The Thermal Structure and Evolution of the Moon: Apollo Heat Flow Results, Unresolved Questions, and Future Measurement Objectives

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Introduction: A recent National Research Council report identified eight science concepts that are important drivers for future lunar exploration. Of these, the second highest ranking concept was “The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body” [1]. 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. Moreover, knowledge of the Moon’s thermal structure will contribute to our ability to interpret other geophysical data sets, such as seismic velocity and electrical conductivity variations with depth. Thus, heat flow measurements are an essential part of the geophysical characterization of planetary bodies. Although the results from the Apollo Heat Flow Experiment provide an important starting point for understanding the Moon’s heat flow and thermal structure, important questions remain unresolved.

Apollo Results: Heat flow is measured as the product of the thermal conductivity and the vertical temperature gradient, $q = -k\, dT/dz$. In the Apollo Heat Flow Experiment [2], the thermal gradient was measured using differential thermocouples in boreholes drilled to depths of 1.5 to 3 meters. Thermal conductivity was measured in the same boreholes, both using transient heating experiments and by monitoring the attenuation of the annual thermal wave associated with the eccentricity of the Earth’s orbit about the Sun. Because of the short length-scale associated with the transient heating experiment (a few cm, [2]) and the heterogeneous nature of the lunar regolith, the annual thermal wave measurements are believed to provide the best measurements of average thermal conductivity.

Lunar heat flow was measured for locations along the rims of the Imbrium and Serenitatis impact basins on the Apollo 15 and 17 missions. Attempts to measure the Moon’s heat flow in highland regions (Fra Mauro on Apollo 13, Cayley Plains on Apollo 16) were unsuccessful for reasons unrelated to the actual heat flow experiment packages. Based on monitoring over intervals of 3.5 and 2 years, respectively, the heat flow at Apollos 15 and 17 are 21 and 14 mW m^{-2} [2]. In comparison, the Earth’s globally averaged heat flow is 87 mW m^{-2} [3]. The low value of the lunar heat flow is consistent with its small size, which favors rapid, early cooling of the interior.

Unresolved Questions: Although these results provide a useful first step in assessing the Moon’s thermal structure, important issues remain to be resolved.

1) What is the Moon’s average heat flow, and how does the heat flow vary by geologic region?

Both Apollo measurements of lunar heat flow were made at the boundary between the lunar highlands and the maria. Because of the low thermal conductivity of the lunar megaregolith and the strong difference in megaregolith thickness in these two terrains, it is likely that regions on the boundary between highlands and mare experience a focusing of heat flow. Estimates of the magnitude of this effect have varied substantially, but a perturbation of 15-20% seems likely [2,4,5]. Moreover, the Apollo 15 measurements were made on the periphery of a geochemically unique unit, the Procellarum KREEP Terrane (or PKT, [6]), which orbital geochemistry observations show is highly enriched in thorium and presumable also in uranium [7,8]. Thermal modeling shows that the effect of the high radioactivity in the PKT likely contributes 5 mW m^{-2} to the heat flow at Apollo 15 and could contribute as much as 20 mW m^{-2} to the heat flow in the center of the PKT [9]. Because the Imbrium basin impact occurred in PKT-dominated material, regions with significant thicknesses of Imbrium basin ejecta may also have their heat flows affected by enhanced U and Th abundances in the upper-most crust [10].

2) What is the Moon’s bulk abundance of radioactive elements, and how does that affect our knowledge of the Moon’s origin and evolution?

An important prediction of the giant impact model [11] for the origin of the Moon is that the Moon should have a bulk chemical composition similar to the silicate portion of the Earth. The Moon’s heat flow depends strongly on the abundance of radioactive elements in the interior, particularly uranium and thorium. Based on the Apollo heat flow results, estimates of the Moon’s bulk uranium content range from an earth-like 20-21 ppb [5] to 46 ppb [2]. This range of uncertainty is currently too large to serve as a useful test of the giant impact model. A larger geographic network of measurements is necessary to derive a well-constrained estimate of the Moon's globally averaged heat flow. In turn, this should lead to a more realistic estimate of mantle radioactivity and thus provide a better test of lunar origin models.

3) How do temperature variations affect the interpretation of seismic velocity and electrical conductivity models?

Although the most important control on lunar seismic velocity is the chemical composition, the effect of temperature can not be ignored, with a typical change being about 0.1 km/sec for a 200 ^oC change in temperature [12]. Previous geophysical studies of the Moon's structure have assumed uncertainties in the internal temperature of 250 to 400 ^oC [12-14]. By improving our knowledge of the Moon's thermal structure, a global heat flow experiment would sharpen our ability to interpret results obtained from a lunar seismic network.

Similarly, electrical conductivity profiles that are obtained using electro-magnetic sounding methods [e.g., 15] are also sensitive to both chemical composition and temperature. For example, because the liquidus temperature depends on composition, knowledge of the physical state of the core (from seismology or magnetic sounding) combined with constraints on its temperature will help to constrain the core's composition.

Important Future Measurements: This discussion illustrates the scientific importance of additional, geographically distributed observations to better determine the Moon's average heat flow and thermal structure. In addition to the Apollo 15 and 17 results, measurements should be obtained from the center of a mare basin, for several locations in the highlands (both nearside and farside), and for a location near the center of the PKT unit. Another desirable measurement is from the floor of the very deep South Pole-Aitken basin, where lower crust or possibly even mantle material is exposed at the Moon's surface [16,17]. Combining measurements from all of these various geologic units will lead to a vastly improved knowledge of the Moon's thermal structure.

The proposed new measurements would be made in a manner conceptually similar to those made during Apollo. Huang et al. describe several possible deployment mechanisms for such an experiment [18]. In order to avoid the effects of the large-amplitude diurnal thermal wave, it is essential to make measurements at least 1 meter below the lunar surface. A minimum goal for measurement depth should be 3 meters, which was the design goal for the Apollo Heat Flow Experiment (the actual maximum measurement depth was 2.5 meters on Apollo 17 [2]). Temperature measurements as a function of depth and time need to be made in the 1-2 meter depth range to sample the annual thermal wave (and thus to measure thermal conductivity) and at greater depths to measure the intrinsic lunar thermal gradient. Deeper measurements (~5 meters or deeper) are desirable to minimize the effects of surface thermal variations on the thermal gradient.

In order to use the annual thermal wave to make an *in situ* thermal conductivity measurement, it is necessary for the measurements to extend over at least 2 to 3 years. In addition to the annual thermal wave, there is also an 18.6 year thermal cycle associated with the Moon's orbital precession. The effects of this longer cycle may be observable in a recent analysis of the Apollo Heat Flow Experiment time series [19]. A measurement period that extends over a significant fraction of this cycle (at least 6 years) is desirable. Because thermal perturbations propagate downward with time, measurements over a broad range of depths can be used as a partial substitute for a long measurement time series.

Because heat flow, seismology, and magnetic induction studies all require globally distributed measurements and observation periods of several years, there is considerable scientific and operational synergy in making all three sets of measurements on the same missions [20]. Unlike seismology, however, the heat flow observations do not require simultaneous measurements in a network mission. It is possible to build up the heat flow results one station at a time. Indeed, even a single new heat flow measurement would be a substantial addition to the currently available data set.

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