**MODELING THERMAL EMISSION FROM THE ANISOTHERMAL LUNAR REGOLITH.** P. Prem[1]*, B. T. Greenhagen[1], K. L. Donaldson Hanna[2], K. A. Shirley[3], and T. D. Glotch[4]; [1]Johns Hopkins Applied Physics Laboratory, Laurel, MD, USA; [2]University of Central Florida, Orlando, FL, USA; [3]University of Oxford, Oxford, UK; [4]Stony Brook University, Stony Brook, NY, USA; *parvathy.prem@jhuapl.edu.

**Introduction:** Thermal emission from the surface of the Moon and other airless bodies can carry key information regarding surface composition, physical properties, and temperature. However, under lunar surface environmental conditions, the uppermost millimeters of the regolith (referred to as the 'epiregolith' [1]), from which measured thermal emission originates, may sustain steep temperature gradients. Lab measurements under simulated lunar conditions indicate that such gradients can lead to changes in the location and shape of characteristic spectral features (e.g., [2]), complicating the interpretation of remote sensing data. The magnitude of epiregolith temperature gradients also has implications for volatile transport and other temperature-sensitive surface processes (e.g., [3]).

In this work, we develop and apply a numerical method to model thermal emission from particulate media with varying subsurface temperature profiles, and investigate the effects of composition, particle size, and packing density. We also compare model results to lab measurements acquired in a simulated lunar environment, in order to constrain the magnitude of thermal gradients established in the lab and on the lunar surface, and to determine epiregolith thickness.

**Method:** We model thermal emission spectra using a Monte Carlo radiative transfer approach ("ReBL", the Regolith Boundary Layer model) that tracks the propagation, scattering, and attenuation of a large number of representative "energy bundles" emitted within the medium of interest, as illustrated schematically in **Figure 1**. The simulated medium is 1 mm deep and is discretized into 100 layers, each with a specified temperature that determines the amount of energy carried by emitted bundles. The results presented here were obtained by tracking $10^5$ energy bundles per wavelength per layer. Energy that exits the medium is summed to obtain an emission spectrum. Simulated spectra have a wavelength resolution of < 5 $cm^{-1}$, determined by the resolution of available optical constant data from Zeidler et al. [4] for pyroxene (enstatite) and olivine (San Carlos), and from Ye et al. [5] for plagioclase (labradorite).

Like other radiative transfer models, ReBL requires some prior knowledge of the scattering properties of the modeled medium. Scattering and absorption coefficients and asymmetry parameter for each modeled composition, grain size, and packing density are obtained using a Mie scattering code [6]. The Monte Carlo calculation assumes a Henyey-Greenstein phase function (defined by the asymmetry parameter) for each scattering event. Although Mie theory is strictly applicable only to isolated, spherical scatterers, which is seldom the case in a planetary regolith (or lab sample), we find that useful results can be obtained using Mie scattering parameters, as discussed below.

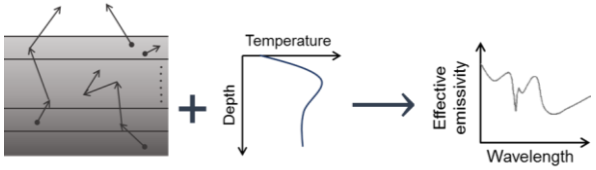


**Figure 1.** Schematic depiction of the modeling approach used in this work. We perform a Monte Carlo radiative transfer calculation and specify a temperature profile to generate a simulated emission spectrum.

**Results & Discussion:** Emission spectra modeled using ReBL were compared to laboratory measurements of well-characterized samples under ambient and simulated lunar conditions. **Figure 2** compares modeled and measured spectra for two different size fractions of enstatite, a 32–45 μm size fraction (modeled using Mie scattering properties for 38 μm spheres) and a < 25 μm size fraction (modeled using Mie scattering properties for 10 μm spheres). Given optical constants for the three orthogonal crystal orientations of enstatite [4], model results were obtained using scattering properties for a best-fit mixture of crystal orientations. Key findings illustrated in **Figure 2** include the following:

(i) Modeled isothermal spectra generally agree well with measured ambient spectra for larger grains (**Figure 2a**), with more pronounced discrepancies for smaller grains (**Figure 2b**). These discrepancies are attributable primarily to the approximations inherent in using Mie theory to model a closely-packed particulate medium. *We leverage the availability of lab measurements under ambient conditions* by applying the difference between modeled and measured emissivity in the isothermal case as a correction factor to modeled spectra for anisothermal conditions.

(ii) This modeling approach is generally successful at predicting changes in spectral contrast under lunar-like conditions. In the cases shown in **Figure 2**, measurements under simulated lunar conditions are

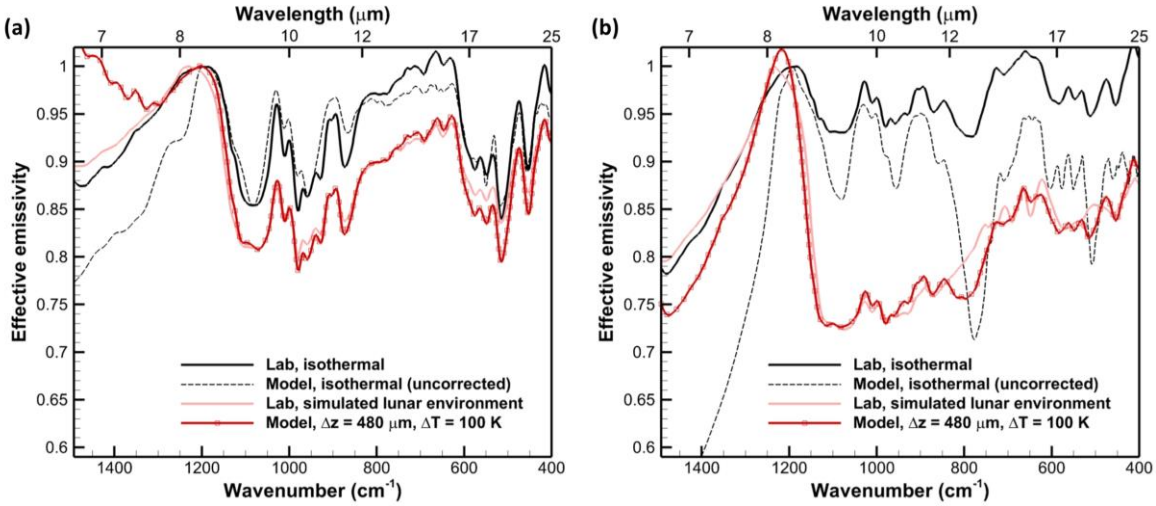


**Figure 2.** Modeled and measured ("lab") emission spectra for (a) larger (~38 μm) and (b) smaller (~10 μm) enstatite grains under ambient (isothermal) and simulated lunar (anisothermal) conditions. Dashed lines indicate uncorrected modeled isothermal spectra. Out of a suite of linear thermal gradients investigated, lab spectra measured in a simulated lunar environment were best matched by the modeled cases shown in **red**, corresponding to an increase in temperature of 100 K within the uppermost (a) 480 μm and (b) 230 μm.

well-matched by linear near-surface temperature gradients of ~21–44 K/100 μm. Model results also suggest that the thermal gradient established in a finer-grained medium is steeper but extends to a shallower depth. These results are consistent with earlier work [7].

(iii) The model is less successful at accurately capturing the shift to shorter wavelengths of the mid-infrared emissivity maximum (the Christiansen feature, CF). While lab measurements indicate shifts of ΔCF = –0.20 μm and –0.36 μm for larger and smaller particles, respectively, the modeled spectra shown in **Figure 2** exhibit shifts of ΔCF = 0.00 μm and –0.24 μm.

Besides pyroxene, we also modeled two other major lunar mineral phases – olivine and plagioclase – and performed similar comparisons to lab data, with broadly similar findings. The model generally provides useful constraints on the magnitude of the temperature profiles established under lunar-like conditions, but in some cases, lab spectra are not well-represented by the linear temperature profiles considered here.

In addition to modeling emission spectra, ReBL also quantifies the depth within which measured thermal emission originates. The 'isothermal sensitivity depth' shown in **Figure 3** varies with composition, and increases with *increasing* particle size and *decreasing* packing density (i.e., the epiregolith is effectively thicker for a more porous medium).

We anticipate that agreement between modeled and measured spectra could be improved by adopting more physically realistic models of regolith microstructure to compute the scattering properties that are provided as input to ReBL – an area of interest for future work.

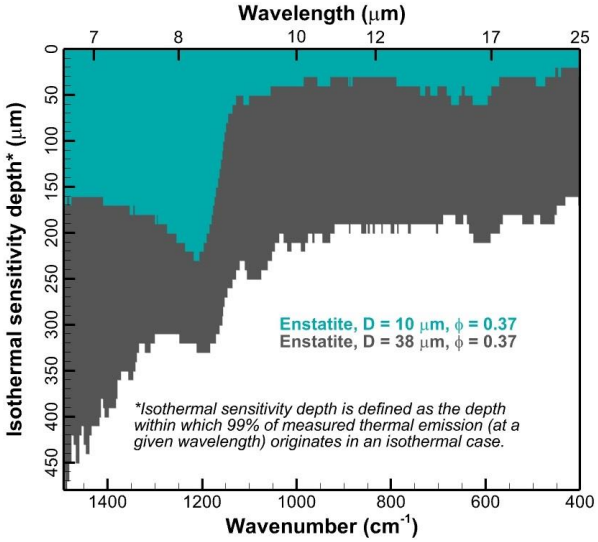


**Figure 3.** Modeled isothermal sensitivity depth for two grain sizes of enstatite; packing density ϕ = 0.37.

**Acknowledgments:** This work was supported by NASA's Lunar Reconnaissance Orbiter (LRO) mission through funding to the Diviner instrument team.

**References:** [1] Mendell & Noble (2010), *LPSC*, #1348; [2] Logan et al. (1973), *JGR*, 28, 73, 4983–5003; [3] Sarantos & Tsavachidis (2020), *GRL*, 47, e2020GL088930; [4] Zeidler et al. (2015), *ApJ*, 798, 125; [5] Ye et al. (2019), *Earth & Space Sci.*, 6, 2410–2422; [6] Mätzler (2002), *Uni. Bern*. [7] Henderson & Jakosky (1997), *JGR*, 102, E3.