Ice stability on Psyche and implications for the planetary core hypothesis

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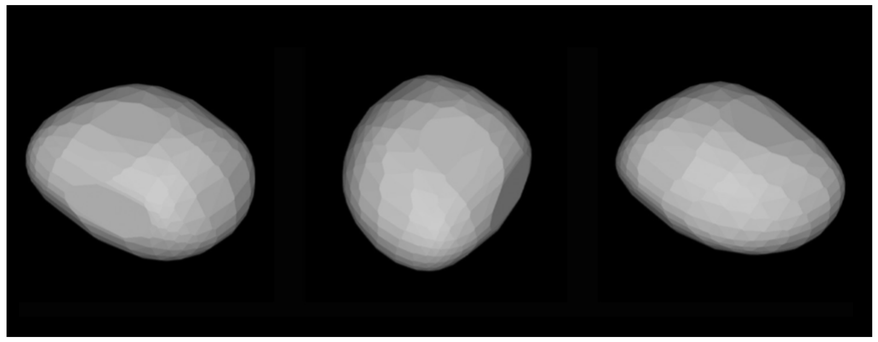
Attributes of Psyche (the asteroid)

Psyche, one of the largest objects in the asteroid belt, is hypothesized to be the exposed metal core of a planetesimal. This idea is largely driven by 3 attributes of Psyche inferred from telescopic observations:

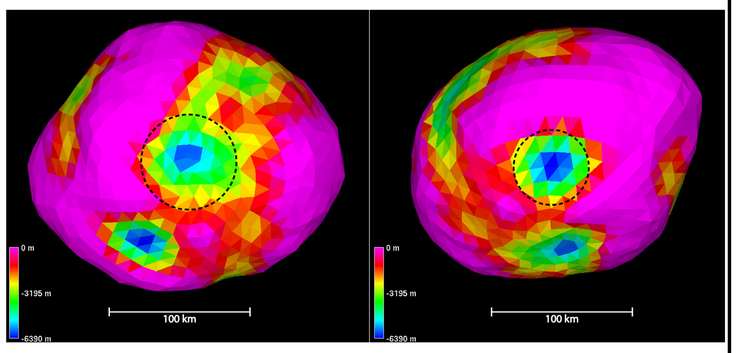
1. High density, [e.g., 1–3]
2. High thermal inertia, 120 J m^{-2} K^{-1} $s^{-0.5}$ [4]
3. Radar albedo consistent with metal [5, 6]

Any model of Psyche's structure must match these observations. We also note a 4th observation of potential importance, the detection of orthopyroxene [7].

These attributes are consistent with the planetary core hypothesis, but there are two observations that may complicate this idea. We address them here.



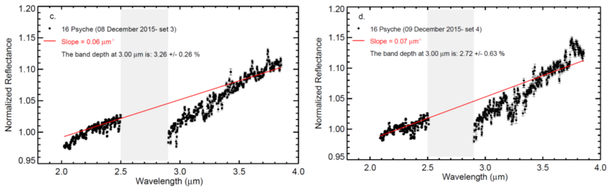
Above: The most recent shape models of Psyche [6] reveal a non-spherical world of dimensions 279 x 232 x 189 km.



Above: Shape models [6] reveal the presence of two craters. Here, we call them "Id" and "Ego." They have diameters 53 ± 15 and 67 ± 15 km respectively.

Complication 1: Water/hydroxyl detection

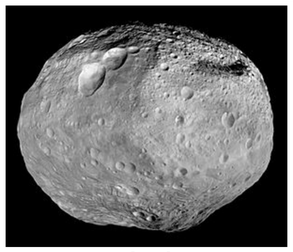
Recent spectroscopic analysis [8] has revealed an absorption feature characteristic of water or hydrated minerals. What does this signature imply about Psyche's composition?



Left: Detection of water or hydrated minerals from [8].

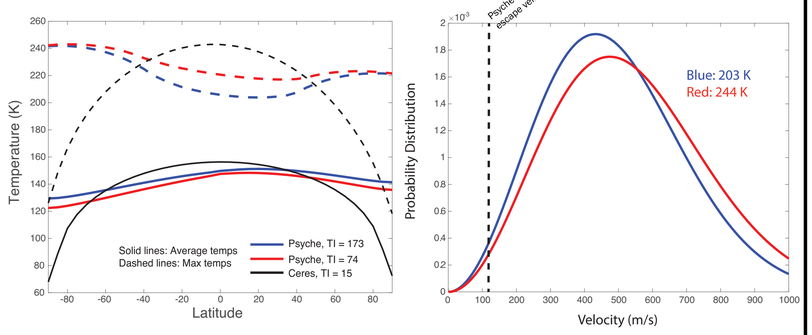
Possible Solution: infall of carbonaceous material

One source of hydration that directly addresses the spectroscopic detection of [8] and is consistent with Psyche as a planetary core is exogenic infall of hydrated material, as observed on Vesta [9] (*right*).

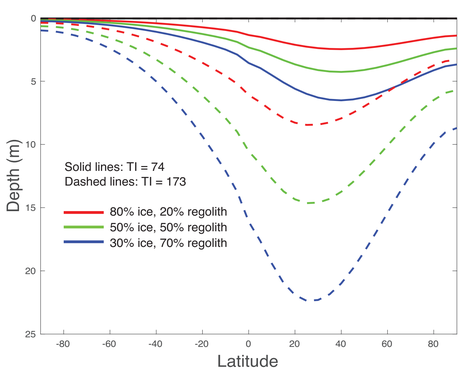


Possible Solution: endogenic or exogenic ice

Psyche's density is too high for ice to be a large component of its volume, but localized ice, perhaps delivered by comets, may cause the detections of [8]. We test this possibility using thermal models to quantify ice stability.



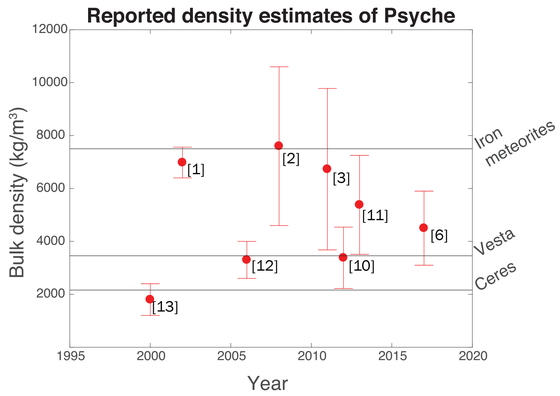
Even with Psyche's high thermal inertia [4], Psyche's high obliquity prevents any portion of its surface from attaining low annual-average temperatures (*upper left*). Ice is not stable anywhere on Psyche's surface (1 m of ice sublimates away in 250 years), and sublimated ice escapes Psyche quickly via Jeans escape (*upper right*).



Subsurface ice may cause detections via sublimating molecules that adsorb to the surface before being lost. Starting from an initial condition of ice near the surface, we allow sublimation of ice to occur over Gyrs. Results (*left*) show that ice would retreat 10s of cm to 10s of m into the subsurface over 4 Gyr.

Complication 2: Potential lower density

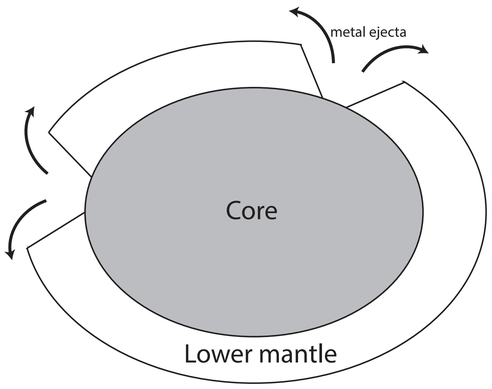
Estimates of Psyche's density vary widely (*right*), and not all are consistent with the grain density of metal. The most recent density estimate [6] is 4500 ± 1400 kg/m^3. The density is almost certainly higher than Vesta's, implying a large metal component in some capacity.



Possible Solution: A metal world with macroporosity

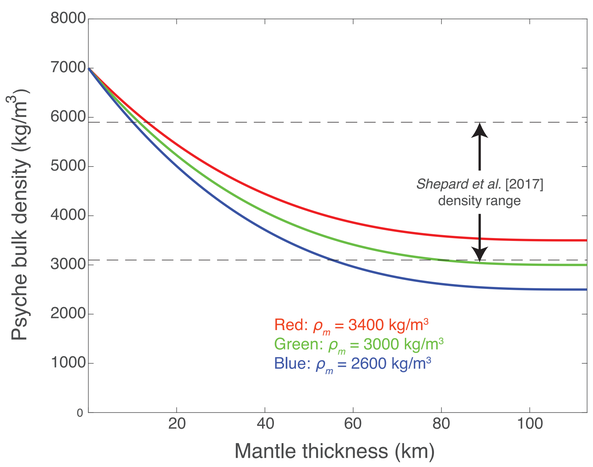
A density of 4500 ± 1400 kg/m^3 is consistent with Psyche as an Fe-Ni core, but with 25–60% porosity throughout. It is unclear if Psyche's mass allows such high porosity to exist, as it is near the value for which porosity is expected to be efficiently compressed away [10]. More work is needed for Psyche's specific parameters to resolve this question.

Possible Solution: Psyche as an exposed lower mantle



Perhaps Psyche is volumetrically dominated by a core, but still retains the lower mantle from its original differentiated planetesimal (*left*). Because there is evidence for metal on the surface, we invoke large impacts excavating core material. In order for this idea to be plausible, the lower mantle layer must be thick enough to lower the density from that of metal to 4500 ± 1400 kg/m^3, but thin enough such that impacts can penetrate.

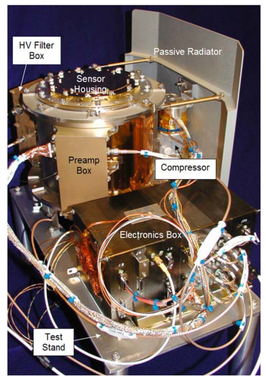
Our calculations (*right*) suggest a 10 km thick lower mantle layer overlying a metal interior yields an appropriate density. Can impacts penetrate such a layer? The craters Id and Ego have diameters 53 ± 15 and 67 ± 15 km. Perhaps there is a larger, yet to be detected crater "Superego," or perhaps the lower mantle layer has heterogeneous thickness.



The lower mantle layer provides a natural explanation for the detections of orthopyroxene [7] and hydrated minerals [8]. We note that there is another object in the solar system, the KBO Haumea, that is thought to represent a lower mantle exposed from destructive impacts on the basis of density estimates and surface properties [14].

Predictions for Psyche (the mission)

Many of the nuances we raise relating to Psyche's structure will be answered with the upcoming NASA mission to Psyche [15]. The spacecraft will have three instruments: a gamma ray and neutron spectrometer, a multispectral imager, and a magnetometer. Additionally, radio science will determine the gravity field.



Above: MESSENGER's gamma ray spectrometer [16], from which Psyche's is based upon.

The gamma-ray/neutron spectrometer should be sensitive to hydrogen at depths of 10s of cm. Our modeling shows that if any ice is present, it will be at those shallow depths at the south pole and only at the south pole.

The gravity science from the Psyche mission should be able to detect the two-layer structure we hypothesize, if it exists. Detection of deep craters that may plausibly excavate material ~10 km deep would support the hypothesis.

Arguably, the most valuable measurement the mission will make to resolve the issues we raise is a high-precision density measurement.

Conclusions

1. The water/hydroxyl detection on Psyche [8] is consistent with the planetary core hypothesis. It is most simply explained through exogenic infall of carbonaceous material, which we consider most likely. Alternatively, it may be explained with buried ice. This scenario is easily testable with NASA's upcoming mission [15], as such ice would be detectable in the upper meter by the mission's gamma ray and neutron detector at the south pole.

2. Psyche's bulk density is high, but likely not as high as the grain density of metal. An interior structure in which Psyche has a rocky mantle and a metal interior may plausibly explain the observations. Such a structure invokes an additional complication of requiring large impacts to excavate metal ejecta, but does not require macroporosity.

Other compositions for Psyche, such as mesosiderites, may be possible and warrant study; we have not considered them here.

Overall, the idea of **Psyche as the exposed core of a differentiated planetesimal is plausible, but so are other structures.** It is clear that Psyche is not a "normal" asteroid, and each plausible structure would supply fundamental information about the early solar system and/or planetary interiors, yielding great scientific return from the upcoming mission.

[1] Kuzmanoski and Koračević (2002), *Astron. & Astrophys.* 395. [2] Shepard et al. (2008), *Icarus* 195. [3] Baer et al. (2011), *Astronom. J.* 141. [4] Matter et al. (2013), *Icarus* 226. [5] Shepard et al. (2010), *Icarus* 208. [6] Shepard et al. (2017), *Icarus* 281. [7] Hardersen et al. (2005), *Icarus* 175. [8] Takir et al. (2017), *Astronom. J.* 153. [9] McCord et al. (2012), *Nature* 491. [10] Carry et al. (2012), *Planet. Space Sci.* 73. [11] Hanuš et al. (2013), *Icarus* 226. [12] Lupishko (2006), *Solar Sys. Res.* 40. [13] Viateau (200), *Astron. & Astrophys.* 354. [14] Brown et al. (2007), *Nature* 446. [15] Elkins-Tanton et al. (2017), *LPSC*, this issue, 1718. [16] Goldsten et al. (2007), *Space Sci. Rev.*, 131.