HOW COLD ARE THE FLOORS OF LUNAR POLAR SHADOWED CRATERS? W. W. Mendell, NASA/JSC/KA, Houston TX 77058 (wendell.mendell@nasa.gov),.

Introduction: Almost five decades ago Watson, et al, [1] speculated that molecules of volatile species might accumulate within the cryogenic environments of permanently shadowed polar craters. The subject was largely a scientific curiosity until recently. In the mid-1980's, people began to seriously discuss the feasibility of long-term or permanent human settlement of the Moon. Given that the Moon was known be missing the compounds need to support life and that importing volatiles from Earth is prohibitively expensive, lunar colonists were pictured as processing the putative polar volatiles.

A bistatic radar experiment performed with the Clementine spacecraft was interpreted to suggest the presence of large quantities of ice at some polar locations. [2] The neutron spectrometer aboard the Lunar Prospector spacecraft reported high concentrations of hydrogen in the polar regolith, [3] and some interpretations of the data set pointed to very high concentrations in permanently shadowed craters.

The reformulation of civilian space policy in 2004, known as the Vision for Space Exploration, emphasized lunar exploration with eye toward development of economic returns from cislunar space and long-term human presence on the Moon. The theme of finding lunar resources was an impetus for the inclusion of the Diviner Lunar Radiometer Experiment on the Lunar Reconnaissance Orbiter. Preliminary results from Diviner report an unexpectedly low temperature down to 35K in the depths of some craters. [4]

Implications of Low Temperature: One way to estimate the lowest possible temperature is to assume that the only thermal source for surface material is heat flow from the lunar interior. The highest value of the two Apollo heat flow measurements is about 22 mW/m^2 [5], giving an equivalent blackbody radiant surface temperature of about 25K, consistent with the measurement. However, a surface element at the bottom of a crater will receive radiation from the walls, whose temperatures are higher than that of free space; and estimates of the real temperatures at the crater bottoms range from 40K to 90K [6].

The physical temperature of the surface will determine what substances, particularly volatiles, will condense at the extremely low partial pressures of the lunar 'atmosphere'. A triple point for N_2 occurs at 61 K and 12 kPa, still much higher pressure than the Moon. Nitrogen ice is detected on Triton at a temperature of 38 K and a pressure of 1 Pa, still too high for the Moon. However, extremely porous surface layers and cold temperatures might favor development of interstitial gas pressures higher than those of the general lunar surface.

Radiometric Temperatures: Our mental picture of the crater interior is that of a *solid surface* at a *physical temperature* (that could be measured by a contact thermal sensor). The physical surface emits *thermal radiation* that is detected by a Diviner radiometer over a defined spectral bandpass. The signal is interpreted as a temperature via a preflight calibration procedure, wherein the signal in the radiometer is compared to signals from an artificial blackbody whose temperature is varied. The calibration sources are painstakingly constructed to simulate an ideal blackbody with unit emissivity. As the lunar scene will have an emissivity less than unity, the assigned radiometric temperature may be lower than its physical temperature

The emissivity of the lunar surface has been a topic of discussion for more than 45 years. [7] By consensus, it is greater than 0.9, implying <3% difference between the radiometric and physical temperatures. Radiometric measurements of the Moon have been made from Earth, but no good extended calibration sources exist in the sky. The uncertainties in the detected radiance itself outweigh those of the emissivity.

Laboratory measurements on natural samples tend to be in the range 2.5 μm – 25 μm because that is a standard commercial spectrometer configuration. Much of the analysis has focused on wavelengths in the range of 8 μm - 14 μm, known as the thermal infrared and coincident with a window of transparency in the terrestrial atmosphere. Diviner detects extremely low temperatures only in its 100-μm to 400-μm band.

The most abundant particle sizes in lunar soils are on the order of the thermal infrared wavelengths but rather smaller than the wavelengths measured by Diviner. I suggest that this dimensional relation is significant.

Planck & Kirchhoff: The experiment design and data analysis is grounded in the familiar principles of blackbody radiation from a solid surface. The lunar surface is particulate, a characteristic regarded as a minor perturbation on the process of temperature assignment. However, I believe that the optically active surficial boundary is an unusual, tenuous structure that I term the *epiregolith*. [8] Charging of the surface particles creates a mutual repulsion, creating an open network that has been characterized as a "fairy castle". The epiregolith is the source of the thermal radiation seen by Diviner. In this extremely porous and open structure, the innate emissivity of the individual particles is important.

Ruppin and Englman [9] analyzed optical phonons in *small* ionic crystals and showed that the absorptivity at *long* wavelengths was constrained by the crystal size, only surface modes being active. Consequently, emission of thermal radiation would be confined to a region around the Frohlich frequency in the basic model. The absorption cross section from Mie theory appears to be the appropriate representation for the spectral emissivity. Lynch and Mazuk [10] suggest that the appropriate size parameter to define the 'small particle' regime in not the standard Mie scattering parameter using the real part of the index of refraction but rather the equivalent expression with the imaginary index k , $\Omega = 4\pi ka/\lambda = 2kX_R$, where a is the particle diameter and λ is the wavelength. Calculation of the emissivity of an olivine sphere shows dramatic decrease at 100µm for diameters 10µm and less.

For wavelengths another order of magnitude larger, the photon's electric field spans a number of particles, creating a coherent dipole response within adjacent grains. In this case, the particulate mass can be modeled as a mixture of matter and space, leading to a representation of the dielectric response known as *effective medium theory.* [11]

Further difficulties arise in this measurement regime with the fundamental assumptions behind the Planck distribution and Kirchhoff's Law. Salisbury et al [12] have noted the nonequilibrium thermal state of the epiregolith in the diurnal thermal regime militates against using direction-hemispherical reflectivity data as a surrogate for emissivity. Those nonequilibrium conditions would not seem to exist in the very static thermal regime at the bottom of doubly-shadowed craters. Nevertheless, Baltes [13] notes that Kirchhoff's formulation assumes that "the wavelengths occurring are infinitesimally small compared to any occurring lengths."

At the Bottom: Speculation abounds that ices at the bottom of the polar shadowed craters create a distinct surface structure. I believe the regolith is granular (i.e., normal) but the size distribution may be more fine-grained than elsewhere.

Fine-grained material accumulates at the foot of slopes as seen by the Apollo 17 Infrared Scanning Radiometer [14] as well as the miniSAR aboard Chandrayaan. The interiors of shadowed craters may exhibit permanent negative charging by mechanisms similar to those created a negative surface charge on the unilluminated Moon. Henley [15] remarks that if extremely fine particles are indeed levitated electrostatically to high altitudes on ballistic trajectories, they could be trapped eventually in the permanently shadowed craters where photoelectric charging no longer occurs. The efficiency of Henley's mechanism could be substantially enhanced by an attraction of the small, postively charged particles to the negative surface charge in the dark interiors.

Deep Dark Pixie Palace: The structural fragility of this epiregolith, coupled with the ubiquity of the optical properties, implies that it must be dynamic to the extent of self-repair. [8] I suggest that its structure might be the product of mutual electrostatic repulsion among particles charged positively by the photoelectric effect on the lunar dayside. Whether the "fairy-castle" (pixie-palace) structures would persist as the surface charges transitions to negative on the nighttime hemisphere is not clear.

A fine-grained, porous surficial layer inside permanently shadowed regions would be a very poor emitter of submillimeter thermal radiation, implying that the physical temperature of the grains would be somewhat higher than that reported by a remote radiometric measurement at those wavelengths. While the enhanced temperature would not be great enough to affect the stability of water ice, volatiles with lower sublimation temperatures would not exist in predicted concentrations. A continuous deposition of levitated fine-grained material over geologic time could explain the finding of a desiccated overburden by the Lunar Prospector neutron spectrometer. [16]

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