CONSTRAINTS FOR THE LUNAR REGOLITH POROSITY AT THE SURFACE FROM SOLAR WIND PROTON REFLECTION.

P. S. Szabo[1], A. R. Poppe[1], H. Biber[2], A Mutzke[3], J. Pichler[2], N. Jäggi[4], A. Galli[4], P. Wurz[4] and F. Aumayr[2], [1]Space Sciences Laboratory, University of California, Berkeley, USA (szabo@berkeley.edu), [2]Institute of Applied Physics, TU Wien, Vienna, Austria, [3]Max Planck Institute for Plasma Physics (IPP), Greifswald, Germany, [4]Physics Institute, University of Bern, Bern, Switzerland

Introduction: The grain stacking and thus the porosity of the uppermost regolith layer of the lunar surface play a key role for the Moon. They affect mechanical and thermal surface properties and determine the boundary of the surface with the surrounding space [1,2]. The porosity especially influences how precipitating radiation is absorbed and reflected, which also impacts scientific observations of planetary surfaces [3,4]. Returned samples only allow limited insights into the porosity of the shallow regolith layer that can be accessed by radiation [5,6]. Therefore, remote sensing is currently required to study the pristine upper regolith. Here, infrared measurements for the Apollo 16 landing site support a very high porosity of 0.83 ± 0.03 at the surface [6]. To add further insights, we have now studied the interaction of impacting solar wind protons with the lunar regolith by performing full three-dimensional simulations of the ion scattering process [7]. By comparing simulation results to spacecraft observations of the solar wind reflection, we are thus able to provide a constraint for the average porosity of the upper lunar regolith.

Figure 1: An example for the regolith structure used in the simulations with a porosity of about 0.8 (image from [7]).

Solar Wind Reflection from the Lunar Surface: To model ion impacts on the lunar surface, we use the SDTrimSP-3D code for the simulation of ion impact and energy loss in a solid [8]. We account for the porous regolith geometry by randomly created grain stackings at different porosities, using both spherical and several irregular grain shapes (see Figure 1 for an example). Simulation results of the total solar wind proton reflection are compared to measurements of solar wind proton reflection as energetic neutral atoms (ENAs) from the CENA instrument aboard the Chandrayaan-1 lunar orbiter. Using CENA data, ENA emission from the lunar surface has previously been characterized in detail [9-12]. Comparisons with data on reflection as protons show that most solar wind protons are neutralized during the scattering from the lunar surface [13].

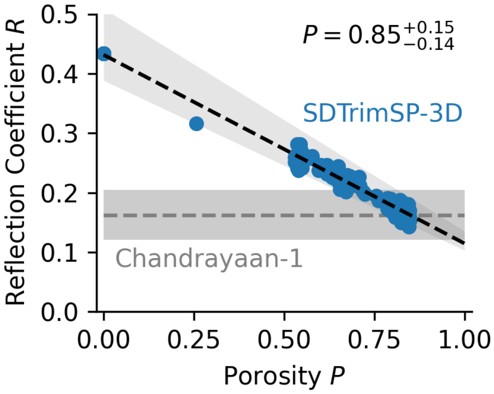

Figure 2: For the angle of incidence of 60°, Chandrayaan-1 observations (from [12]) and SDTrimSP-3D simulations of the reflection coefficient R are compared. In doing so, the regolith porosity P can be constrained to 0.85 with an uncertainty of about 0.15 [7].

Results: CENA observations found that the solar wind proton reflection coefficient from the lunar surface as ENAs is about 0.16 ± 0.05 [12]. It does not show a significant dependence on the solar-zenith angle and thus on the incidence angle on the lunar surface. This behavior vastly differs from a flat surface, where a steep increase under oblique incidence would occur [7]. Our SDTrimSP-3D regolith model improves the description of this process. However, agreement with Chandrayaan-1 observations can only be achieved for regolith grain stackings with very high porosity at the surface close to the 0.83 value suggested by Hapke and Sato [6]. In particular, Figure 2 depicts the dependence of the simulated reflection coefficient on the porosity. A clear linear trend of decreasing reflection with increasing porosity is observed. Considering uncertainties from both the CENA measurements as well as simulation input parameters, the averaged porosity for the lunar surface can be constrained to about 0.85 ± 0.15 from our study [7]. This finding agrees with the previous result by Hapke and Sato [6]. However, it holds a wider validity as an average for the lunar surface on a global scale, supporting that the surface of the Moon is generally covered by a loosely stacked fairy-castle like regolith layer (see Figure 1). Such high porosities should thus be accounted for in future analysis and modeling of the lunar surface. Our study also demonstrates how ENA emission from rocky bodies in the solar system can be used as a valuable technique for probing properties of planetary surfaces from an orbiting spacecraft. In a similar manner, it will be possible to expand this research to Mercury, where ESA's BepiColombo mission will provide an analysis of the ENA emission from the planet's surface [14,15].

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