THE CASE FOR A LONG-LIVED GLOBAL LUNAR GEOPHYSICAL NETWORK - 2: MAGNETIC AND HEAT FLOW DATA.

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Introduction: Geophysical observations made by the Apollo Lunar Surface Experiments Packages or ALSEPs (at Apollo 12, 14, 15, 16, and 17). However, these observation were clustered in the equatorial regions of the Moon on the near side and the same experiements were not carried on each mission.

Therefore, fundamental science questions still remain unanswered: *What is the composition and size of the lunar core? What is the internal structure of the whole Moon? What is the thermal budget of the Moon and how has this impacted its evolution? Did the early Moon have a dynamo and if so, when did it start and when did it stop?* The deployment of a long-lived (≥6 years), global lunar geophysical network will address these questions. This network will use a complementary combination of seismic, magnetic field, and heat flow data. To realize such a network in a timely and cost effective manner, the development of a small, self-contained, multiple-deployment lunar geophysical instrument package is required. Here, we demonstrate the science that can be obtained from a Lunar Geophysics Instrument Package (L-GIP) distributed as a global network across the Moon. The L-GIP will combine a seismometer, heat flow probe, and a surface magnetometer into an integrated suite of instruments that may be deployed by a variety of methods. The science rationale for inclusion of a seismometer has been reported by [1]. Here, we concentrate on the science provided by heat flow and magnetic measurements, especially when combined with seismic data.

Lunar Magnetism: The Moon has no large-scale intrinsic magnetic field although unexpected magnetization of portions of the lunar crust is observed [2-4]. Paleointensity estimates for returned samples indicated the existence of a “high-field epoch" between 3.6 to 3.9 Ga [3,5]. The Lunar Surface Magnetometer (LSM) and low-altitude orbital measurements (Apollo subsatellites, Lunar Prospector) showed that anomalies on the lunar near side correlated often with impact basin ejecta materials [6-10], although none of the LSMs were deployed in any of the large magnetic anomalies (>300 nT). The global distribution of anomalies was characterized by large concentrations of strong anomalies in regions antipodal to the four youngest large impact basins [8,11,12]. Finally, correlative studies have shown that the strongest individual anomalies often occur coincident with unusual albedo markings of the Reiner Gamma class [13,14].

Future LSM deployments should include known sites of strong magnetic anomalies. In particular, deployments at the Descartes mountains and the Reiner Gamma site would address the following specific questions: *What are the sources of lunar magnetic anomalies?* and *What is the origin of the Reiner Gamma-type albedo markings?* The first has implications for the origin of the magnetizing field(s) since deep-seated sources would strongly suggest a core dynamo while surficial, rapidly forming sources would allow transient fields, perhaps generated during large impacts.

The proposed source materials of the magnetic anomaly are exposed at the surface of the Descartes Mountains site, but appear to be buried at the Reiner Gamma site (Oceanus Procellarum). LSM measurements at the former together with existing orbital measurements would constrain the depth of the source as well as the mean subsurface magnetization intensity. Since this site is also characterized by a relatively high albedo, a direct test of the solar wind deflection model (see [15]) for the origin of this albedo marking would be possible if a solar wind detector was included. If there is no solar wind detector on the station, time variations of the surface field intensity for varying solar wind conditions (as measured by existing orbital assets) could still be used to test the hypothesis that a “mini-magneto-sphere” exists at the site [e.g., 15]. For the Reiner Gamma site, if basin ejecta materials are the sources [cf. 8], then they must be buried beneath the visible veneer of mare basalt flows. If a thin surficial layer is the source, then very high magnetizations are implied. LSM measurements together with existing low-altitude orbital data would constrain which of these 2 models is correct. The LSM data would also test whether no significant ion fluxes reach the surface as predicted by the solar wind deflection model for the origin of the albedo markings.

What is the electrical conductivity profile of the Moon? With laboratory conductivity data, an electrical conductivity profile can be used to bound the temperature profile of the deep interior, and thus would integrate with the heat flow and seismic data. The conductivity profile also directly constrains the size of a possible metallic core. For this deep electromagnetic sounding, new simultaneous surface and orbital magnetometer data are required over substantial time periods.

Lunar Heat Flow: Lunar heat flow was measured along the rims of the Imbrium and Serenitatis basins during the Apollo 15 and 17 missions. Based on monitoring over 3.5 and 2 years, respectively, the heat flow at Apollo 15 and 17 sites were 21 and 14 mW m^{-2} [16]. In comparison, the Earth's globally averaged heat flow is 87 mW m^{-2} with variations from ~65 mW m^{-2} (continents) to ~100 mW m^{-2} (oceans) [17]. The low lunar value is consistent with the Moon's small size, which favors rapid, early cooling of the interior. However, important issues remain to be resolved.

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 [16,18], but a perturbation of 15-20% seems likely [19]. Moreover, the Apollo 15 measurements were made on the periphery of a geochemically unique unit, the Procellarum KREEP Terrane (PKT [20]), which is highly enriched in Th and presumably also in U [21]. Thermal modeling [21] shows that the effect of the high radioactivity in the PKT likely contributes 5 mW m^{-2} to the heat flow at the Apollo 17 site and could contribute as much as 20 mW m^{-2} to the heat flow in the center of the PKT.

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 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 U and Th. Based on the Apollo heat flow results, estimates of the Moon's bulk U content range from an earth-like 20-21 ppb [19] to 46 ppb [16]. This range of uncertainty is currently too large to serve as a useful test of the giant impact formation hypothesis.

How do temperature variations affect the interpretation of seismic velocity models? An important objective of future lunar geophysical observations is to measure the Moon's seismic velocity profile as a function of radius and to interpret the results in terms of the Moon's chemical and physical structure. Although the most important control on lunar seismic velocity is the chemical composition, the effect of temperature cannot be ignored. A typical change in velocity is about 0.1 km/sec for a 200˚C change in temperature [22]. Previous geophysical studies have assumed internal temperature uncertainties of 250-400˚C with increasing depth [22-24]. Improving our knowledge of the Moon's thermal structure will improve our ability to interpret the seismic data.

The inclusion of heat flow in the L-GIP is crucial to resolve the above issues. The addition of lunar heat flow measurements from different terranes will also improve our understanding of the energy processes near the suface of the Moon including exploration-indeced thermal perturbations.

In addition to the currently available results, measurements should be obtained from: the center of a mare basin; several locations in the highlands (nearside and farside); for a location near the center of the PKT unit; the floor of the very deep South Pole-Aitken basin. Combining measurements from all of these various geologic units will lead to a vastly improved knowledge of the Moon's thermal structure.

Heat flow, seismic and magnetic data have considerable synergy for our understanding of the lunar interior. Combining complementary geophysical instruments to obtain such data in a single modular package, that can be deployed multiple times and networked, followed by long-term data acquisition for (≥6 years), will lead to a greatly enhanced understanding of the lunar interior as well as yielding critical information needed for the safe location and construction of any lunar habitat facility.

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