Why the opposition spikes of regolith-like media are usually sharp and do not show rounding off

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For particulate surfaces the slope of photometric phase curves must be zero at zero phase angle, otherwise the Maxwell equations are violated. In experiments such surfaces usually reveal sharp opposition spikes; however, we found samples that show tendency to have rounded phase functions. We also show that blocking of reciprocal trajectories at coherent backscattering could influence the rounding.

INTRODUCTION

The brightness phase curves at small phase angles near opposition were measured for a great number of different particulate surfaces, including planetary regoliths and laboratory samples consisting of irregular particles with sizes greater than the wavelength [1]. The shadow-hiding effect and contribution of single scattering are leading factors forming such phase dependencies for dark particulate surfaces. For rather bright surfaces the effect of coherent backscattering enhancement manifests itself against the background of the shadow-hiding effect weakened by incoherent multiple scattering. A fundamental property of measured backscattering curves of powdered surfaces is that almost all of them do not reveal rounding at small phase angles. We might anticipate the behavior for the shadowing effect, when electromagnetic wave diffraction and the angular size of the light source can be ignored; however, coherent backscattering models [e.g. 2,3] predict the rounding, otherwise the Maxwell equations are violated. Thus, theory predicts concave curves, while experiment shows convex curves at small phase angles. This contradiction between experimental and theoretical results has been noted in different papers [e.g. 4]. We discuss possible reasons of the discrepancy.

LABORATORY MEASUREMENTS AT VERY SMALL PHASE ANGLES

An obvious explanation of the contradiction could be that in all mentioned astrophysical and laboratory measurements the minimum phase angles are too large to reveal the peak flattening. However, photometric observations of Kuiper belt objects at phase angles <1° do not show the rounding [5]. Photometrical laboratory measurements of rather bright powders also do not show such a peak flattening [1,6,7], though they were carried out at very small phase angles. For instance, in case of measurements [6] the minimum angle was 0.01°, however, the

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flattening was not found. To improve this parameter we reconstructed our small-phase-angle photometer, lengthening the distance between the sample place and the detector. We also decreased the light source and detector apertures up to 0.001°. This enables us to reach the minimum phase angle equals 0.002°. Figure 1 shows photometric measurements of MgO smoke deposits on a smooth substrate. The phase function appears to have a slight bend towards zero slope at these small phase angles, though we do not yet observe explicit flattening. Note, that the MgO sample is a very complicated surface consisting of particles < 1 μm.

Another example is more prominent. Figure 2 shows photometric measurements of MgO smoke deposits and blue water-color crusts, which were measured with another laboratory photometer [8]. The MgO deposits demonstrate a sharp opposition spike that is very typical for bright regolith-like surfaces. The water-color crusts with albedo 25% show the tendency to have a rounded response that we expect from the wave-based models, but which are not commonly observed. This, perhaps, relates to the crust structure that is very dense and the crust surface that is smoother than in case of MgO deposits. Thus, the problem of flattening near opposition is not as dramatic as noted in [4]. The questions, however, are why the rounding of photometric curves is so rare and why, if the phase curve is nevertheless concave, the rounding effect is so weak.

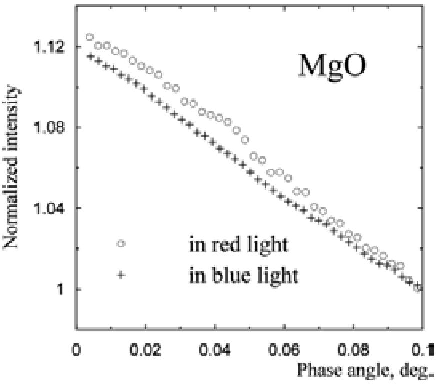

Figure 1. Phase function for MgO smoke deposits at λ=0.66 and 0.47 μm measured with the modified laboratory photometer [6].

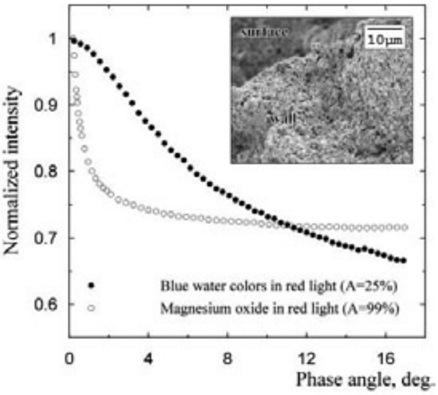

Figure 2. Phase function for MgO deposits on a substrate of smoke from burned Mg at λ=0.63 μm measured with the laboratory photometer described in [8]. The inset shows an electron micrograph of a fracture in the water-color crust.

TRAJECTORY BLOCKING IN COHERENT BACKSCATTERING

The shadow-hiding effect accompanying single scattering may sharpen concave phase curves produced by the coherent backscatter. The same can be observed at higher scattering orders. Indeed, shadowing could influence the coherent backscatter by blocking reciprocal components of coherent backscattering. We illustrate this in Fig. 3, which shows how one of the complementary trajectories can be blocked in the second scattering order.

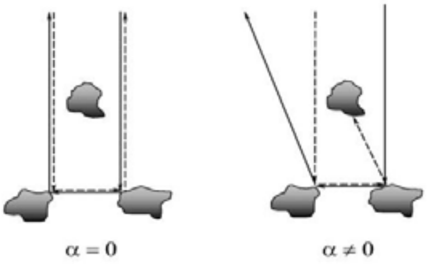

Figure 3. Blocking of a complementary trajectory of coherent backscattering.

We carried out a computer ray-tracing [9] that allows us to estimate the number of complementary trajectories with and without blocking of one of the reciprocal components for different orders of scattering. We studied a particulate medium with packing density near 0.3. Figure 4 shows that high scattering orders have peaks in the number of successful trajectories, when both complementary ways are open and may interfere. This influences coherent backscattering, making the phase functions sharper near opposition.

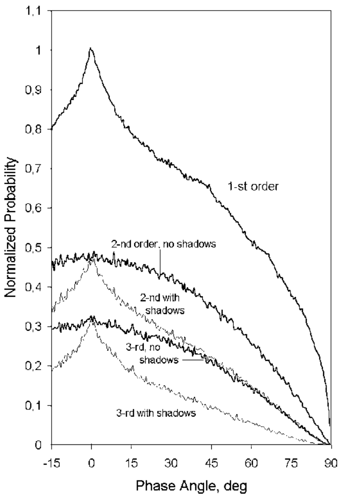

Figure 4. Phase functions of the normalized number of complementary trajectories with and without accounting for the shadowing in second and third orders of scattering, computed using ray-tracing [9]. The first scattering order presents the "classical" shadow effect.

Obviously, we cannot expect that the shadowing effect is valid for a system consisting of small particles. However, such a particle (Fig. 2) instead of actual shadowing may produce a small electromagnetic phase shift influencing the interference. Recent computations carried out by K. Lumme [10] with the *T*-matrix method have shown that some particulate systems, e.g., a cylinder particulate layer, may have convex phase functions. This suggests either unknown factors in forming the coherent backscattering or a manifestation of the blocking mechanism that is automatically taken into account in the *T*-matrix calculations.

CONCLUSION

Our experiments show that the discrepancy between laboratory measurements and theoretical calculation results are not dramatic. We have experimental examples of rather bright particulate surfaces that have phase curves whose slope could approach zero at small phase angles. While the Maxwell equations require zero slope in the exact backscattering direction, measured peaks are sharper than expected. Our simulations suggest that a blocking mechanism of one of the reciprocal components can increase the sharpness of the backscattering peak. This mechanism is valid for all orders of scattering. In case of small particles the blocking may produce an electromagnetic phase shift that also can destroy the constructive interference of reciprocal trajectories.

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