WATER OR ICE: HEAT FLUX MEASUREMENTS AS A CONTRIBUTION TO THE SEARCH FOR WATER ON MARS

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The thermal structure of the upper crust of Mars is an important component of the search for water on Mars: if water is present, is it liquid or solid? Measurements of the surface heat flux, combined with a model for the increase of thermal conductivity with depth and the heat conduction equation, can be used to predict the thermal structure of the crust as a function of depth.

Experimental Methods

Estimates of the present-day mean surface heat flux on Mars are in the range 15 to 30 $\mathrm{mW\,m^{-2}}$ [1,2]. Finite element mantle convection simulations suggest that there can be lateral variations of about 50% relative to the mean value [3]. The thermal conductivity for an intact basaltic crust is in the range 2–3 $\mathrm{W\,m^{-1}\,K^{-1}}$ [e.g., 4]. For a granular regolith, the thermal conductivity would be significantly reduced [5]. On the Moon, the measured thermal conductivity in the Apollo 15 and 17 boreholes is 0.009 to 0.013 $\mathrm{W\,m^{-1}\,K^{-1}}$ [6]. If lunar-like thermal conductivities occur in the martian regolith, thermal gradients could exceed 1 K/meter in the upper several meters of the regolith.

In marine geophysics, heat flux is measured using probes about 6 meters long. Themistors are located at spacings of 1 meter, each with a measurement accuracy of about 1 mK [7]. The resulting thermal gradient has a measurement accuracy of 0.2 K/km. The thermal conductivity is also measured *in situ* (see below); the heat flux is determined as the product of the thermal gradient and the thermal conductivity. On Mars, it is unlikely that a 6 meter long probe will be feasible during the first measurements. However, it will be desirable to make measurements over the largest practical depth range to increase the accuracy of the thermal gradient measurement. A deep measurement would also get below the immediate surface layer, where the seasonal thermal wave is strongest and the regolith's thermal conductivity probably has its greatest variability. The accuracy of thermistors on a martian heat flux probe may depend on how the probe is emplaced; thermistors designed for use on a penetrator probe might not be as sensitive as those used in terrestrial studies. Assuming a 3 meter long probe and 3 mK measurement accuracy for the thermistors, the thermal gradient could be measured to an accuracy of 1 K/km on Mars.

The thermal conductivity can be measured *in situ* by measuring the transient response to energy input from an electrical heater. This approach works very well in marine geophysics [7]. This was also attempted on the Moon but was not very successful due to the variability of thermal conductivity in the upper part of the regolith. A better approach on the Moon turned out to involve measuring the thermal wave associated with the month-long "day-night" thermal cycle [6]. The martian experiment should include the capability to perform transient heating measurements of thermal conductivity. However, it will also be desirable to make measurements over most or all of a Mars year so that measurements of the seasonal thermal wave can be used to constrain the thermal conductivity. The energy dissipated during probe emplacement (whether by drilling or penetrator) will cause a temporary heating of the probe site. Measuring the transient cooling from this event might also be a way to constrain the conductivity, but further analysis of this approach is needed. With measurements of both thermal gradient and thermal conductivity at the surface, one can use the heat conduction equation to estimate temperatures at greater depths. The thermal conductivity will increase with depth due to the closing of pore space with increasing pressure. Other geophysical methods (seismic, electro-magnetic sounding) may be used on the same mission to characterize regolith and crustal structure. By constraining porosity as a function of depth, such experiments may contribute to estimates of how thermal conductivity increases with depth.

In addition to the thermal wave associated with the annual seasonal cycle, there will also be thermal waves associated with climate variations due to long-term orbital and rotational variability. Observational characterization of these climatic fluctuations would require drilling to depths exceeding a kilometer. While that is a worthy goal for future climate studies of Mars, it will not be feasible on robotic missions. Removing the effects of these long-term climatic fluctuations from the heat flux data will require theoretical modeling that builds on existing studies [8].

Experiment Emplacement Mechanisms

The proposed experiment requires measurements taken at least one to a few meters below the surface. Two different experiment emplacement mechanisms deserve consideration, insertion of a probe in a drilled borehole, and insertion as part of an impact penetrator probe. Use of a drilled borehole has the potential advantage of a relatively long measurement probe. By increasing the measurement depth range, the thermal gradient and hence the heat flux can be measured with greater accuracy. Also, a probe attached to a surface lander has the potential for a relatively long measurement lifetime. This would allow time for the thermal anomaly associated with drilling to decay and for the seasonal thermal wave to be accurately measured and separated from the background heat flux. On the other hand, robotic drilling to depths of several meters may be quite difficult - at two of the three sites where deep drill holes were made on the Moon, the drilling turned out to be unexpectedly difficult, even with the support of a human crew [9]. In addition, the expense of soft landers means that this approach to heat flux measurements will be possible at no more than a few locations.

The alternative approach is to emplace the experiment using an impact penetrator, similar to the Deep Space 2 microprobes. This should have lower costs per spacecraft, allowing heat flux measurements to be made at a larger number of locations. However, the experience with the Deep Space 2 probes shows that penetrators remain a high risk technology. The limited length of such penetrators (the DS2 probes were 0.6 meters long) sets a lower limit on the uncertainty in the thermal gradient and hence in the heat flux. If penetrators are used for this purpose, it will be necessary to measure the inclination of the penetrator from the vertical so the vertical component of the thermal gradient can be accurately determined. Another concern with this method is the possibility of a very short mission lifetime. For heat flux measurements to be useful, they must be made over a sufficiently long period of time that the background thermal flux can be distinguished from heating due to mechanical dissipation of energy during penetrator emplacement and from the seasonal thermal wave.

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