APOLLO LUNAR HEAT FLOW EXPERIMENTS AND THE LRO DIVINER RADIOMETER.

M. A. Siegler[1], D. A. Paige[1], S. J. Keihm[2], A. R. Vasavada[2], R. R. Ghent[3], J. L. Bandfield[4], K. J. Snook[5] , [1]UCLA Earth and Space Sciences (595 Charles Young Dr., 3806 Geology, Box 951567, Los Angeles, CA, 90095, siegler@ucla.edu), [2]NASA Jet Propulsion Laboratory, [3]Dept. of Geology, U. Toronto, [4]U. Washington, Earth and Space Sciences [5]NASA Headquarters

Introduction: The instruments aboard the Lunar Reconnaissance Orbiter (LRO) continue to shed new light on old questions of the Apollo era. One of these instruments, the infrared radiometer (Diviner), aims to create the first global radiometric temperature maps of the lunar surface. An initial desire to extrapolate these surface temperatures to depth has lead to a detailed examination of the Apollo 15 and 17 Heat Flow Experiments (the only existing measurements of subsurface temperature).

To first order, the Apollo derived values for soil thermal properties [1-3] give excellent agreement with measured Diviner brightness temperatures (Figure 1). However, discrepancies do exist between the Apollo regolith model and the actual Heat Flow Experiment measured subsurface temperatures. Being housed within a hollow bore stem, the Apollo thermal probes were subject to diurnal variations due to the flow of heat down the bore stem itself. This effect has been assumed to have not impacted the lower temperature sensors in the probe. However, this has not been thoroughly tested. In addition, an unexplained upward temperature drift was seen even in the deepest temperatures measured by the probe, leaving it unclear when the probe was to be assumed in equilibrium with the surrounding regolith.

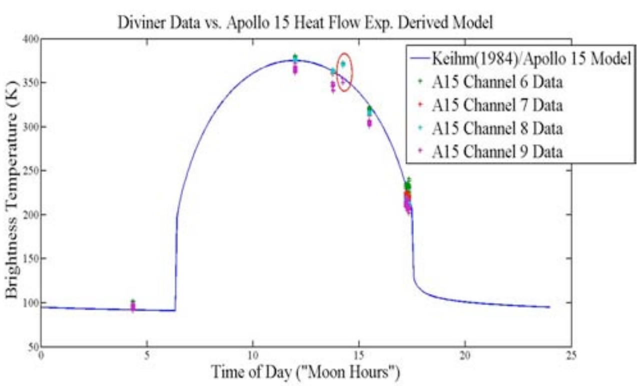

Figure 1: Diviner brightness temperature measurements as of Dec, 2009 at the Apollo 15 landing site vs. Apollo 15 soil model. The red ellipse marks a 50 degree off nadir measurement.

Using new thermal modeling tools developed in association with Diviner we hope to reexamine these issuesand determine that the derived Apollo subsurface properties model [1-3] represent the best possible base model for extrapolation of Diviner temperatures into the Lunar subsurface. Such models may be especially crucial for identifying any possible variations in surface temperatures caused by anomalies such as subsurface polar volatiles and for modeling the movement of volatiles in response to thermal forcing.

Heat Flow Data: The Apollo heat flow experiments reveal the complex nature of heat flow in the lunar subsurface. Due to the high porosity of the lunar regolith and near vacuum environment, heat transfer is limited to solid intergrain contact conduction and radiation. Radiative heat transfer through the regolith (which can be treated as a form of temperature dependent thermal conductivity, $k=A+BT^3$) lets surface heat flow into the regolith more efficiently during the day, and out less efficiently at night. This effect was seen to cause a 45K rise in mean temperatures within the top 35cm at the Apollo 15 site[1].

In addition to this radiative transfer between regolith grains, heat also transferred radiatively through the bore stem of the heat flow probes themselves. This had clear effects on the upper thermal bridge sensors of Apollo 15 probe 1, dominating the measured amplitude and phase of monthly variations down to at least 45cm depth. The effect of this "shunting" of heat on the lower bridge measurements is unknown and may be part of the cause of a mysterious long term positive drift in measured subsurface temperatures (Figure 2).

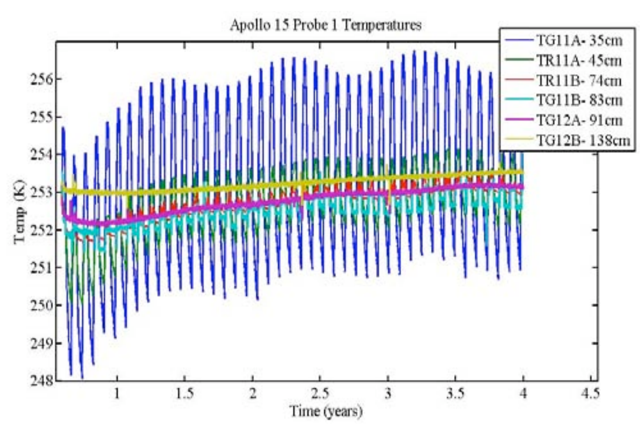

Figure 2: Apollo 15 Heat Flow Experiment probe 1, subsurface temperature measurements. Notice the general upward drift in temperatures over time.

Other possible causes of the long term temperature drift: Beyond some form of instrument failure or degradation, past authors have attributed this drift to either alteration of surface thermal properties by the Apollo astronauts [1-3] or the 18.6 year component of the lunar orbit [5,6, 9].

Surface alterations by the Apollo astronauts were inevitable. The extremely low density surface layer of the lunar regolith compacted easily under astronaut footfalls. This compaction would increase the conductivity of this surface layer, causing heat to flow more readily into the subsurface. This alteration would also cause local variation in the surface albedo, which itself could allow the surface to absorb more solar radiation.

An 18.6 year component of the lunar orbit is believed to cause a slight change in length of day, especially in areas with rugged terrain such as the Apollo 15 and 17 landing sites. Several authors have examined this possibility and its effect on Apollo surface temperatures [5,6], but it is unclear and unlikely [9] that this effect could cause changes on surface temperatures noticeable at depth. However, a full thermal model including topography and cyclical illumination patterns has not been implemented.

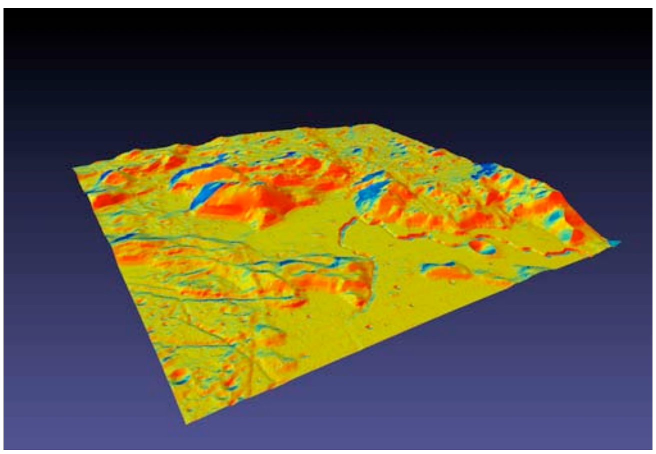

Figure 3: Snap shot from Diviner ray tracing thermal model of the Apollo 15 landing site using a 50m USGS DEM [10, 4].

This Analysis: Using a ray tracing model designed for analyzing Diviner data, we can recreate surface illumination for any given topography and sun position. Combined with modeled near-surface thermal and radiative properties, this model can calculate the incident visible and infrared flux on a given location. We are currently focusing on the Apollo 15 landing site, but this analysis may also be extended to Apollo 17. Detailed Apollo 15 site topography maps (at 50, 10, and 4.5m resolution) [4, 8] allow us to examine both at large scale illumination effects (such as hills blocking illumination) and small scale illumination effects (such as surface roughness) on the Diviner measurements.

This method can be used to calculate the incident visible and infrared flux at a given location for any time period. The derived insolation can be used to force a more detailed model of the heat flow probe and surrounding soil to attempt to recreate the Apollo 15 1971-74 measurement (Figure 2, data available from NSSDC: PSPG-00752). He we present results of a simple 2-dimensional cylindrical finite element thermal model combining radiative heat transfer down the bore stem of the probe and temperature dependent thermal conduction within the lunar regolith.

Once this full framework is implemented, we intend to examine subsurface temperature variations with and without surface thermal property alterations, an 18.6 year orbital cycle, and the thermal effects of the probe itself. If any of these effects play a larger role then envisioned in the thermal properties and heat flow values measured by the Apollo Heat Flow experiments, it may demand an updated model of near subsurface regolith structure.

A model consistent with the Apollo data can then be used as a general reference to predict likely temperatures as a function of depth over the entire measured lunar surface. Implementing these properties into the full ray tracing tools developed for Diviner [10], rock abundance, near subsurface thermal property and dramatic heat flow differences from this regolith model are hoped to be visible in the Diviner data set. The Apollo 15 and 17 landing sites themselves, with mapped rock abundances and soil samples at various locals, will aid in understanding how Diviner measurements vary due to variations from this standard model.

References: [1] Keihm S. and Langseth (1975) Icarus 24, 211-230. [2] Keihm (1984) Icarus 60, 56S-589; [3] Langseth, M. G. et al. (1976) Proc. Lunar Sci. Conf., 7th, 3143. [4] Courtesy Rosiek M., USGS Astrogeology Science Center, http://astrogeology.usgs.gov [5] Saito, Y. (2007) Proc. 38th Lunar Planet. Sci. Conf., Abstract #2197; [6] Saito, Y. (2008) Proc. 39th *Lunar Planet. Sci. Conf.,* 1663; [7] Vasavada A. and Paige D. A. (1999) Icarus 141, 179–193. [8] Courtesy of the LROC team, R. Li et al (2009).[9] Wieczoreck, M, personal communication. [10] Paige et al (2010), in preparation.