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Scattering properties of lunar dust analogs

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ABSTRACT

The Lunar Atmosphere and Dust Environment Explorer (LADEE) spacecraft is designed to characterize the exospheric dust environment using an on-board suite of specialized sensors. The objective of this paper is to present results from scattering experiments using an aqueous suspension of lunar simulants that contains a population of dust grains ranging in size from ~0.1 μm to 10 μm. The intensity of scattered light is measured with a commercial version of the ultraviolet–visible spectrometer (UVS) used in the LADEE mission. We show that our data is consistent with the fact that micron-sized particles tend to form agglomerates rather than remaining isolated entities and that certain characteristics of the target particles can be predicted from intensity measurements alone. These results can be used directly to assess general features of the lunar exosphere. Further analysis of particle properties from such remote sensing data will require more refined measurements such as polarization features or other components of the Stokes vector.

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1. Introduction

Airless bodies in the Solar System outnumber those with viable atmospheres. Missions designed to understand the physical characteristics of asteroids and planetary moons are being planned or are actively underway. The archetypal airless body with a surface boundary exosphere is the Moon and remains the subject of numerous missions. The Apollo project (1961–1972) was the primary data source for these bodies, and lunar properties from this and other early space missions (to 1991) are documented in the "Lunar Sourcebook" (Heiken et al., 1991). In particular, the lunar regolith was identified as a continuous distribution of granular material with many of the particles being sharp or glassy with irregular shapes. It is now known from recent measurements (Greenberg et al., 2007) that the regolith contains grains of all sizes down to submicron as a result of "meteoritic gardening." It is possible that the Moon possesses a thin dust-laden exosphere. The Surveyor mission captured images of streaks above the horizon at sunset —the so-called "horizon glow." Rennilson and Criswell (1974) analyzed the video images and concluded that the horizon glow is real and caused by charged dust grains being electrostatically levitated by intense electric fields within tens of centimeters of the surface. Photometric data from a contemporary spacecraft (Lunokhod-2) also showed increased brightness in the terminator region (Severny et al., 1975) but observed from a local zenith so the two data sets were not completely equivalent. In any event, this phenomenon is often explained by scattering of sunlight by a cloud of dust particles. The Lunar Ejecta and Meteorites experiment – deployed on the lunar surface by Apollo 17 – recorded dust impacts as evidence of surface dust dynamics. This indicated the presence of slow moving highly charged dust particles, particularly at the location of the day–night terminator. The crew of several Apollo missions also observed excess brightness at the lunar horizon as viewed from orbit. McCoy (1976) interpreted this data as forward-scattering of sunlight by submicron particles.

The presence of solar wind and electron photoemission on the Moon generates a surface charge. The major feature of this charge is that the lunar dayside reaches a positive potential (~5 V) and the nightside a higher (~75 V) but negative potential. Each side contains an associated electric field with approximate Debye scale heights of < 1 m on the dayside and ranging between ~10 m and ~1 km on the nightside. The forces acting on small dust particles in this environment was reviewed and previous work surveyed by Colwell et al. (2007). In particular, Stubbs et al. (2006) suggests that sub-micron particles can be electrostatically lofted on ballistic trajectories (a "fountain model") far beyond the plasma sheath. Thus, the lunar exosphere might possess an extensive vertical dust profile that scatters ambient sunlight and this scattered signal could have been captured by the sensors aboard the missions described above.

Another possible dust source could be high-speed impacts of micrometeorids or interstellar grains. An analytical model of the

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dust cloud surrounding a spherical body without an atmosphere was considered by Krivov et al. (2003). They found that dust particles could be lofted to ~1000 km on Jupiter's moon Ganymede assuming uniform dust production at the surface and Keplerian dynamics of the ejected material. Sunlight interacting with particles from this source may account for the scattered signal. However, due to its tenuous nature these ejecta clouds would be difficult to discern with optical sensors although very small populations could be captured with in situ sensors.

The Apollo 15 data was carefully reanalyzed in a recent paper (Glenar et al., 2011) using a credible dust model to resolve Mie scattering along a ray tube from the dust cloud to the orbiting spacecraft. They generate plausible dust maps in a plane extending from the terminator. They observe that time-resolved solar wind intensities do not correlate with the Apollo dust photographs. This suggests that other mechanisms such as dust ejecta from micrometeoroid impacts might have been scattering targets. Since excess brightness was detected at the sunrise terminator and coincided with enhanced meteoroid stream activity they speculate that a saltation-like cascade initiated by meteoritic impacts could be the source of the exospheric dust. In this mechanism impact ejecta that do not escape returns to the surface to eject more dust from the surface, and ejecta falls back to eject yet more dust from the surface. As the process evolves it is argued that dust abundance increases while the average dust velocities (and scale height) decrease, which could result in a population similar to that inferred from the Apollo 15 observations. It should be noted that analysis of the Apollo light scattering observations (Glenar et al., 2011) did not indicate that dust was present above ~30 km. The actual source of high-altitude (> 50 km) dust, or the still open question of whether or not it even exists, is a focus of the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission.

LADEE is scheduled for launch in 2013 to study the Moon's exosphere with two on-board dust-related instruments. The Lunar Dust Experiment (LDEX) is an in-situ dust detector that will measure the size distributions of particles captured along the spacecraft trajectory (25–100 km above the lunar surface). The second instrument is an ultraviolet–visual spectrometer (UVS) to measure scattered sunlight from dust grains or at least set some rigorous upper limits. The pre-programmed spacecraft trajectory will enable intensity measurements at many positions in the Sun-dust-sensor scattering plane from near forward- to backscatter-directions. Using these two instruments, it is feasible to determine average values of particle size, mass and density.

The LADEE mission with its modern suite of sensors has already inspired new lunar research activities. Stubbs et al. (2010) presents a detailed study of the UVS spectrometer on board the LADEE spacecraft and describes intensity spectra of combined dust (continuum) and sodium (discrete) emission. These computations represent forward scattered sunlight at discrete phase angles as the spacecraft enters the lunar shadow. The objective of the current study contributes to the mission with laboratory experiments on aqueous suspensions of lunar simulants to measure the phase function, which is the angular distribution of intensity at wavelengths within the bandwidth of the UVS.

It is recognized that intensity measurements alone are probably not sufficient to fully determine the characteristics of exospheric dust grains using remote sensing technology. In fact, early planetary science investigations identified polarization properties as a viable measurement technique. This parameter was first used by Lyot (1929) to infer properties of the lunar regolith which enabled him to correctly conclude that the surface consisted of a powdery material closely resembling terrestrial volcanic ash. Telescopic observations of polarization from the atmosphere of Venus was correlated with scattering theory by Hansen and Arking (1971) and was shown to be a relevant parameter.

The particular feature of interest was the negative loop of the polarization phase function in the backscatter region (160–180 deg). This feature was explored numerically by Petrova et al. (2007) using phase functions and polarization curves to explain the backscattering phenomenon. A related experimental study (Worms et al., 1999) used an apparatus similar to that used in the current paper but optimized to study levitated particles in vacuo rather than in suspension. However, a comprehensive study (Hadamcik et al., 2009b) using a wide variety of grain morphologies showed only polarization curves. Data from light scattering experiments with the same apparatus using an aerosol analog of Titan's atmosphere (Hadamcik et al., 2009a) presented an intensity phase function, but with large error bars. The preponderance of the reported data also refers to polarization signatures. The polarization of backscattered sunlight has a long history since first reported by Lyot and its importance in remote sensing of Solar System bodies has been amply demonstrated. In this paper we focus on intensity phase functions scattered by suspensions, but follow-up studies will include polarization measurements and detailed comparisons with existing data bases.

Recent laboratory studies using a variety of micron-scale particles to generate particle-laden clouds were reported by Marshall et al. (2011). They found that these clouds tend to be composed of aggregates rather than individual dust grains. It is explained that cohesive forces and sediment inhomogeneity would cause particles to form clumps or aggregates rather than remaining as individual particles (a universal property of dust and powders). Based on these findings they conclude that a dusty lunar exosphere would have an array of aggregates in preference to small individual particles. The sizes and abundances of these populations are unknown and would presumably vary with location on the Moon and distance above the lunar surface. In this paper, we therefore consider the case of light scattering from aggregated particles, but utilize a liquid suspension rather than air. An aqueous suspension can be maintained for extended periods of time (c.f. Table 2) and van der Waals forces induce stable grain clusters.

The objective of this paper is to present preliminary results from scattering experiments that simulate the function of the LADEE UVS spectrometer in detecting exospheric dust. We first describe the laboratory apparatus and the system used to acquire and process the data. The spectrometer used to measure the scattered signal is a commercial version of the LADEE instrument. The simulant is designated NU-LHT-700-1x and is representative of the mature regolith present in the lunar highlands. This simulant is compared with other lunar simulants by Gaier et al. (2012) and is typical of fine grained lunar regolith. Physical properties of the lunar simulant are described along with two reference scattering targets (used as control cases) consisting of 2 μm and 8 μm borosilicate microspheres. The relative index of refraction for both the silicate and the simulant (in aqueous solution) is taken as 1.19. This value is exact for the microspheres and a good approximation to the lunar regolith at the considered wavelength. Experimental data are then compared to Mie theory using measured size distributions obtained from SEM images. From the experimental data we found reasonable agreement with theory but detailed comparisons indicated a likely population of aggregated particulates rather than monodispersed material. We conclude that angular intensity measurements alone from the LADEE mission are sufficient to glean general characteristics of the light-scattering particles.

2. Experiment and data reduction

2.1. Experimental configuration

The scattering experiments were designed to measure the angular phase function from light scattered by lunar dust simulants in