**PLANETARY HEAT FLOW MAPPING FROM ORBIT.** P. O. Hayne[1], M. A. Siegler[2], D. A. Paige[3], T. Reck[1], S. Piqueux[1], [1]NASA – Jet Propulsion Laboratory, California Institute of Technology (Paul.O.Hayne@jpl.nasa.gov), [2]Planetary Science Institute, [3]University of California, Los Angeles

**Introduction:** Heat flow is a fundamental quantity in planetary science, because it is a signature of a body's formation, interior structure, and dynamics [1]. Primordial materials forming the planets and their satellites produce heat through gravitational accretion and radioactive decay. Heating may be sufficient to initiate convection and interior differentation into a core, mantle, and crust. On Earth, heat flow is spatially variable due to crustal composition, plate tectonics, and volcanism. On the Moon, segregation of radiogenic elements in the crust, particularly the nearside Procellarum terrane, may have also resulted in spatially heterogeneous heat flow [2]. Mars boasts a massive volcanic complex (Tharsis rise) which may overlie a persistent mantle hot spot. However, very few heat flow measurements have been performed to test predictions of planetary formation/evolution models [3].

*Potential Advantages of Orbital Heat Flow Mapping.* Historically, heat flow has been measured using thermometers placed in the ground at different depths surrounding a material of known conductivity – a technique that has been applied on the Earth, Moon [4], and soon with the InSight mission, Mars [5]. However, this approach requires landing on the surface and drilling to make physical contact with the subsurface, adding significant cost and risk. Furthermore, a distributed network of heat flow probes would be critical to identifying the underlying geophysical mechanisms involved (Fig. 1). If it were possible to detect heat flow from orbit, these measurements (combined with ground-truth from missions like InSight) would pioneer a new way to study the interiors of the planets, at dramatically lower cost.

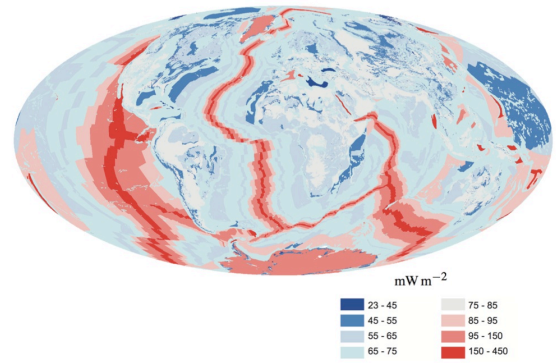


Figure 1: Global heat flow of the Earth, showing variations of ~0.5 W m$^{-2}$ at this scale. These variations are primarily due to plate tectonics driven by mantle convection. Figure from [9].

**Background:** The possibility of measuring planetary heat flow from orbit was first seriously considered by *Keihm* (1984) [6]. He studied the sensitivity of microwave emission from the Moon to variations in interior heat flow, finding that this technique would yield a marginal detection for the heat flow values measured at the Apollo landing sites, ~15 – 20 mW m$^{-2}$. However, these equatorial sites are subject to large diurnal surface temperature cycles, which complicate the extraction of the heat flow signature (Fig. 2).

An alternative approach was proposed by *Paige et al.* (2010) [7], using the extremely cold permanently shadowed regions (PSRs) at the lunar poles: in the absence of direct insolation, interior heat flow can be a

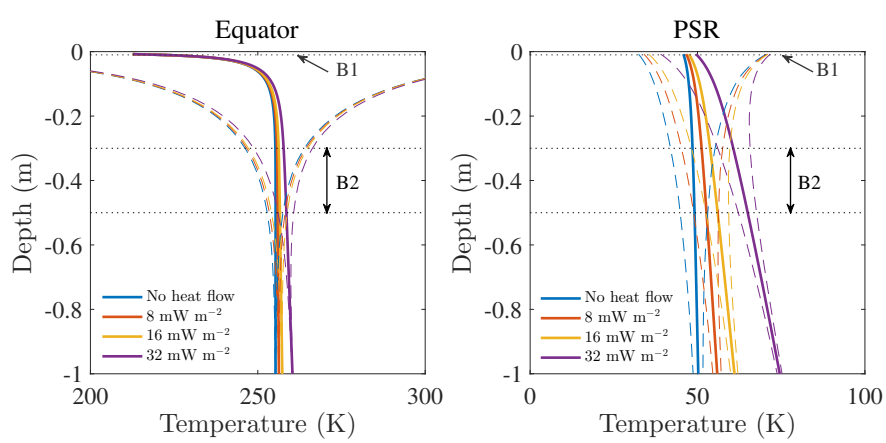


Figure 2: Thermal model [12] results for the Moon showing temperature profiles over one complete diurnal cycle at the equator (left) and in permanent shadow (right). Heat flow is much more easily detectable in the PSRs using the temperature difference between two spectral channels making short-wave ("B1") and long-wave ("B2") radiometric measurements of emission at two different depths. This is because surface temperature variations are much smaller, and thermal conductivity is nearly constant.

significant contribution to the surface energy budget. Using data from the Diviner Lunar Radiometer onboard the Lunar Reconnaissance Orbiter (LRO), the Moon's heat flow at the poles has been constrained using this technique to be < 10 mW $m^{-2}$. This is much lower than the values for the Apollo sites, likely due to concentrations of radiogenic elements on the lunar nearside [2,8]. Thus, the Diviner measurements reveal a primary feature of the lunar crust and interior evolution, without having touched the surface.

**Proposed Technique:** We suggest that future missions could map heat flow on solid planetary bodies using a combination of the two techniques described above: 1) microwave radiometry, and 2) targeting low-temperature surfaces using infrared and/or microwave measurements. Next, we outline the advances needed to accomplish this goal by 2050.

*Advances Needed in Planetary Science.* Knowledge of surface temperature cycles driven by insolation is critical to interpreting the microwave emission spectrum, especially at higher frequencies. Dedicated surface temperature mapping investigations like the one perfomed by Diviner for the Moon would also reveal the presence of PSRs, which can be utilized for bodies where the equatorial energy budget is dominated by insolation. Detailed knowledge of thermal conductivity can also be derived from surface temperature measurements and complementary techniques such as radar.

*Advances Needed in Technology.* A two-channel radiometer accurate to less than 1 K brightness temperature is needed. Spacing in wavelength between the channels should be maximized to increase the difference in depths measured by the radiometer. *Keihm* (1984) [4] found that wavelengths 15–50 cm were optimal for measuring lunar heat flow near the equator, so an instrument similar to Juno's Microwave Radiometer [10] could be used. Miniaturizing this type of instrument would be limited by the antenna aperture size for the long-wavelength channel and the power consumption and sensitivity of the short-wavelength channel. A low-power CMOS synthesizer could save the system several watts of power. To avoid bulky, power-hungry optical flip mirrors for calibration, a compact waveguide calibration switch can also be applied to the system. These are innovations with a clear technology development path.

**A Vision for 2050 and Beyond:** Orbital heat flow mapping will be a critical component of future combined surface- and orbital-based geophysical networks. Synergistic heat flow, gravity, and magnetic measurements of the terrestrial planets and icy satellites will provide a clearer picture of planetary interiors. Global heat flow measurements will also constrain the factors

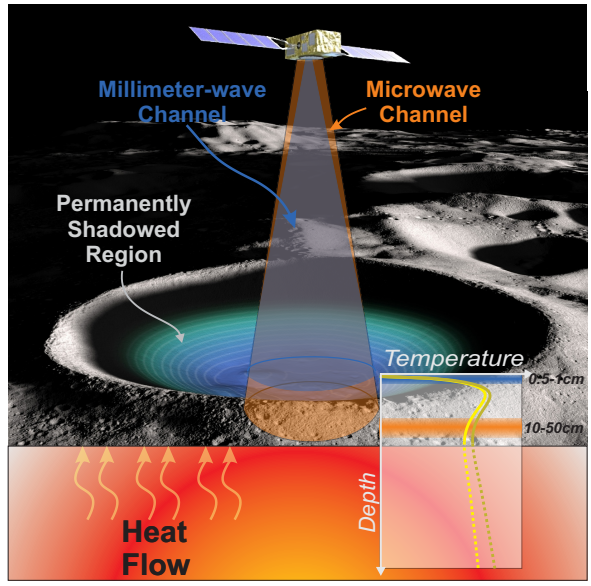


Figure 3: Concept for remote measurement of heat flow using microwave radiometry. Within permanently shadowed regions (PSRs) at the poles of a planet, surface and subsurface temperatures are sensitive to small variations geothermal heat. On some planets, similar sensitivity may be achieved outside of the PSRs.

behind the onset of plate tectonics, which may be a critical factor in planetary habitability [11]. Mapping heat flow on the icy satellites will reveal recent or ongoing activity, tidal dissipation, and will constrain the depths to subsurface oceans. Mars will also be a compelling target for orbital heat flow mapping, due to its higher expected heat flow than the Moon and a pervasive insulating dust layer. Thus, if successfully demonstrated, the orbital heat flow technique has the potential to provide a fresh new window on planetary interiors.

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