THERMAL AND PHYSICAL PROPERTIES OF LUNAR METEORITES AT LOW TEMPERATURES.

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Introduction: We report low-temperature specific heat capacity, thermal conductivity, and linear thermal expansion for six lunar meteorites: Northwest Africa [NWA] 5000, NWA 6950, NWA 8687, NWA 10678, NWA 11421, and NWA 11474, over the range $5 \leq T \leq 300$ K. From these, we calculate thermal inertia and thermal diffusivity as a function of temperature. Additionally, heat capacities were measured for fifteen other lunar meteorites, from which we calculate their Debye temperature and effective molar mass. Measurements follow the procedures as described in [1] utilizing a Quantum Design Physical Property Measurement System (QD-PPMS) at Boston College, cooled at temperatures ranging from 2 - 400 K and thermally isolated in near-vacuum of 10^{-6} Torr.

Thermal Conductivity: For the specimens in this study, thermal conductivities vary by approximately a factor of three over the range 20 to 100 K and are noticeably lower than that of their individual component minerals. The top layers of lunar regolith exhibit eons of micrometeorite gardening which makes them extremely porous; cracks and voids inhibit heat flow. This may account for the difference between our thermal conductivity measurements and those inferred from thermal infrared data of the lunar surface ($7 - 34 \times 10^{-3}$ W m^{-1} K^{-1}, depending on depth [2]).

Heat Capacities and Debye Temperature: Heat capacities are independent of porosity and structure. Like conductivity, its temperature dependence is very pronounced, particularly at temperatures below ~100 K. The heat capacities for the specimens in this study vary by a factor of 5 between 20 K and 100 K, and by another factor of 3 from 100 K to 300 K. Calculated Debye temperatures among the specimens ranged from 486 to 561 K.

Thermal Diffusivity: Because thermal inertia and thermal diffusivity are both calculated from heat capacity and thermal conductivity (and density, assumed here to be independent of temperature), both of these properties likewise are strong functions of temperature. In the case of thermal diffusivity, which varies with the ratio of these factors, the temperature dependence flattens out above 50 K. Below 50 K, however, thermal conductivity and heat capacity exhibit vastly different behaviors with temperature: the denominator (heat capacity) trends towards zero faster than thermal conductivity. There, as temperature drops the thermal diffusivity can increase to a maximum (which varies significantly among the specimens), before falling toward zero at absolute zero. This should be a major caveat for any thermal modeling of the lunar surface that depends on thermal diffusivity in the range 10 K to 50 K.

Thermal Inertia: Because thermal inertia varies as the square root of the product of heat capacity and thermal conductivity, it is a very strong function of temperature over the entire thermal range in this study. It increases by a factor of five from 20 K to 100 K, and by another factor of two from 100 K to 300 K. At extremely low temperatures, where both conductivity and heat capacity trend toward zero, it likewise trends continuously toward zero as one approaches 0 K; here it is much more well-behaved function of temperature than thermal diffusivity.

Coefficient of Linear Thermal Expansion: Negative thermal expansion (NTE) is observed below ~100 K in every one of the specimens measured in this study. We have now seen this unusual trait in two very different meteorite types: lunar meteorites and CM carbonaceous chondrites [1]. However, the two meteorite types exhibit NTE in two different temperature regimes, indicating that at least two different minerals are responsible for this very unusual thermal behavior. It raises the question of whether other meteorites may also exhibit NTE; there are so few measurements of the coefficient of thermal expansion at low temperatures for meteorites that it would be quite conceivable that this the property had been missed elsewhere. For lunar materials, the degree of NTE is significantly less than that of CM chondrites, and at low temperatures reached only in a few regions on the surface, i. e. permanently shadowed craters; but material in permanent shadow would not experience much diurnal cycling. Nevertheless, it ought to be at least considered when trying to understand the thermal evolution of those regions.

Discussion: Because these trends are strongest at the lowest temperatures, it is worthwhile considering how the infrared signature from permanently shadowed craters might reflect the presence of ices. One can speculate that the thermal properties of ice might provide a notable contrast from what we have measured here for lunar rocks, given that the thermal inertias of cold icy bodies like TNOs at temperatures at or below 50 K, as expected for permanently shadowed craters, has been measured to be around 2.5 ± 0.5 J m^{-2} K^{-1} s$^{-1/2}$ while that of the lunar samples measured here are at or below 0.5 J m^{-2} K^{-1} s$^{-1/2}$. Since the thermal inertia of ice at 50 K is near 2100 J m^{-2} K^{-1} s$^{-1/2}$ [3] it would not take much ice to account for the difference. Due to the nonlinear way that thermal conductivity—and consequently thermal inertia—varies with composition, we do not attempt to quantify it here, but leave it as an exercise for more sophisticated thermal models.

References: [1] Opeil C. P. et al. (2020) *Meteoritics & Planetary Science* 55, no.8:E1-E20. [2] Müller T. G. et al. (2021) *Astronomy and Astrophysics* 650:A38. [3] Fukusako S. (1990) *International Journal of Thermosphysics* 11:353-372.