A REANALYSIS OF APOLLO 15 AND 17 SURFACE AND SUBSURFACE TEMPERATURE SERIES.

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Introduction: Geophysical packages were deployed on the lunar surface as part of the Apollo program that continuously transmitted data to the Earth until 1978. The Apollo Lunar Surface Experiment Package (ALSEP) at the Apollo 15 and 17 sites contained a heat flow experiment that both monitored surface and subsurface temperatures and conducted thermal conductivity measurements. Analyses of these data placed constraints on the heat flow of the Moon and the near-surface thermal conductivity profile [1, 2].

One important result obtained from these analyses is that the heat flow at the Apollo 15 site is apparently significantly greater than at the Apollo 17 site [1] (21 vs. 16 mW m^{-2}). This had been recognized to correlate with the abundance of near-surface radioactive elements as obtained from orbital gamma-ray measurements made along the equatorial ground tracks of the Apollo Command Service Module [1, 3]. However, it was not until the acquisition of near global measurements from the Lunar Prospector mission that it was realized that incompatible elements were highly concentrated in only a single geologic province [4-6]. In retrospect, unbeknownst to researchers at the time, the Apollo 15 and 17 heat flow experiments were performed in two of the most prominent geochemical provinces of the Moon: the Apollo 15 site lies within the confines of the Procellarum KREEP Terrane, which has elevated abundances of heat producing elements, whereas the Apollo 17 site lies in the more incompatible-poor Feldspathic Highlands Terrane (see Figure 1).

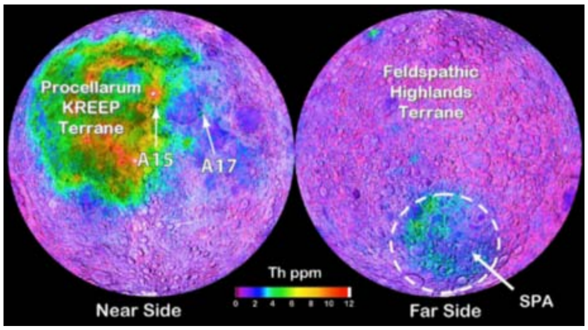

Figure 2. Thorium abundances at the lunar surface as obtained from Lunar Prospector data. Apollo 15 lies within the Procellarum KREEP Terrane, whereas the Apollo 17 site lies within the Feldspathic Highlands Terrane. Modified from [7].

The goal of this project is twofold. First, a reanalysis of the Apollo Heat Flow Experiment data using improved modeling techniques will offer a more precise estimate of the heat flow in the Procellarum KREEP Terrane and Feldspathic Highlands Terrane. Such measurements will help constraint the total abundance of heat-producing elements in the crust at these two sites, and will be crucial for understanding the asymmetric thermal evolution of the Moon (the magmatic activity of the Moon is largely confined to the Procellarum KREEP Terrane). Secondly, as a byproduct of analyzing the surface temperatures, we will attempt to constrain variations in the Sun's total irradiance. Satellite measurements of the total solar irradiance have shown that the solar "constant" in fact varies by ~0.2% with an ~11 year period that correlates with the sunspot cycle [8]. Unfortunately, these measurements only extend back to 1978. If this solar signal can be constrained by the temperature measurements taken at the lunar surface, these data could potentially be used to construct a total solar radiance function extending from 1971 to the present.

Why Should We Reanalyze These Data? In the final publication by the Apollo Heat Flow Experiment team, the lunar heat flow was estimated in a two step approach. First, the thermal diffusivity was estimated by the attenuation with depth of the annual thermal wave. (The annual thermal wave is caused primarily by the orbital eccentricity of the Earth.) Using estimates for the regolith heat capacity and density that were based upon independent analyses of returned Apollo drill cores, the thermal conductivity was constrained. Second, the mean temperature profile was estimated by removing the diurnal, annual, and short-term transient signatures from these temperature series. The heat flow was then simply obtained by multiplying the temperature gradient by the thermal conductivity.

The above analysis can be improved upon in several ways. Most importantly, when calculating the mean temperature gradient, the measured time series were corrected only for diurnal, annual, and short-term transient signals. However, several other periodicities exist, such as the 18.6-year precession of the lunar orbit's longitude of ascending node, and these could potentially have a dominating effect. As an example, Figure 2 shows the maximum predicted surface temperature per lunation for a 19-year time

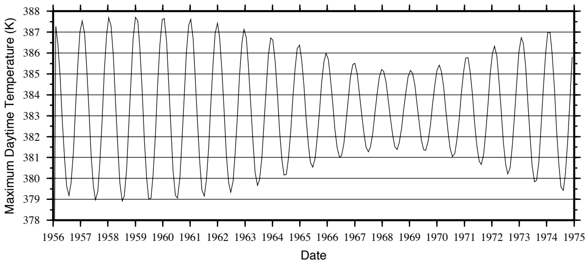

Figure 2. Predicted maximum surface temperatures per lunation at the Apollo 15 site between 1956 and 1975. As a result of the 18-year period for the precession of the lunar orbit, which modifies the maximum solar zenith angle, the amplitude of the annual term is seen to vary by a factor of 2.

span that makes use the JPL DE405 ephemerides. As is readily seen, the amplitude of the maximum surface temperature varies not only annually, but also with an ~18-year periodicity. Annual peak-to-peak differences in maximum temperature vary from ~4 to 8 K—a factor of two variation that will surely affect the subsurface temperature profile, and by consequence, the obtained heat flow.

We propose to improve upon the initial analyses by using a forward modeling approach. In particular, by use of the JPL ephemerides, and knowledge of the surrounding topography, we will first construct a radiation model of the Apollo 15 and 17 sites. Then for an arbitrary thermal conductivity profile and heat flow, the time-dependent thermal conduction equation will be solved over a period that is longer than the major orbital periodicities. By comparing the model results to the observed subsurface temperatures, bounds on both the heat flow and thermal conductivity profile will be obtained.

Surface Temperatures: The first aspect of this project is to develop a radiation model for the Apollo 15 and 17 sites that takes into account (1) direct solar radiation, (2) solar radiation reflected from the surrounding topography, (3) the time variable Sun-Moon separation and geometry, and (4) re-emitted thermal radiation from the surrounding terrain. The accuracy of this model will be tested against thermocouple temperature measurements made in the cables of the heat flow experiment that were left exposed at the lunar surface.

Example temperature series obtained by the surface thermocouples are shown in Figure 2 (color) with the elevation angle of the Sun above the surface (black). Several features are to be noted. First, the maximum temperature readings do not always correspond to the time of solar zenith. This is because the temperature of the thermocouples depends upon the orientation of the cables of which they are embedded. Second, irregularities are seen for specific time intervals that generally correspond to shadowing of the sensor. Third, "bumps" in the temperature series after sunset for Apollo 15, and before sunrise for Apollo 17, correspond to solar radiation reflected off the surrounding terrain.

Conclusions: Lunar surface temperatures are strongly affected by the 18.6-year precession of the lunar orbit. As this signal was neglected in the initial heat flow analyses, the reliability of the obtained heat flow estimates is unclear. Furthermore, as the subsurface temperatures at these two sites were recorded at two different depth intervals, the previously obtained heat flow estimates will not be equally affected by this signal.

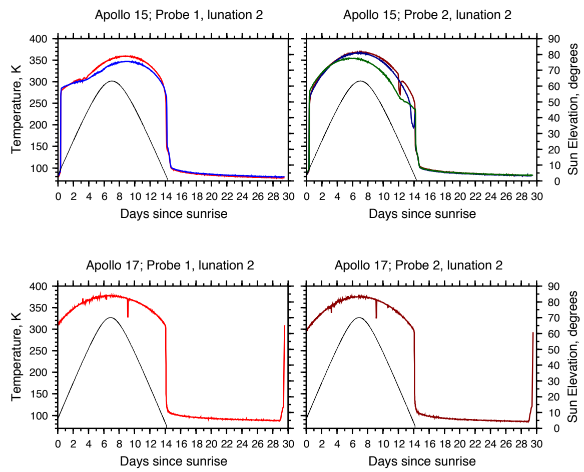

Figure 3. Thermocouple temperatures of cables lying on the lunar surface (color), and elevation of the Sun from the surface (black). Time span is for the second lunation following the ALSEP emplacement on the lunar surface. The solar elevation angle is set to zero if it is below the horizon.

References:

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