ICE STABILITY ON PSYCHE AND IMPLICATIONS FOR THE PLANETARY CORE HYPOTHESIS

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Introduction: Psyche, one of the largest objects in the asteroid belt, may represent the exposed core of an ancient planetesimal. This hypothesis is formed on the basis of its high density [e.g., 1–3], high thermal inertia [4], bright radar albedo [5, 6], and spectroscopic analysis [7], all of which suggest a world composed nearly entirely of metal. Alternatively, Psyche may not be an ancient core, but an accreted pile of primordial metal-rich material. A NASA Discovery-class mission will visit Psyche in 2030 to test these hypotheses [8].

Recent spectral analysis using the NASA Infrared Telescope Facility has discovered a 3 μm absorption feature on Psyche [9]. The nature of this feature is ambiguous, and could imply the presence of adsorbed water, ice, or hydrated minerals. This result implies either (a) endogenic presence of water at some point in Psyche's past (perhaps analogous to Ceres, where hydrous modification of the near surface geology has occurred [10]), or (b) exogenic infall of hydrated material (perhaps analogous to Vesta, where dark material represents carbonaceous impactors [11]).

Adsorbed surface water molecules in theory could be continuously supplied by buried ice. We test the endogenic vs. exogenic cases by exploring the implications and plausibility of ice on Psyche. We use thermal models to simulate temperatures and quantify ice stability as a function of location on the surface, time of year, and depth. Our work is similar to pre-Dawn simulations of ice stability on Ceres [e.g. 12], however, we expect significantly different results due to Psyche's high thermal inertia, high obliquity, high eccentricity, and non-spherical shape. Our predictions will allow for interpretation of observations of Psyche from robotic spacecraft [8] in regards to how any direct or indirect detections of H, or lack thereof, would lend evidence for or against the planetary core hypothesis.

Thermal Results: We simulate temperatures using a 1D semi-implicit thermal model that accounts for surface energy balance, blackbody radiation, and thermal conduction through subsurface layers. For Psyche, we use an albedo of 0.12, an emissivity of 0.9, eccentricity of 0.14, obliquity of 95°, argument of perihelion 228°, and no geothermal heat flux. We consider the two end-member allowable thermal inertias, as observed by terrestrial telescopes [4]: 74 and 173 J m^{-2} $s^{-0.5}$ K^{-1}. For comparison, we also estimate temperatures for Ceres (albedo of 0.09, emissivity of 0.9, eccentricity of 0.0758, obliquity of 4°, and no geothermal heat flux).

Because sublimation of volatiles is extremely sensitive to temperature, annual maximum temperature largely controls stability at the surface. We show results for annual maximum temperatures as a function of latitude in Figure 1, assuming Psyche is a sphere. Maximum temperatures on Psyche range from 203–244 K depending on thermal inertia and latitude, whereas maximum temperatures range from 118–243 K on Ceres. Ceres has a classical temperature distribution: warmest near the equator and coldest at the poles. Psyche's temperature distribution is unusual because of its high eccentricity and obliquity: the coldest maximum temperatures are at latitudes 20°–30° N.

In contrast to surface ice, subsurface ice is protected by overlying material that dampens thermal waves, and subsurface ice stability is largely controlled by annual average temperature at the surface. We show results for Psyche's annual average temperatures in Figure 1, which vary from 122–152 K (67–157 K for Ceres).

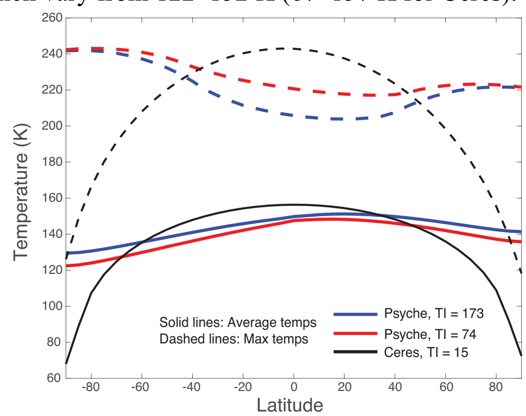

Figure 1. Annual-average and annual-maximum surface temperatures on a spherical Psyche and Ceres as a function of latitude and thermal inertia (SI units).

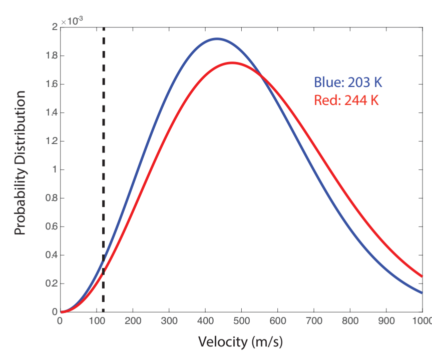

Figure 2. Velocity distributions of sublimated H_2O molecules for the range of maximum temperatures we calculate for different latitudes on Psyche. Vertical dashed line represents Psyche's escape velocity.

Ice Stability: Our thermal model results (Figure 1) show that any surficial ice would not be stable over long timescales under normal conditions on Psyche. Furthermore, because of Psyche's high obliquity, permanently shadowed regions within craters that can preserve ice (like those on Ceres [13]) are not possible on Psyche. Therefore, we expect ice to not be stable anywhere on Psyche's surface; for example, in our coldest scenario (thermal inertia of 173 J m^{-2} $s^{-0.5}$ K^{-1} at 20° N, see Figure 1) water ice sublimates at a rate of 18 kg/m^2 each Psychean year. Furthermore, any sublimated ice is quickly lost to space due to Psyche's small escape velocity (~120 m/s), with >98% of sublimated H_2O molecules lost as soon as they leave the surface (Fig. 2).

Although ice is not stable on Psyche's surface, it may exist in the shallow subsurface. To quantify the depth at which ice may be present, we ran an ice retreat model in which Psyche's initial state contains ice everywhere below 3 cm of a dry surface. After 4.5 Gyr of sublimation, ice retreats to depths of cms–10s of m, depending on latitude, the volumetric mixing ratio of regolith and ice, and thermal inertia (Figure 3).

We are continuing to refine our model by incorporating the non-spherical shape [6] of Psyche.

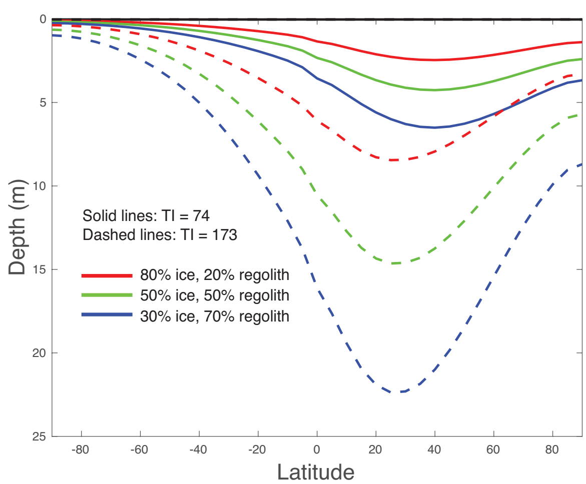

Figure 3. Depth to ice on Psyche after 4.5 Gyr for various regolith-to-ice mixing ratios and two surface thermal inertias.

Implications for Psyche as a planetary core: If Psyche is the exposed metallic core of an ancient planetesimal, it is expected to be anhydrous. However, the presence of hydration features does not necessarily imply that Psyche is not a core because water or carbonaceous material could have accreted late after Psyche's initial formation. Our work provides a framework with which to interpret the direct detection, indirect interpretation, or lack of identification of ice or hydration features on Psyche from a spacecraft mission [8]:

1. If no evidence for ice or hydrated features are found on Psyche, an alternate explanation, such as solar wind-implanted H, for the detection of [9] will be required. This scenario is consistent with Psyche as a planetary core or as primordial metals accreted from the inner solar system.
2. If surface water ice is exposed on Psyche, our thermal models show it must be recently exposed, perhaps by impacts (a 1-m-thick pure ice deposit on Psyche would sublimate away completely in ~250 years). Such surface ice does not constrain Psyche's origin by itself.
3. If Psyche has a subsurface distribution of H that is different from our predictions for retreat of a global ice table (Fig. 3), an exogenic source for the detections of [9] is plausible. Such a scenario implies water was not an important component in Psyche's formation, consistent with the planetary core hypothesis.
4. If Psyche has a subsurface distribution of H consistent with predictions from our ice retreat models (Fig. 3), the most direct explanation is that Psyche formed with water as an important component, which sublimated into its current state after 4.5 Gyr. This scenario lends evidence against the planetary core hypothesis. Similar observations [10] successfully matched predictions [e.g., 12] on Ceres.

Conclusions: Given radar observations [6] and the lack of stability we have shown for surface ice on Psyche, we favor option (3) above, where the detection of [9] is attributed to exogenic infall of hydrated material. However, we cannot entirely discount the possibility of subsurface ice as deep as ~25 m that continuously supplies water molecules through an overlying regolith layer, where they adsorb to surface material before being lost from Psyche, causing the detections of [9]. NASA's mission to Psyche [8] can distinguish between these two cases using its gamma ray and neutron spectrometer, which can confirm or rule out the shallow ice-regolith mixture at the south pole (Fig. 3).

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