A NEW MODEL FOR DETERMINING LUNAR ROCK ABUNDANCE AND LANDING HAZARDS.

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Introduction: With NASA's return to the Moon, the determination of safe landing sites for future robotic and human missions is crucial, and rock abundance will be important criteria for landing site selection. Thermal inertias derived from remote sensing in the thermal infrared is a powerful technique for assessing rock abundance for the purpose of landing site selection on Mars [1,2]. Rocks a meter or more in size present similar hazards for lunar landing systems as for Mars landers, and safe lunar exploration will depend in part upon the determination of the rock abundance at potential landing sites. Mars thermal data, however, vastly exceeds current lunar thermal data. The Diviner Lunar Radiometer [3] on Lunar Reconnaissance Orbiter (LRO) will provide a new opportunity for acquisition of thermal data that can be used in the evaluation of potential landing sites. In anticipation of LRO we have created a new lunar thermal model that, when coupled with lunar nighttime temperature data, will assist in the creation of rock distribution maps covering potential lunar landing sites at most latitudes.

Thermophysics of the Lunar Surface: Surface temperatures of planetary regoliths depend on many factors including albedo, isolation, topography, heat flow, the atmosphere (if present), and the thermophysical properties of surface and near-surface materials. In many ways the Moon represents a simpler thermal modeling problem than does Mars. The absence of an atmosphere simplifies the thermal modeling of the lunar surface relative to Mars. However, the diurnal period of approximately 29.5 Earth days combined with the lack of atmosphere results in a large diurnal temperature range for non-polar latitudes. In the equatorial region, the 300 K difference in minimum and maximum diurnal temperatures results in significant changes in two of the three regolith thermal properties that impact the thermal inertia; the specific heat of silicates increases by a factor of four and thermal conductivity of fines increases by a factor of more than three from predawn to midday [4]. In the colder polar regions, the temperature dependence of thermal conductivity is no longer important, but thermal inertia will be lowered by the decrease in specific heat with temperature. The thermal inertia (the resistance to change in temperature) of lunar surface materials, therefore, must be treated as temperature dependent.

Temperatures and Rock Abundance: Lunar daytime surface temperatures, such as those measured by Clementine's Long-Wave Infrared Camera (LWIR), are strongly controlled by albedo and topography [5], but only very weakly by thermal inertia unless it is very high [4,6]. Differences in thermal inertia are most apparent during the long lunar night. Rocks too large to thermally equilibrate effectively act as thermal batteries, and the addition of just a few percent of rocks can raise minimum surface temperatures by 10 K [4]. However, neglecting the temperature dependence of thermal inertia can also raise model nighttime temperatures, thus lowering the derived rock fraction. When the temperature dependence of thermal inertia is included and albedo is known, nighttime temperature measurements provide an effective tool for determining the rock fraction at the surface.

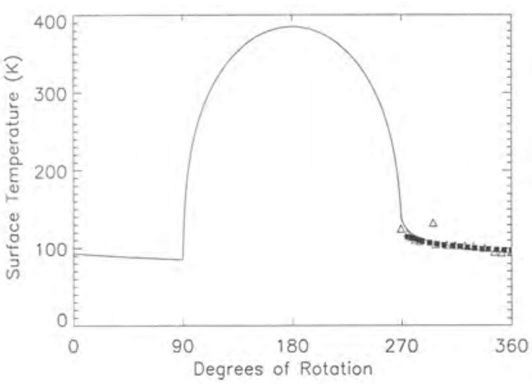

Figure 1: Temperature-dependent model for the Apollo 15 landing site including a 2% fraction of rocks exceeding ~1 m in average dimension compared with surface temperatures derived from the Apollo 17 infrared scanning radiometer [5] and the Apollo 15 heat flow experiment [7]. Figure from Urquhart and Jakosky, 1997.

Our Lunar Thermal Model:

Our lunar thermal model utilizes the 1-D finite-difference model of Urquhart and Jakosky (1997) adapted for the moon from models previously used for Mars [8,9]. The temperature-dependence of thermal properties is included in the solution to the thermal conduction equation. In addition, we have incorporated the lunar ephemeris created by Mellon for analysis of

Clementine LWIR data to allow for more accurate insolation histories at specific locations on the lunar surface [5]. The resulting model can be combined with Clementine albedo measurements and surface temperature measurements to constrain meter-scale and larger rock abundances on the lunar surface.

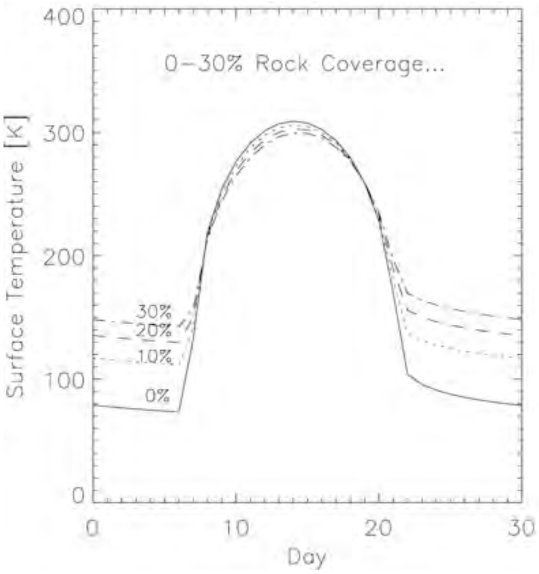

Figure 2: A modeled lunar diurnal cycle in 2008 at latitude of 65 N is shown for surface rock abundances ranging from 0 to 30%. An albedo of 0.1 and is assumed and the thermal inertias for rock and fines are adopted as 2500 J $m^{-2}s^{-1/2}K^{-1}$ and 25 J $m^{-2}K^{-1}s^{-1/2}$ respectively for a temperature of 200 K.

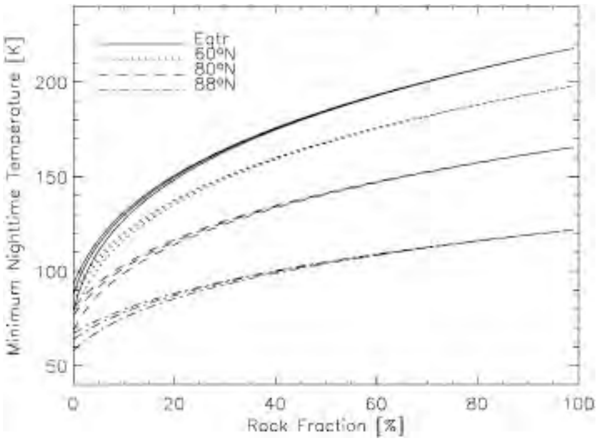

Figure 3. Minimum nighttime temperatures are shown as a function of rock abundance at four different latitudes for thermal inertias of fines of 23 J $m^{-2}s^{-1/2}K^{-1}$, 34 J $m^{-2}s^{-1/2}K^{-1}$, and 45 J $m^{-2}s^{-1/2}K^{-1}$ at 200 K based on laboratory measurements of Apollo fines [10,11].

Although the rock fraction has a much more significant impact on lunar nighttime temperatures than variations in the grain size or thermal conductivity of the fine grained component of the lunar regolith, these differences are not entirely negligible and indeed become more significant at higher latitudes, as shown in Figure 3. A reasonable range in temperature-dependent thermal inertias for both fines and rocks should be considered in the derivation of rock abundances. Fortunately laboratory data is available for both Apollo lunar samples and terrestrial analogs.

The ability to distinguish between thermal properties of fines and variations in the rock abundance is more difficult near the poles, as shown in Figure 3. In addition, our current 1-D thermal diffusion model assumes a planar surface. Topography plays a major role in lunar surface temperatures at a particular time of day [5]. Although not explicitly included in the model, measured local slope and topographic variations in sunset time, if available, can be adjusted for, as can the albedo for a specific longitude and latitude. At this time we have ignored lateral heat flow, which may be important in polar regions. Significant modification would be required to include this effect.

Conclusions: Our state-of-the-art lunar thermal model, combined with data anticipated from Lunar Reconnaissance Orbiter, can be used to constrain rock abundances over a majority of the lunar surface, and is especially sensitive to small changes in the rock fraction at low overall rock abundances. Despite limitations that may impact model performance at very high latitudes, we are confident that this tool can aid in the assessment of landing hazards for future robotic and human exploration of the Moon.

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