HEAT FLOW, THERMAL CONDUCTIVITY, AND THE PLAUSIBILITY OF THE “WHITE MARS” HYPOTHESIS.

M. L. Urquhart¹ and V. C. Gulick², ¹NASA Ames/NRC (MS 239-20, NASA ARC, Moffett Field, CA, 94035, murquhart@mail.arc.nasa.gov), ²NASA Ames/SETI Institute (MS 239-20, NASA ARC, Moffett Field, CA, 94035, vgulick@mail.arc.nasa.gov).

Introduction: The controversial “White Mars” model proposed by Hoffman [1] suggests that the fluvial erosional features on the surface of Mars were created by CO₂ debris flows rather than water. This is in sharp contrast to the view long-held by the majority of the Mars research community that the outflow channels, longitudinal valleys, and valley networks on the Martian surface were carved by water. A critical component of the “White Mars” hypothesis is that the near-surface crust of Mars is cold and dominated by CO₂ (solid and liquid) and CO₂ clathrate, with liquid water confined to the deep subsurface. Under this scenario, surface or near-surface access to reservoirs of liquid water is severely limited. Here we examine Hoffman’s thermal assumptions regarding the Martian crust and how CO₂ ice or clathrate in place of water ice would affect the temperature structure of the subsurface.

The temperature at a given depth in the Martian crust below diurnal and seasonal thermal waves is roughly determined by the mean annual surface temperature and the thermal gradient. The thermal gradient is defined by the heat flow out of the Martian interior (Q) and the thermal conductivity (κ) as given in equation 1.

\[
\frac{dT}{dz} = -\frac{Q}{\kappa} \quad (1)
\]

The mean annual surface temperature is a function of both latitude and albedo. Assumptions regarding both Q and κ can have a dramatic impact on the predicted depth to liquid water.

Heat Flow: Various researchers have made estimates of Martian heat flow throughout its history. Theoretical globally averaged values for present day range from a low of 15 to 25 mW/m² [2] to a high of 45 mW/m² [3]. Most estimates fall between 30 and 40 mW/m², and 30 mW/m² is frequently adopted as a moderate value. Hoffman [1], in contrast, uses a value of 20 mW/m². For comparison purposes, measured globally averaged values for the Earth and Moon are 82 mW/m² [4] and 14-18 mW/m² [5] respectively.

The difference between a Q of 20 mW/m² and the more commonly used value of 30 mW/m² can be seen in Figure 1. By reducing Q by 50%, melting of pure water is predicted to occur at a 2 km greater depth.

Heat flow will decrease with time due to loss of the initial energy of accretion (within approximately the first 0.5 Gyr after formation) and heat from the decay of radioactive elements. During the first billion years or so of its history, Mars would have had substantially higher heat flow than at the present, with typical model cooling histories predicting approximately 120 mW/m² at 1 Gyr and substantially higher values in the first 0.5 Gyr.[6]. In the mid to late Hesperian, when the bulk of outflow channel formation occurred [7], models of cooling histories predict globally averaged heat flow to be at more than twice current levels[6]. Depths to melting for water would have been correspondingly higher in the past. Hoffman [1] does allow for a thermal gradient twice as high for “early Mars”, which is consistent with models of cooling history during the Hesperian rather than early Mars. However, this has only a modest impact on the subsurface temperatures of his model, in part due to his assumption of lower surface temperatures.

Thermal Conductivity: The thermal conductivity of Martian crustal materials will depend upon a variety of factors. Particle size, bulk density, the presence of volatiles, and temperature all play a role in the ability of a material to transport heat. Dry silicate materials under Mars atmospheric pressure exhibit a range of
possible thermal conductivities covering approximately two orders of magnitude. Fine-grained particulates have the lowest values and solid rock has the highest values. Variations in composition between silicates have only a minor effect.

The addition of even a small amount of water ice can significantly raise the thermal conductivity of particulate silicates. Mellon et al [8] quantifies the effect of ice in-fill in pore spaces using the following relationships:

\[ \kappa = \frac{\kappa_w \kappa_i}{(1 - \varepsilon_0) \kappa_i + \varepsilon_0 \kappa_w} \]  \hspace{1cm} (2)

\[ \kappa_i = (1 - f_A) \kappa_{i0} + f_A \kappa_{ice} \]  \hspace{1cm} (3)

Where \( \varepsilon_0 \) is the dry porosity, \( \kappa \) is the bulk conductivity of the particulate medium, \( \kappa_w \) is the conductivity of the solid grains, and \( \kappa_i \) is the conductivity of the space between grains, and \( \kappa_{i0} \) is the ice-free interstitial conductivity. The term \( f_A \) is equivalent to the square root of the fraction of the pore space which is filled with ice.

Using equations 2 and 3, it is clear that when ice fills as little as 10\% of the total volume of a fine dust with \( \kappa = 0.02 \) W/m-K, the thermal conductivity of the bulk material increases to nearly 2 W/m-K, which is also a reasonable value for dense basaltic rock. A value of \( \sim 2 \) W/m-K is frequently adopted for a column-averaged thermal conductivity for the Martian crust. [i.e. 9, 10], and was also used in the “White Mars” model.

The addition of CO\(_2\) ice or clathrate in place of water ice will not have the same impact on the thermal conductivity of the bulk material. Water ice has a substantially higher thermal conductivity than does either CO\(_2\) ice or CO\(_2\) clathrate hydrate [11]. Once again we have used equations 2 and 3. At 220 K, we find that replacing 10\% by volume of water ice with CO\(_2\) ice or clathrate will raise \( \kappa \) to 0.5 W/m-K. Completely filling the pore space will raise \( \kappa \) to only 0.8 W/m-K. Such a significant decrease in \( \kappa \) will have a dramatic impact on the subsurface thermal gradient, as shown in Figure 2. This would especially apply to the near-surface, where the crust is likely composed of ice-cemented particulates. The column-averaged thermal conductivity used in a model with a significant fraction of CO\(_2\) ice or CO\(_2\) clathrate should be lower than the commonly adopted value of 2 W/m-K in order to be self-consistent.

**Figure 2:** A comparison of the depth to melting at the equator for different assumed values of column-averaged thermal conductivity. Line \( \alpha \) assumes a thermal conductivity of 2 W/m-K appropriate for both ice-cemented regolith and solid basalt, whereas line \( \beta \) assumes a thermal conductivity of 0.8 W/m-K representative of a CO\(_2\)/clathrate cryosphere. Even using \( Q = 20 \) mW/m\(^2\), melting of water ice would occur at less than 3 km. Both assume a mean annual surface temperature of 218 K and a heat flow of 20 mW/m\(^2\).

**Conclusions:** Hoffman’s choices of heat flow are possible, but are at one end of parameter space - the end most favorable to a very cold Martian subsurface for which on a global scale liquid water will be confined to the deep crust. However, if CO\(_2\) ice and clathrate are assumed to be present in large quantities, as they are for “White Mars”, then the typically adopted value for the column-average crustal thermal conductivity of 2 W/m-K no longer valid. Contrary to the predictions of “White Mars” [1], the steeper thermal gradient would allow liquid water to be stable at depths closer to the surface than it would be beneath a crust containing substantial amounts of water ice. (Note that CO\(_2\) ice and clathrate will also be less stable at these higher temperatures.) Even if Hoffman’s assumptions of heat flow and a CO\(_2\)/clathrate cryosphere are correct, liquid water will not be confined on a global scale to the deep subsurface today, and certainly would not have been in the distant past. Based purely upon accessibility to subsurface fluid reservoirs, Martian channels and valley networks would be as likely to have formed by liquid water under this scenario as they would for the more standard model with a water-ice cryosphere.