MODELING NEAR-SURFACE TEMPERATURE GRADIENTS AND THERMAL EMISSION FROM THE LUNAR REGOLITH. Parvathy Prem[1]*, Benjamin T. Greenhagen[1], Chanud N. Yasanayake[1] and Kerri L. Donaldson Hanna[2], [1]Johns Hopkins University Applied Physics Laboratory, Laurel, MD, [2]University of Oxford, Oxford, UK; *parvathy.prem@jhuapl.edu.

Background & Motivation: Measurements of thermal emission from a planetary surface can provide key insights into surface composition and texture. However, in order to accurately interpret an emission spectrum, it is critical to develop an understanding of how temperature varies within the region of the subsurface from which observed thermal emission originates. Subsurface temperature variations may play a particularly significant role on the Moon (and other nominally airless bodies), where the low thermal conductivity of a fine-particulate regolith under near-vacuum conditions can give rise to steep near-surface temperature gradients [1-3] that qualitatively change the nature of emission spectra – as observed when thermal emission is measured under ambient and simulated lunar environmental conditions in the lab [4].

The objectives of this work are twofold: (i) to model the magnitude and shape of near-surface temperature gradients under lunar-like conditions, and (ii) to investigate the relationship between near-surface temperature gradients and characteristic spectral features, with a view to better informing the interpretation of lab and remote-sensing data.

Methods: Lunar "surface" thermal emission originates within the upper few millimeters of the subsurface – the "epiregolith" [5]. Most thermal models of the lunar subsurface operate on the centimeter to meter scale, at which the effects of radiative heat transfer within the medium can be approximated by a temperature-dependent thermal conductivity (i.e., $k = A + BT^3$, where A and B are constants), as in [6]. This approximation breaks down at scales comparable to the infrared extinction length (10-100 μm), and to obtain accurate temperature profiles at the sub-millimeter scale, radiative heat transfer must be modeled more explicitly. However, previous models that have accounted for radiative heat transfer in the epiregolith predict significantly different temperature profiles [1, 2].

This work uses the recently-developed ReBL (Regolith Boundary Layer) thermal model. ReBL uses a Monte Carlo approach [7] to compute the radiative flux term, q_R [W/m^2] in the one-dimensional heat equation:

$$\rho c(\partial T/\partial t) = \partial(k\partial T/\partial z - q_R)/\partial z$$

where ρ is density [kg/m^3], c is specific heat capacity [J/kg·K] and k is thermal conductivity [W/m·K]. We then apply a finite-differencing scheme to solve for temperature, T as a function of depth, z and time, t. The radiative flux incident at the surface varies with insolation over the course of the lunar day, and a constant heat flux of 0.018 W/m^2 from the lunar interior is assumed at depth [8]. Besides ρ, c and k, the other key variables in this problem are the extinction coefficient, single-scattering albedo and asymmetry parameter at visible and infrared wavelengths, which control the scattering and absorption of solar and thermal radiation within the modeled regolith.

Given a subsurface temperature profile and spectrally resolved scattering properties, ReBL can also be used to generate simulated emission spectra corresponding to the specified thermal conditions. In this case, the subsurface temperature profile is approximated by a series of isothermal layers, and the contribution of each layer to the simulated spectrum is modeled by tracking the propagation of a large number of emitted "energy packets" through the medium.

Results & Discussion: *What is the thermal structure of the lunar epiregolith?* Figure 1 illustrates the difference in computed subsurface temperature profiles when radiative heat transfer is modeled using a Monte Carlo approach, as opposed to being approximated by a temperature-dependent thermal conductivity. (In the former case, we specify $k = 2.6\times10^{-3}$ W/m·K, and in the latter case, $k \equiv A + BT^3$, where $A = 1.5\times10^{-3}$ W/m·K and $B = 9.45\times10^{-11}$ W/m·K^4.)

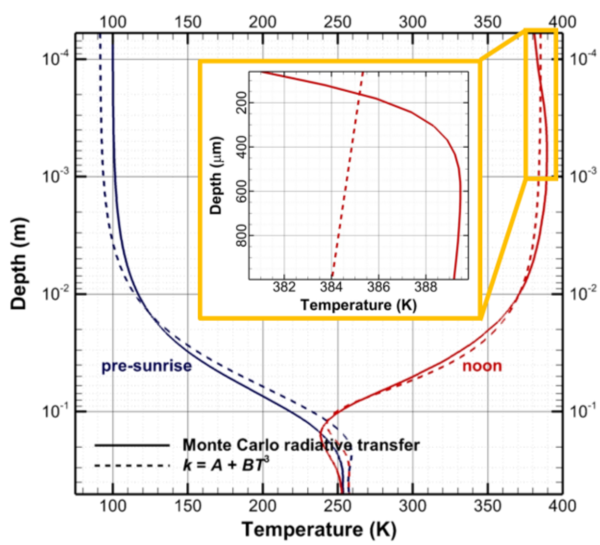

Figure 1. *Lunar subsurface temperature at equatorial dawn (pre-sunrise) and noon, based on two different approaches to modeling radiative heat transfer.*

Radiation becomes the more important heat transfer mechanism (relative to conduction) at higher temperatures, and as a result, the explicit inclusion of radiative heat transfer makes the most significant difference to the shape of the computed temperature profile at equatorial noon, when temperatures in the shallow subsurface are at their highest. For the case shown in Figure 1, we assume that both visible (solar) and infrared radiation are isotropically scattered within the regolith, with an extinction length of ~140 µm and a single scattering albedo of 0.36 [2]. For simplicity, in this initial calculation, regolith density and specific heat capacity are set to representative constant values of 1300 kg/m^3 and 550 J/kg·K, respectively [2].

The temperature profiles shown in Figure 1 are generally in agreement with the results of Hale and Hapke [2], who adopted a similar but different modeling approach (based on a numerical solution of the radiative transfer equation) and obtained near-surface gradients that are much lower in magnitude than those computed by Henderson and Jakosky [1]. The causes of the discrepancies between these two models bear further investigation, particularly since both models address important aspects of the problem: for instance, Hale and Hapke notably account for the "inherent time dependence of the planetary thermal transfer problem", while Henderson and Jakosky account for the important fact that extinction coefficients in the visible and infrared are often different. ReBL can accommodate both these considerations.

How strongly does the near-surface thermal environment affect infrared emission spectra? Figure 2 shows a set of simulated emission spectra for 10 µm (diameter) enstatite grains under different thermal environments, illustrating the increase in spectral contrast and the shift of the Christiansen feature (the emissivity maximum near 8 µm for silicate minerals) to shorter wavelengths – changes that occur when significant near-surface temperature gradients are present. It should be noted that the temperature gradients modeled in Figure 2 are far more dramatic than those shown in Figure 1, in which temperature varies by only ~10 K over a few 100's of µm (as opposed to 100 K in the cases shown in Figure 2). However, it is also interesting to note that that when enstatite is measured under ambient (isothermal) and simulated lunar conditions in the lab, the Christiansen feature shifts by ~0.2 µm [4], comparable in magnitude to the modeled shifts shown in Figure 2.

These early results raise a number of interesting questions. Do the nominal regolith scattering properties used to generate Figure 1 underestimate the magnitude of near-surface thermal gradients on the Moon? If so, what scattering properties are representative of the interaction of visible and infrared radiation with the lunar regolith? From another perspective, how do thermal gradients generated under simulated lunar conditions in the lab compare to those generated in the actual lunar environment (where varying insolation an subsurface heat storage play a role in determining near-surface conditions)? What constraints do numerically modeled and experimentally measured spectral changes provide regarding the thermal gradients that exist under measurement conditions?

We will report on our progress towards addressing the questions above, and towards constructing a more complete view of the thermal and physical structure of the lunar regolith at the sub-millimeter scale, and of the imprints left by this structure in the thermal infrared.

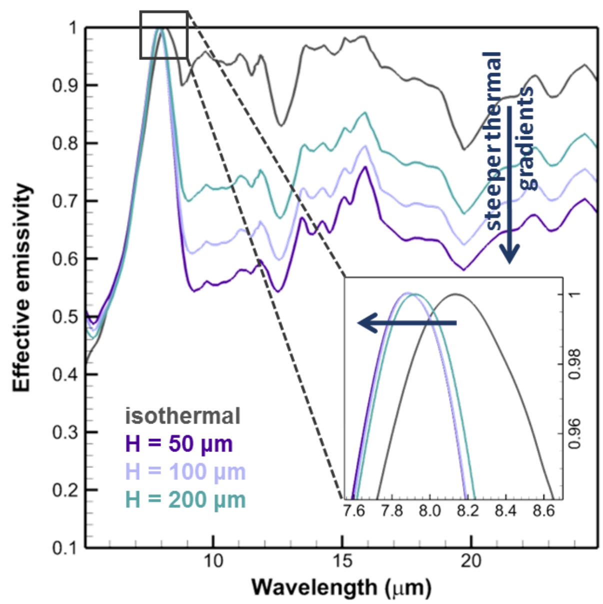

Figure 2. *Modeled effective emissivity spectra for 10 µm (diameter) enstatite grains under different thermal conditions. In the non-isothermal cases, the subsurface temperature profile is parameterized as* $T(z) \equiv T_d - (T_d - T_s)\cdot\exp(-z/H)$*, where* $T_d = 400$ *K,* $T_s = 300$ *K, and H varies as indicated (lower values of H correspond to steeper near-surface temperature gradients). Arrows indicate the nature of changes in spectral characteristics as near-surface gradients become steeper.*

References: [1] Henderson and Jakosky (1997), *JGR*, 102, 6567–6580. [2] Hale and Hapke (2002), *Icarus*, 156, 318–334. [3] Millán et al. (2011), *JGR*, 116, E12003. [4] Donaldson Hanna et al. (2012), *JGR*, 117, E00H05. [5] Mendell and Noble (2010), *LPSC*, #1348. [6] Vasavada et al. (1999), *Icarus*, 141, 179–193. [7] Prem et al. (2018), *NESF*, #038. [8] Hayne et al. (2017), *JGR*, 122, 2371–2400.