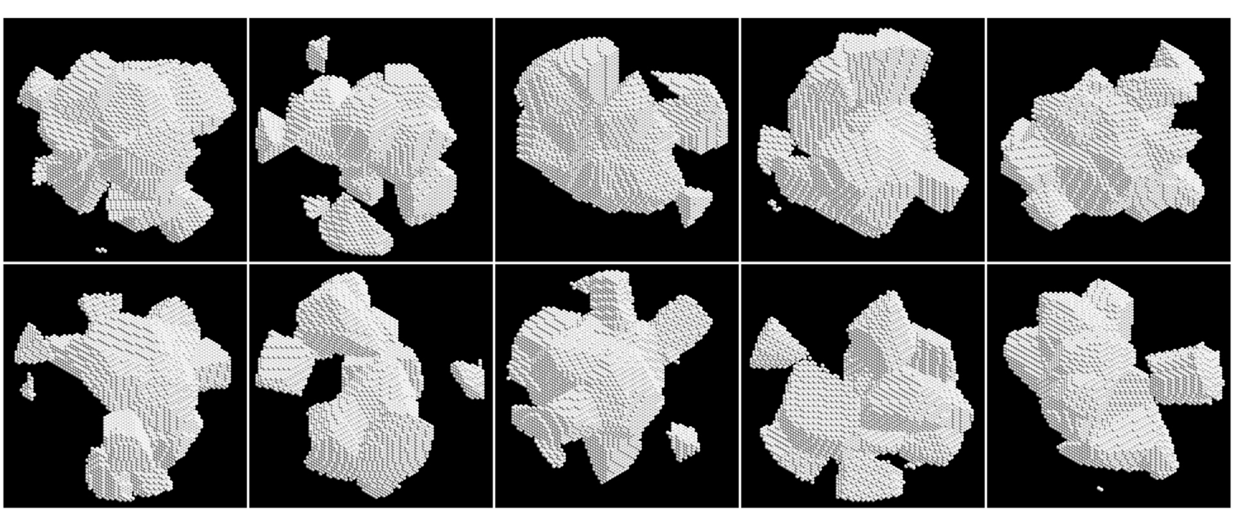

Fig. 2. Ten examples of agglomerated debris particles.