THE DIVERSITY OF LUNAR EJECTA MATERIALS AT GIORDANO BRUNO CRATER DERIVED FROM LRO DIVINER OBSERVATIONS.

J.-P. Williams[1], C. L. Gallinger[2], P. O. Hayne[3], D. A. Paige[1], A. V. Pathare[4], and E. S. Costello[5,6], [1]Earth, Planetary, and Space Sciences, University of California, Los Angeles, CA, [2]Department of Earth Sciences, University of Toronto, ON, Canada, [3]Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, CO, [4]Planetary Science Institute, Tuscon, AZ, [5]Department of Geology and Geophysics, University of Hawai'i at Mānoa, Honolulu, HI, [6]Hawaii Institute of Geophysics and Planetology, Honolulu, HI.

Introduction: Giordano Bruno (GB) is a prominent, 22-km diameter crater near the eastern limb on the lunar far side (36 °N, 103 °E). The fresh morphology, bright ray system, and spectral immaturity of GB all suggest the crater is very young [1,2,3]. Crater counts on the proximal ejecta yield a model age <10 Ma [4], though many of the craters on the ejecta may be self-secondary craters and the age could be < 1 Ma [5].

Radiance measurements by the Diviner instrument on the Lunar Reconnaissance Orbiter [6] show a substantial diversity of thermophysical properties across the ejecta around GB [7,8]. Nighttime temperatures are controlled by the density (ρ), thermal conductivity (k), and specific heat capacity (c_p). One-dimensional thermal models fit to surface temperatures observed by Diviner can provide estimates of vertical and lateral variation of these parameters within the diurnal skin depth of the regolith (upper ~4 – 20 cm) [9,10,11].

Due to the relatively young age of GB, the ejecta materials have experienced little modification since emplacement and thus regolith development has been minimal. This provides an opportunity to observe the thermophysical properties of relatively fresh crater ejecta materials on the Moon.

Thermal Model: One-dimensional heat transfer models have been developed to derive thermophysical properties of the regolith from Diviner observations [9,10,11]. These models find that the nighttime surface temperatures are well characterized by regolith with ρ and k that increase exponentially with depth with a scale height H. The regolith is generally very insulating with a low thermal inertia, $TI = \sqrt{\rho k c_p}$, that is temperature dependent and generally within ~10 – 100 J m^{-2} K^{-1} s$^{-1/2}$ within the diurnal skin depth [11].

By varying H in their model, Hayne et al. [11] were able to globally map variations in regolith thermophysical properties. However, for GB, varying the single parameter H was not adequate for characterizing the properties of the ejecta as the materials have a substantially higher TI than typical regolith. We therefore need to employ a model that can handle not only higher TI materials, but a diversity of materials that include granular media comprised of small clasts, sizeable blocks, and impact melt deposits, as well as complex mixtures of these materials.

Analytic models exist that attempt to account for the relevant physics of heat flow through regolith [e.g. 12,13]. The effective k will depend on the quality of heat conduction pathways within the material and these models strongly depend on the nature of the thermal contacts between particles. However, it is unclear how parameters within such models should be varied with changes in terrain properties. Here, we take a more generalized approach that is agnostic of the configuration of the materials in order to capture the full range of thermal inertias observed by Diviner without requiring poorly constrained model parameters. This at least can provide meaningful estimates of relative differences in thermal inertia.

For simplicity we modify the existing Hayne et al. [11] model by varying the lower boundary thermophysical parameters ρ_d and k_d in addition to the H parameter. The lower boundary is assumed to be a simple volumetric mixture of the regolith ($k_{d,reg}$ = 3.4×10^{-3} W m^{-1} K^{-1}, $\rho_{d,reg}$ = 1800 kg m^{-3}) and rock ($k_{eff,rock}$ = 1.492 W m^{-1} K^{-1}, ρ_{rock} = 2940 kg m^{-3}) [9] while keeping the surface density, ρ_s, and conductivity, k_s, unchanged from the Hayne et al. [11] model (k_s = 7.4×10^{-4} W m^{-1} K^{-1}, ρ_s = 1100 kg m^{-3}). The volume fraction of regolith at depth is then $v_{reg} = (\rho_{rock} - \rho_d) / (\rho_{rock} - \rho_{d,reg})$ where $\rho_{d,reg} < \rho_d < \rho_{rock}$, and conductivity is then $k_d = v_{reg}k_{d,reg} + (1 - v_{reg})k_{rock}$ with c_p similarly mixed. By setting H = 0, we can model homogenous materials, including pure rock. The effective conductivity then scales exponentially with depth as in the Hayne et al. [11] model, but now with the modified value of ρ_d and k_d. This represents a parallel model for a two-component mixture (i.e. a weighted arithmetic mean); however, other valid mixing models can be employed (see [14] for example) and the choice of mixing model will influence how density and conductivity are coupled with increasing TI. Therefore, absolute values of ρ and k should always be interpreted with caution with these models.

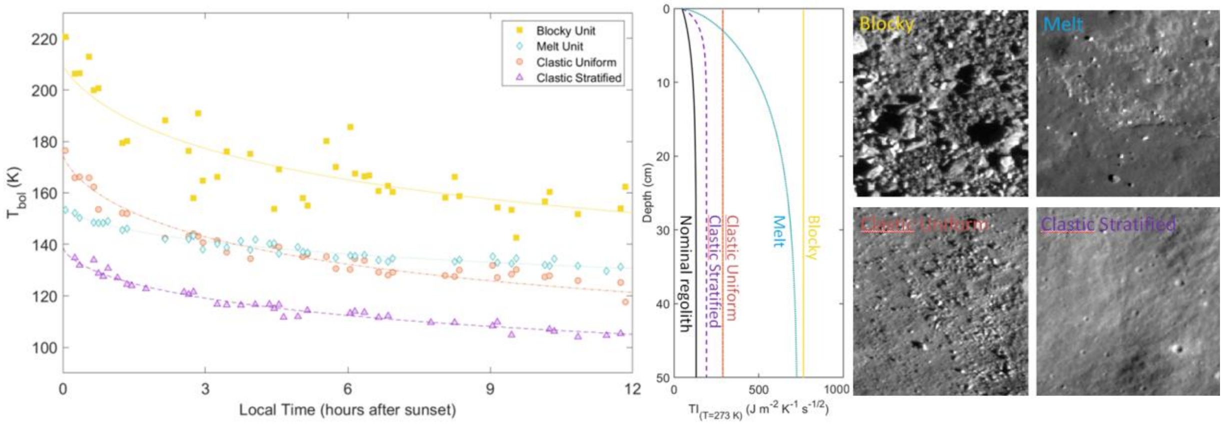

Fig. 1 (*left*) Nighttime bolometric temperatures observed by Diviner for four terrain types with model curves derived using a parallel mixing model of regolith and rock. (*middle*) The resulting vertical thermal inertia profiles for the models for $T = 273$ K. (*right*) Portions of LROC NAC image M1122936950LE of the 128 ppd bins showing the surfaces of the terrain types.

Results: Our model was applied to bolometric temperatures derived from Diviner IR radiance observations binned at 128 ppd (see [7,15] for details) and fit for H and ρ_d across a portion of the southern ejecta blanket of GB. This approach differs from [11] where nighttime "rock-free" regolith temperatures modeled from [9] were used to derive H values for the regolith. Fig. 1 shows nighttime bolometric temperatures for four thermophysically distinct terrain types we identify. All four terrain types require higher-*TI* materials than nominal regolith to varying degrees. Heat is conducted to the surface from increasing depth through the night and thus the rate of cooling over this time period is sensitive to the vertical structure of the thermophysical properties. Differences in the cooling curves reveal different vertical structure of the units. This is readily apparent where the temperatures of the impact melt (*cyan*) and the uniform clastic material (*red*) crossover ~3 hours local time after sunset. This clastic material requires *TI* to be vertically uniform suggesting a homogenous column of material. Conversely, the area characterized by visible impact melt deposits requires rapid initial cooling at sunset followed by slower cooling suggesting a vertical transition in properties near the surface from a lower-*TI* material to a higher-*TI* material at depth. Clastic ejecta devoid of visible blocks at Lunar Reconnaissance Orbiter Camera (LROC) Narrow Angle Camera (NAC) resolution also appear to have a vertical transition in properties (*magenta*) possibly related to compaction of material or an increase in the size of clasts or rocks with depth. Areas dominated by large blocks (*yellow*) require a constant and high-*TI* with depth.

Conclusions: We have modified the regolith thermal model of Hayne et al. [11] assuming a simple linear mixing model of rock and regolith to extend the model to higher-*TI* materials on the Moon. The model is applied to derive surface and subsurface material properties of a portion of the ejecta blanket of crater Giordano Bruno which has a multitude of terrain types that include large blocks, impact melts, and granular, clastic materials with variable vertical structure (Fig. 1). A parallel model is a natural choice to implement using the existing Hayne model [11] as it is also a parallel model and thus treats the coupling of density and conductivity in a consistent manner. The ability of a simple parallel model to provide a good fit to the Diviner data and demonstrate the existence of lateral and vertical variations in thermal inertia further supports this straightforward approach. This model provides a new tool for investigating material properties of complex and stratified units [e.g. 16,17], and could be applied to numerous other ejecta and impact melt deposits around young craters to better understand the process of crater degradation and regolith formation on the Moon and other solar system bodies.

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