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Lunar single-scattering, porosity, and surface-roughness properties with SMART-1/AMIE

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We analyze the single-scattering albedo and phase function, local surface roughness and regolith porosity, and the coherent backscattering, single scattering, and shadowing contributions to the opposition effect for specific lunar mare regions imaged by the SMART-1/AMIE camera. We account for shadowing due to surface roughness and mutual shadowing among the regolith particles with ray-tracing computations for densely-packed particulate media with a fractional-Brownian-motion interface with free space. The shadowing modeling allows us to derive the hundred-micron-scale volume-element scattering phase function for the lunar mare regolith. We explain the volume-element phase function by a coherent-backscattering model, where the single scatterers are the submicron-to-micron-scale particle inhomogeneities and/or the smallest particles on the lunar surface. We express the single-scatterer phase function as a sum of three Henyey-Greenstein terms, accounting for increased backward scattering in both narrow and wide angular ranges.

The Moon exhibits an opposition effect, that is, a nonlinear increase of disk-integrated brightness with decreasing solar phase angle, the angle between the Sun and the observer as seen from the object. Recently, the coherent-backscattering mechanism (CBM) has been introduced to explain the opposition effect. CBM is a multiple-scattering interference mechanism, where reciprocal waves propagating through the same scatterers in opposite directions always interfere constructively in the backward-scattering direction but with varying interference characteristics in other directions.

In addition to CBM, mutual shadowing among regolith particles (SM_p) and rough-surface shadowing (SM_r) have their effect on the behavior of the observed lunar surface brightness. In order to accrue knowledge on the volume-element and, ultimately, single-scattering properties of the lunar regolith, both SM_p and SM_r need to be accurately accounted for.

We included four different lunar mare regions in our study. Each of these regions covers several hundreds of square kilometers of lunar surface. When selecting the regions, we have required that they have been imaged by AMIE across a wide range of phase angles, including the opposition geometry. The phase-angle range covered is 0-109°, with incidence and emergence angles (ι and ϵ) ranging within 7-87° and 0-53°, respectively. The pixel scale varies from 288m down to 29m. Biases and dark currents were subtracted from the images in the usual way, followed by a flat-field correction. New dark-current reduction procedures have recently been derived from in-flight measurements to replace the ground-calibration images . The clear filter was chosen for the present study as it provides the largest field of view and is currently the best-calibrated channel. Off-nadir-pointing observations allowed for the extensive phase-angle coverage. In total, 220 images are used for the present study.

The photometric data points were extracted as follows. First, on average, 50 sample areas of 10×10 pixels were chosen by hand from each image. Second, the surface normal, ι, ϵ, ϕ, and α were computed for each pixel in each sample area using the NASA/NAIF SPICE software toolkit with the latest and corrected SMART-1/AMIE SPICE kernels. Finally, the illumination angles and the observed intensity were averaged over each sample area. In total, the images used in the study resulted in approximately 11000 photometric sample points for the four mare regions.

We make use of fractional-Brownian-motion surfaces in modeling the interface between free space and regolith and a size distribution of spherical particles in modeling the particulate medium. We extract the effects of the stochastic geometry from the lunar photometry and, simultaneously, obtain the volume-element scattering phase function of the lunar regolith locations studied. The volume-element phase function allows us to constrain the physical properties of the regolith particles.

Based on the present theoretical modeling of the lunar photometry from SMART-1/AMIE, we conclude that most of the lunar mare opposition effect is caused by coherent backscattering and single scattering within volume elements comparable to lunar particle sizes, with only a small contribution from shadowing effects. We thus suggest that the lunar single scatterers exhibit intensity enhancement towards the backward scattering direction in resemblance to the scattering characteristics experimentally measured and theoretically computed for realistic small particles. Further interpretations of the lunar volume-element phase function will be the subject of future research.