Lunar Heat Flow: Global Predictions and Reduced Heat Flux

Matthew Siegler, Seiichi Nagihara, Matthias Grott, Paul Warren, David Paige, Walter Kiefer, Suzanne Smrekar, Mark Wieczorek

Need For Geothermal Heat Flux Measurements: Geothermal heat flow is a fundamental measure of the internal composition of a planet. On the Moon (which has lost much of its heat of formation, is not strongly tidally heated, and is not likely to have strong mantle convection) surface heat flux results predominantly from the subsurface column abundance of radiogenic material (e.g. U, Th, K…). As U and Th are refractory, the concentration of these elements can be directly related to the refractory composition of the bulk planetary body. These elements are also generally incompatible with rock forming minerals, leading them to be strongly partitioned into the lunar crust during the cooling of an early magma ocean. Therefore, while some heat may originate form the core and mantle, a majority of the flux seen at the surface is expected to be a crustal signal. As on Earth, surface heat flux measurements in areas of differing thickness crust may allow constraints on a reduced heat flux, which will allow for a separation of the mantle heat production component.

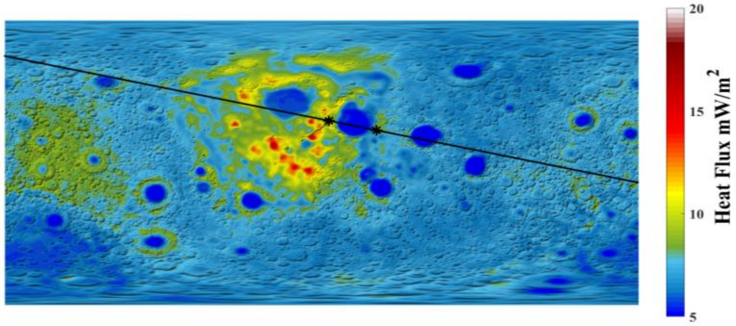

Figure 1: Example global forward model of heat flux from Grail crustal thickness and LP GRS data. The line corresponds to the cross section in Fig 2: Asterisks mark the Apollo 15 and 17 sites.

Lunar Heat Flux Issues: However, the spatial distribution of these elements across the lunar crust has been found to be highly asymmetric. Orbital gamma ray spectrometer data shows most surface rare earth elements are contained in a single region known as the Procellarum KREEP (Potassium-Rare Earth Element-Phosphorous) terrain [Joliff et al., 2000], which is roughly coincident with the near-side mare. Somewhat unfortunately, this anomalous region dominates the near-side landing sites of the Apollo era, including the two heat flux measurements of the Apollo 15 and 17 missions. In Figure 1, the two Apollo sites are marked as black asterisks. These crustal surface measurements are also underpinned by a large theoretical literature [e.g. Laneuville et al., 2018; Siegler et al., 2016] suggesting further asymmetries within the lower crust unseen in surface data.

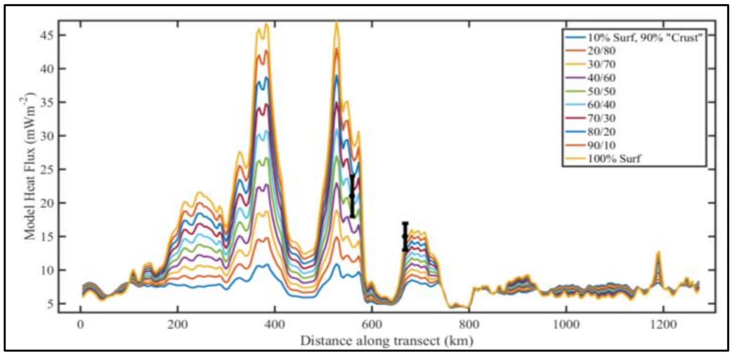

Figure 2: Values of various crustal heat production models across the line connecting the two Apollo heat flow sites in Fig 1.

Global Predictions: A global heat flux network of areas both within and without the Procellarum region would provide a much stronger constraint of the radiogenic composition of the Moon as a whole. Additionally, areas of especially thin crust would help isolate the mantle component of geothermal heat production. Figure 1 gives an example of global expectations for geothermal heat production. This is based on GRAIL constrained crustal thickness values [Wieczorek et al., 2014] and surface measured thorium values from the Lunar Prospector Gamma Ray Spectrometer (LP-GRS) measurements [e.g. Lawrence et al., 2003 with an update from Warren, 2005]. The crust is given nominal parameters as described in Siegler and Smrekar (2015) here with a uniform crustal density of 2800kg/m^3 assumed. We use a relative column abundance of radiogenic materials as mixture of material characterized by the LP-GRS surface Th values and that of feldspathic lunar crust [Wieczorek and Phillips, 2000]. This map shows the resulting heat flux for a 10% GRS and 90% feldspatic mixture. Some lows are due to low GRS Th values, some due to thin crust as constrained by GRAIL. These models assume 4mW/m^2 mantle heat flux.

Model Heat Flux Ranges: Figure 2 shows the resulting heat flux across the transect in Figure 1 for a series of models with simple mixtures where the GRS values represent 10-100% of the crustal radiogenic column abundance. The Apollo 15 site lies at ~550km along this transect with a value of 21+/-3and the Apollo 17 site at ~700km with a value of 15+/-2 W/m^2. One of the apparent issues of the Apollo HFE locations is their location very close to large boundaries in crustal thickness and measured Th (namely because mare flows hide Th in these areas from GRS measurements if present), but assuming they are representative, they already constrain some models (to roughly 40-80% GRS fraction). However, changes in mantle heat flux will cause these model curves to move vertically up and down, leaving mantle vs crustal contribution difficult to separate without further measurements.

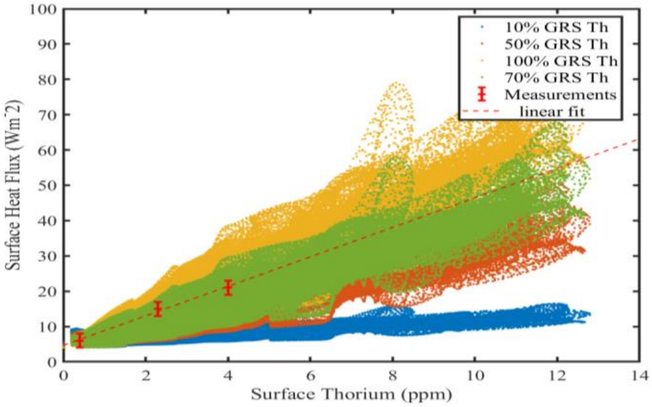

Figure 3: Surface heat flux values vs surface Th value (normalized for crustal thickness) leading to a reduced "mantle" heat flux of ~4mW/m^2.

Reduced Heat Flux: Even on Earth, where we have global heat flux measurements, direct measure of mantle heat flux is not possible. A common technique is to extrapolate a *reduced heat flux*, comparing surface heat producing element composition to surface heat flux for a variety of surface compositions and surface heat fluxes. In Figure 3, we examine how some of the heat production models from Figure 2 plot in this manner, with surface Th values normalized to a 60km crust. Looking at the models in this way, we see a roughly linear relationship between modeled surface heat flux and surface Th. Plotting the Apollo HFE values on this (with an additional 3rd tentative heat flow value of 6mW/m^2 from Diviner lunar South Polar minimum temperatures, Paige et al., [2016]), we can further constrain potential viable models. These results tentatively suggest a model where 70% of the crustal heat production is essentially represented by surface radiogenic abundances with lower heat production deeper in the crust and a mantle heat production in the 3-4mW/m^2 range. Models where the surface heat producing elements represent only a thin veneer (such as the KREEP terrain being Imbrium impact ejecta, e.g. Wieczorek and Phillips, 2000; Siegler and Smrekar, 2015) have difficulty explaining the observed Apollo heat fluxes without hidden lower/sub-crustal heat.

Measurement Recommendations: A landed South Polar mission would provide a measurement in a region feldspatic highlands terrane, which covers about 3/4 of the lunar surface. Additionally, much of this region has relatively thin (~40-50km thick) crust. Ideally, one would measure geothermal heat flux at every point on the Moon. This may be feasible with orbital microwave radiometry (Keihm 1984; Siegler et al., 2017, 2020; 2020 decadal white paper), which can constrain thermal gradients within the upper meters of the lunar surface. Such measurements would be strongest when coupled with ground truth data from several regions with a variety of crustal surface radiogenic compositions and crustal thicknesses, as is planned with the Lunar Geophysical Network (LGN). As a first LISTER probe on the Crisium CLPS lander (which will fall at ~750 km along the transect in Figure 2) will provide a strong constraint on mantle heat production due to its thin crust. An insitu polar measurement (as demonstrated by the Diviner constraint in Figure 3) of heat flux could serve as an endmember for Th poor crust, which dominates much of the lunar polar regions (see Siegler et al., companion white paper). Sites chosen for the LGN, which may be assisted by Artemis nodes, should focus on providing a diversity of crustal thicknesses and surface Th concentrations.

References [1] Lawrence et al., 2003, JGR 108(E9), [2] Wieczorek and Phillips, 2000 JGR 103(E1), 1715-1724., [3] Laneuville et al., 2013 JGR, 118(7), 1435-1452 [4] Jolliff et al., 2000 JGR 105(E2), 4197-4216 [5] Wieczorek et al., 2013 Science 339, no. 6120 (2013): 671-675 [6] Siegler and Smrekar, 2014, JGR 119(1), 47-63 [7] McLennan and Taylor, 1996 The Journal of Geology, 104(4), 369-377. [8] Laneuville, Taylor, & Wieczorek, (2018).*JGR: Planets*, *123*(12), 3144-3166. [9] Paige & Siegler (2016) LPSC [10] Siegler & Feng (2017) LPSC 940 48. [11]Siegler, M. A., Feng, et al. (2020) *JGR Planets*, e2020JE006405 [12] Keihm (1984) *Icarus*, *60*(3), 568-589.