

LOW TEMPERATURE THERMAL PROPERTIES OF LUNAR SOIL. Rachel E. Woods-Robinson¹ and David A. Paige¹, ¹UCLA Department of Earth, Planetary and Space Sciences: woodsrobinsonrachel@gmail.com

Introduction: The thermal properties of lunar soils are well understood for temperatures down to approximately 90K. Extensive laboratory tests were performed on lunar samples collected from the Apollo missions [1], and thermal model calculations using measured lunar soil thermal properties are in good agreement with in-situ orbital remote sensing measurements (Figure 1) [2, 3]. More recently, the Lunar Reconnaissance Orbiter Diviner Lunar Radiometer Experiment has obtained thermal emission measurements in the lunar polar zones that have revealed regions in permanent shadow whose temperatures are as low as 20K [4]. These are amongst the lowest radiometric temperatures measured in the solar system, and their interpretation through thermophysical models is relevant for understanding the behavior of lunar volatiles and constraining the heat flow rate from the lunar interior. In the absence of a complete set of lunar soil laboratory thermal conductivity (TC) and heat capacity measurements in the 20 - 100K temperature range, we are using measurements of the thermal properties of analog materials and theory to derive a physically-based set of low temperature lunar soil properties.

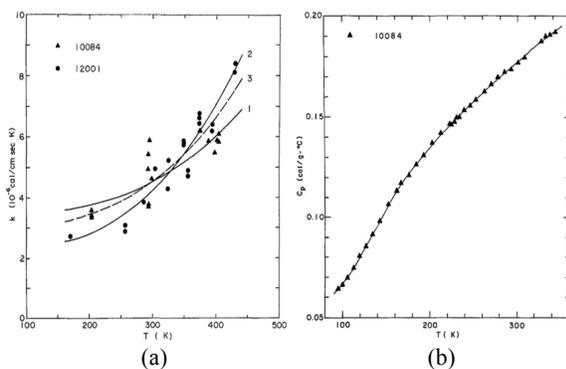


Figure 1: Known experimental data fit to models for lunar soil above 100K. (a) Thermal conductivity k versus temperature T for Apollo 11 (10084) and Apollo 12 (12001) type D fine soils. Curves are Watson's equations [5] fitted to the data [1]. (b) Specific heat at constant pressure of Apollo 11 fine soil (10084) fit to curve derived from the Debye theory of solids [1].

Thermal Properties at Low Temperatures:

Extensive research has been conducted to define the thermal properties of crystalline and amorphous solids at low temperatures (Figure 2). Lunar rocks have also been analyzed at low temperatures.

Crystalline Solids: Analogies to kinetic gas theory, as applied by Debye, show for crystalline materials specific heat at constant volume C_V is proportional to T^3 at very low temperatures [1, 6]. Debye related TC (k) to specific heat (C_V), sound velocity (v) and mean free path (l) at moderate temperatures with $k = 1/3 C_V v l$. In crystalline solids, TC is completely described by phonon scattering due to harmonic and anharmonic crystal vibrations [7]. As shown for α -quartz (Figure 2a), Debye T^3 effects dominate at low temperatures to drive TC to a maximum until the resistive effects of umklapp processes dominate and decrease the TC. This trend is prevalent in *all* crystalline materials, though the location of the peaks and amplitude of TC differs with chemical composition. Imperfect crystals such as KCl:CN (i.e. with lattice defects) exhibit additional scattering due primarily to the isotope effect and impurity mode scattering, which lead to compressed peaks and dips in the TC.

Amorphous Solids: The TC of amorphous solids exhibits universality at low temperatures [8, 9], reaching a plateau at around 10K as in SiO₂ (Figure 2a). Below 1K the thermal conductivity increases with T^2 , explained by tunneling processes [10], and above 100K conductivity is strongly dependent on chemical composition. A soft potential model, with soft localized modes and a stabilizing fourth order term in the potential [11], provides the most accurate thermal conductivity model in our low temperature region of interest. Specific heat in amorphous solids also adheres to Debye's approximations. The slight difference between vitreous and crystalline specific heats (Figure 2b) is most likely attributed to additional localized modes in the glassy state.

Lunar Rocks: A study of Type A and Type C lunar samples cooled rocks to liquid helium temperatures and found all samples to decrease monotonically from 200K to zero [1, 12]. At 4K, the TCs of the two samples were found to differ by one or two orders of magnitude. It has also been suggested that radiative heat transfer becomes more important under high vacuum lunar conditions and may correlate to void shape and distribution [1].

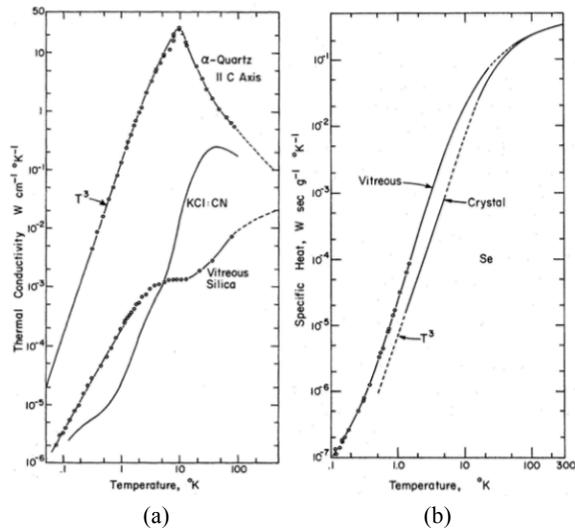


Figure 2: (a) Thermal conductivity as a function of temperature for vitreous silica SiO₂, crystalline α-quartz and imperfect crystalline KCl:CN [8]. (b) Specific heat at constant pressure plotted as T vs. C_V for crystalline and vitreous (amorphous or glassy) SiO₂ [8].

Thermophysical Models for Lunar Soil: Effective TC is the sum of conductivities due to radiative (k_r) and conductive (k_c) heat transfer. According to Winter and Saari [14], lunar soil TC is adequately modeled at moderate temperatures by $k_e = k_c + k_r$ and $k_r = AT^3$, where A is a function of particle size, porosity and emissivity. At low temperatures, the radiative component is typically ignored in standard lunar soil models due to T^3 dependence and only the conductive component k_c is considered. Conductive heat transfer in soil is complex and thermal models of terrestrial soil treat water, air and solid TC components separately. Lunar soil models are somewhat more simplified since taken to exist in vacuum, but components are similarly divided. Unlike TC, specific heat differs trivially by material and has been approximated for lunar soils from around 30K - 400K by $C(T) = -0.034 T^{1/2} + 0.008 T + 0.0002T^{3/2}$ [J/gK] [14].

Methodology and Future Work: A quasi-continuum mathematical model is under construction corresponding to a combination of Watson's [5] and Winter and Saari's [14] methods. The main solid constituents of lunar soil differ by sample type but are predominantly rock fragments, monomineralic fragments, agglutinates and glass spherules (including SiO₂) [1]. Additionally, the following variable soil parameters are integrated: porosity, grain size, aspect ratio, specific surface area, bulk density and relative density. Soil is modeled as beds of solid elastic spheres in a vacuum and reduced

environment [5]. Grains of these idealized soil particles are connected by effective thermal resistors, where resistance R_s is a function of grain contact area [14]. Effects of intergranular radiation and particle boundaries are evaluated by assuming a sufficiently small radiation number and by considering each particle isothermal.

The key difference from previous thermophysical models is our incorporation of the TC temperature dependence of solid particulate constituents – crystalline particles, glass particles and rock materials – at low temperatures. Assuming heat capacity in soil to have a profile similar to heat capacity in lunar rocks (as justified in [1]) and the Debye T^3 relation, the heat capacity equation presented above is modified and fit to extend to low temperatures of interest. Thus, relations from Figure 2 are utilized to derive thermal conductivity and heat capacity as a factor of soil parameters and temperature within the range of 20 - 100K.

References: [1] Horai, K. I., & Fujii, N. (1972). *The moon*, 4(3-4), 447-475. [2] Langseth, M. G. et al. (1971) *LPSC Proceedings*, 7, 3153-3171. [3] Vasavada, A. R. et al. (2012) *JGR* 117, E00H18. [4] Paige, D. A. et al. (2010) AGU P31E-04. [5] Watson, K. (1964). *Unpublished PhD Thesis*. California Institute of Technology. [6] Debye, P. (1912). *Annalen der Physik*, 344(14), 789-839. [7] Cahill, D. G., & Pohl, R. O. (1988). *Annual Review of Physical Chemistry*, 39(1), 93-121. [8] Zeller, R. C., & Pohl, R. O. (1971). *Physical Review B*, 4(6), 2029. [9] Pohl, R. O., Liu, X., & Thompson, E. (2002). *Reviews of Modern Physics*, 74(4), 991. [10] Phillips, W. A. (1972). *Journal of Low Temperature Physics*, 7(3-4), 351-360. [11] Gil, L., Ramos, M. A., Bringer, A., & Buchenau, U. (1993). *Physical review letters*, 70, 182-185. [12] Morrison, J. A., & Norton, P. R. (1970). *Journal of Geophysical Research*, 75(32), 6553-6557. [13] Farouki, O. T. (1981). *Cold Regions Science and Technology*, 5(1), 67-75. [14] Winter, D. F., & Saari, J. M. (1969). *The Astrophysical Journal*, 156, 1135.