The Importance of Measuring Heat Flux Near the Lunar South Pole

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Introduction: The internal temperature distribution is one of the most important properties in understanding the overall physical state of a planet. Measurements of the heat flow directly measure the amount of thermal energy coming out of a planet in a given region and provide a basis for estimating how temperature varies with depth. Thus, heat flow measurements are an essential part of the geophysical characterization of planetary bodies. On the Moon, in situ measurements of heat flow were made at the Apollo 15 and 17 landing sites [1-3] and are planned to be made in Mare Crisium on the 2023 Commercial Lunar Payload System (CLPS) mission. Measuring heat flow near the lunar South Pole on Artemis would be an important extension of this data set.

Science Rationale: Additional measurements of lunar heat flow would contribute to answering several important questions about the Moon's structure and evolution [4]. (1) *What is the Moon's average heat flow and how does it vary by geologic region? What are the implications for lunar thermal evolution?* Numerous thermal evolution models have been proposed for the Moon, and the Moon's present-day average heat flow is an important discriminant among these models [5-7]. The Apollo 15 and 17 heat flow measurements are unlikely to be representative of the Moon as whole because the measurements were made in a region of enriched crustal radioactivity, the Procellarum KREEP Terrane [8], resulting in measured heat flow that is substantially higher than the Moon's global average [9]. Additional heat flow measurements at widely space locations are needed.

(2) *What is the Moon's bulk abundance of radioactive elements, and how are they distributed between crust and mantle? How does that affect our knowledge of the Moon's origin and evolution?* The radioactive elements U, Th, and K are geochemically incompatible, which means that they preferential partition in magma rather than the residual solid and thus tend to be concentrated in the crust rather than in the mantle. Much of this segregation of radioactivity occurs during the magma ocean phase very early in lunar history. The partitioning of radioactivity between crust and mantle has profound implications for the Moon's long-term thermal evolution, including both the time history and spatial distribution of volcanism and the time evolution of the magnetic dynamo. In addition, it also influences the time at which isotopic closure can occur [10] and thus affects the ability to interpret radiometric age dates.

In order to quantify the partitioning of radioactive elements between crust and mantle, it is necessary to measure heat flow in regions with a range of crustal thicknesses. This makes it possible to determine the "reduced heat flow", which is the heat flow out of the mantle into the crust. This is discussed in greater detail in a separate white paper [11]. The Apollo 15 and 17 heat flow measurements, as well as the planned 2023 CLPS measurement in Mare Crisium, are all in regions of relatively thin crust. In contrast, the Artemis landing site will be on substantially thicker crust [12]. The combined data set will allow separation of heat flow into its crust and mantle components. This will improve our understanding of the Moon's early magma ocean stage, and in combination with modeling will also clarify its long-term thermal evolution.

(3) *How do temperature variations affect the interpretation of seismic velocity and electromagnetic sounding models?* Seismic velocity and electrical conductivity are functions of both temperature and composition [13, 14]. By constraining the thermal state of the Moon's interior with heat flow measurements, we sharpen our ability to interpret electromagnetic and seismic measurements in terms of composition, including for important trace components such as water. In addition, the liquidus temperature of the core depends on composition. Knowledge of the core's physical state from seismology or electromagnetic sounding, combined with temperature constraints, will help to constrain the core's composition, particularly the presence of light alloying elements such as sulfur.

The Value of a South Polar Heat Flow Measurement: An accurate estimate of the Moon's global heat flow requires a set of globally distributed measurements, including measurements in all of the major geochemical provinces. The Moon is sub-divided into four main geochemical provinces [8]: The Procellarum KREEP Terrane (PKT), the South Pole-Aitken basin Terrane (SPA), and the Feldspathic Highland Terrane, which is in turn divided into an anorthositic zone (FHA-A) and an outer zone (FHA-O). Apollo

15 is in the central portion of the PKT and Apollo 17 is near the PKT/FHA-O border. Mare Crisium is in the FHT-O. The Artemis 3 landing site will presumably be on the nearside to simplify radio communication and thus will be near the border of SPA and FHT-O. Moreover, Artemis will be located > 3000 km from any of the other heat flow measurement sites, making it an important contribution to determining the Moon's global heat flow (Figure 1).

An intriguing possibility is to measure heat flow both at the Artemis landing site and in the Schrödinger impact basin, which is planned for a 2024 CLPS lander. Artemis and Schrödinger are in the SPA basin terrane, just a few hundred km apart, and thus likely share a common mantle heat flow component. However, depending on the precise landing site locations, the crust may differ by 20 km in thickness, making these two sites an ideal experiment for separating the mantle and crustal contributions to the heat flow.

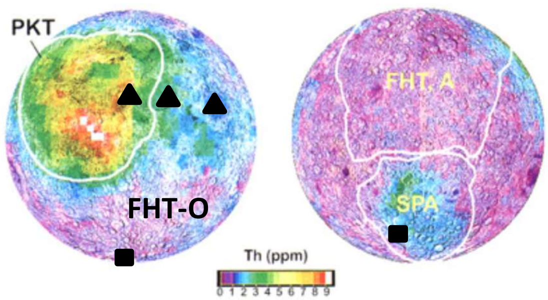

Figure 1: Heat flow measurement locations. Triangles show the locations of the Apollo 15 and 17 and CLPS 2023 measurements. Square indicate locations of possible measurements near the South Pole. Terrane boundaries are based on Jolliff et al. [8].

Measuring Heat Flow: Heat flow, q, is measured as the product of the thermal gradient and the thermal conductivity, q=-kdT/dz. The thermal gradient is measured by making high accuracy temperature (0.01 K) measurements at several depths in a borehole 2-3 meters deep. Thermal conductivity can be measured by measuring the transient thermal response to known perturbations, either using the monthly or annual thermal waves [1] or with an active heating experiment [15, 16]. With a thin thermal probe, thermal equilibrium in an active heating experiment can be obtained quickly [16], although it would also be desirable to measure propagation of the annual thermal wave if the experiment has sufficient lifetime.

There are two options for the heat flow measurement methodology. The first is to deploy a duplicate of the instrument already being developed for the CLPS mission to Mare Crisium [17]. The instrument is a compact, modular system designed for robotic lander missions. It spools out a boom equipped with thermal sensors in a manner similar to a tape measure. Then, the boom penetrates 2 to 3 m into lunar regolith and measures temperature and thermal conductivity at multiple depths. The Artemis astronauts can set the instrument up on a portable platform at the location where they want to take a measurement. Mission control can then remotely operate it. The second option is similar to what was done for the Apollo Heat Flow Experiment [1]. A hole is drilled by the astronauts and then the instrument is lowered into it. In this option, the drill may also be used to collect deep samples for return to Earth [18].

Complementary Measurements: The heat flow measurement may be combined with additional geophysical measurements for greater science return. For example, a co-located magnetotelluric measurement would yield an electrical conductivity profile down through the upper portion of the lunar mantle [19]. Applying temperature correction from the heat flow measurement to the profile would result in a compositional profile. That is the one of the reasons why a heat flow probe and a magnetotelluric instrument are co-manifested for the CLPS mission to Mare Crisium. A co-located seismic observation would also be useful in estimating the thickness of the crust, using receiver functions and comparing it with the estimates from GRAIL [12]. The information on the crustal thickness may be useful in estimating the crust's contribution to the heat flow released through the lunar surface.

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