THE DISCOVERY SCIENCE OF ASTEROID (16) PSYCHE.
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Hit-and-run collisions could create Psyche: Until recently, most scientists modeling planet formation dynamics assumed that pairs of colliding bodies simply merged. When large protoplanets strike one another, however, a substantial fraction of the lid and mantle of the smaller of the two colliding bodies often continues on unaccreted [1, 2]. This kind of impact is now called a hit-and-run. About half of the collisions between planetesimals would have been hit-and-run [3, 4].

When the main phase of planet formation was completed, the small fraction of planetesimals remaining was highly likely to have suffered many more hit-and-run collisions than the norm. The final unaccreted population should include bodies like Vesta, with few or no disruptive collisions, and others like Psyche, which may have had a number of such collisions [5].

Though it is most likely that Psyche is the exposed core of a protoplanet, there is a small but fascinating possibility that Psyche could be primary material, never melted or differentiated, but accreted as is very early from highly-reduced, metal rich material. Some models of the planetary disk [6] and a few meteorite samples hint that such conditions may have existed [7].

We propose a NASA Discovery mission to visit Psyche. Psyche is by far the largest exposed iron metal body in the asteroid belt. At Psyche we will explore for the first time ever a world made not of rock or ice, but of iron (Fig. 1). The evidence that Psyche is a metal body includes:

- High radar albedo of 0.42 [8];
- Thermal inertia of ~120 $Jm^{-2}S^{-0.5}K^{-1}$ [9] (Ceres, Pallas, Vesta, and Lutetia are all between 5 and 30 $Jm^{-2}S^{-0.5}K^{-1}$);
- High density – estimates from 3,300±700 kg m^{-3} [10] to 6,580±700 kg m^{-3} [11]; note that most chondritic asteroids, such as Ida and Eros, have densities of 2,000 kg m^{-3} or less, so even 3,300 kg m^{-3} suggests a denser material.

A 0.9 μm absorption feature suggests 10% of Psyche's surface is not metal, but instead high-magnesian orthopyroxene [12].

What all cores must be: Meteorite compositions demonstrate that early-forming planetesimals heated sufficiently to differentiate and form metallic cores:

- The short-lived radioisotopes ^{26}Al and ^{60}Fe caused some planetesimals to melt and differentiate [13];
- Iron meteorites (fragments of the cores of shattered planetesimals) date to within the first 500,000 years of the solar system [14];
- Achondritic meteorites are the result of melting and differentiation of the silicate from the metal in planetesimals.
- Iron meteorites represent more parent bodies than all other bodies sampled by meteorites combined (chondritic, achondritic, lunar, Mars).

These early-forming planetesimals, both differentiated and primitive, accreted gravitationally and thus grew into planetary embryos, and then further into the terrestrial planets [15]. In each accretionary impact the cores merged into a new, hybrid core, perhaps remelting. Thus all cores, including those in Mercury, Venus, Earth, and Mars, are the end product of multiple generations of melting, disruption, and accumulation.

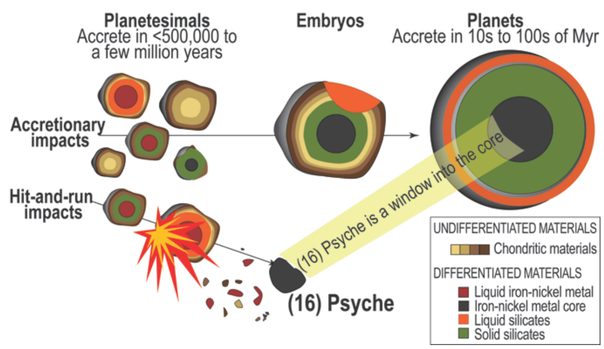

Figure 1: *Planets are built from planetesimals; every core is an accumulation of molten, mixed, pre-differentiated material. Impactor remnants can survive collisions, with most outer layers shed in the process. The largest core-like remnants of the projectile may be like Psyche, which offers a window into the core of the Earth and other terrestrial planets.*

Science of cores: The core of the Earth is known through seismic observations to be solidifying from the inside out; the denser, solid nickel-iron metal settles to the center and expels light-element enriched liquids into the continually-cooling, liquid outer core.

Mercury, in contrast, may have a solid inner core, liquid middle core, and a floating solid outermost core [16]. Planetesimals, as recorded in the meteorite record, provide examples of both directions of solidification.

At low pressures (<4 GPa), core solidification may occur at the lowest available pressures, that is, at the top of the core, near the core-mantle boundary [17] (in contrast, at high pressures, such as in the Earth's core, solidification begins at the highest available pressures, in the center). Small bodies that have experienced hit-and-run collisions may well have solidified from the outside inward as Mercury is doing (Fig. 2).

Slightly slower cooling, settling of large crystals, and different degrees of light elements may for other planetesimals tip the balance to solidification from the inside out, as at the high pressures of Earth's core.

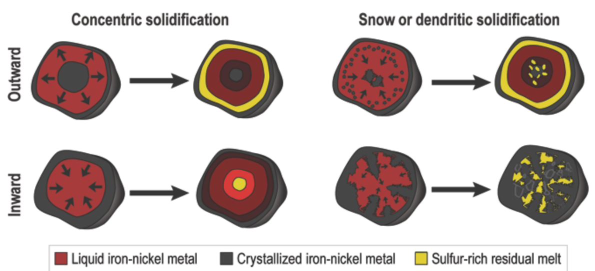

Figure 2: *The Psyche mission will allow us to distinguish, using gravity and compositional data, between the hypotheses of inward or outward core solidification, and between concentric and snow/dendritic solidification. If the core freezes purely concentrically, it creates the structures on the left. If, instead, long pendant dendritic crystals form, or crystals form and snow upward or downward, then a more complex internal structure is formed.*

Implications for geophysical properties: Many differentiated bodies produced magnetic dynamos [18-20]. The compositions and cooling rates of the IVA iron meteorites show strong evidence for rapid stripping, while still molten, of all but several hundreds of meters of their insulating silicate mantle [21, 22]. Further, the IVA meteorites carry clear magnetic signals that their parent body had a core dynamo [23]. One or more hit-and-run collisions provides a good explanation for the data; the IVA parent body may be an analog for Psyche, or indeed it may be Psyche itself.

We expect to be able to determine how Psyche solidified:

- Only crystallization from the outside in would produce material that cools below its Curie point during the period of dynamo action and thus was capable of retaining a magnetic signature.
- Fractional solidification creates a metal compositional signature that may be detectable [22].
- During solidification, light elements that prefer the liquid phase are excluded from growing metal crystals and enriched in the remaining liquid.

Though planetesimals' lids and mantles appear to have been significantly different than those of the terrestrial planets, their cores and core dynamics may have been far closer analogs.

Fundamental advances in understanding planetary formation and interiors: The science questions the Psyche mission will address are:

1. Is Psyche the stripped core of a differentiated planetesimal, or was it formed as an iron-rich body?
   - What were the building blocks of planets?
   - Did planetesimals that formed close to the Sun have very different bulk compositions?
2. If Psyche was stripped of its mantle, when and how did that occur?
3. Did Psyche produce a magnetic dynamo?
4. What are the major alloying elements that coexist in the iron metal of the core? Was the core reduced or oxidized?
5. What are the key characteristics of the geologic surface and global topography? This is a new field: geology of metal objects.

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