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Revisiting collisional stripping of Mercury's mantle

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Abstract

New constraints on Mercury's core size and mantle composition challenge the tradition giant-impact hypothesis for Mercury's iron enrichment. We combine geophysical, astrophysical and geochemical modeling to illustrate an alternative giant-impact scenario.

1. Giant Impact Hypothesis

Mercury is unique among the terrestrial planets for its relatively low mass (3.302×10^{23} kg) and high average density (5.427 g cm^{-3}) that together imply an unusual iron-rich bulk composition. The high-Fe content of Mercury could be the result of chemical and thermal gradients in the solar nebula or partial removal of the silicate portion of a differentiated planet by giant impact or vaporization [1,7,8]. These hypotheses provide important constraints on planet formation and evolution. Here, we reevaluate collision stripping of Mercury's mantle in light of new discoveries.

Mercury could have formed from an initial roughly chondritic proto-Mercury and subsequent removal of silicate material by a giant impact [1]. This scenario is consistent with dynamical models of planet formation that suggest widespread mixing and high relative velocities in Mercury's formation region [8]. Models indicate that a giant impact can eject sufficient silicate material to explain Mercury's high density [1-2]. However several outstanding questions remain, including: (1) how much ejected material is actually lost and how much reaccretes to Mercury and (2) what chemical signatures result from processes related to a giant impact?

2. Reaccretion of ejected material

The amount of reaccreted material limits the efficacy of silicate removal by giant impact. The relative timescales of removal of silicate material by Poynting-Robertson (PR) drag and reaccretion onto Mercury control the amount of reaccreted material. The PR drag timescale is proportional to particle size. Benz [2] used thermodynamic principles to estimate the sizes of particles produced by the impact as rock vapor expands and cools. The exact particle sizes depends on the initial state of the gas but typically are cm- and sub-cm-sized. The rate that cm-sized particles migrate radially due to PR drag and the rate that particles are reaccreted onto Mercury are comparable, implying reaccretion of a substantial amount of ejected material (~40%). This greatly alters the inferred size or initial metal-to-silicate ratio of the proto-Mercury.

Assuming an initial chondritic metal-to-silicate ratio, the mass of Mercury's core and the maximum amount of reaccretion can be calculated (Figure 1). This is a gross overestimate, assuming ejection of 100% of the mantle and retention of 100% of the original core. A giant impact that also ejected core material or did not eject the entire mantle would have tighter limits on the amount of reaccreted material.

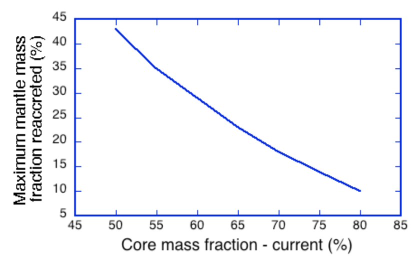

Figure 1: The maximum amount of ejected mantle material that can be reaccreted as a function of present-day core mass (see text for details).

The size of Mercury's core is constrained from low-order gravity measurements during MESSENGER's three flybys [4]. The ratio of the polar moment of inertia of the mantle relative to the whole planet (C_m/C) was estimated from gravity data. Monte Carlo models of Mercury's interior structure relate C_m/C to the radius of the core (~1800-2000km, 1σ uncertainty of C_m/C).

Using the methods of [6], we modeled Mercury's interior with three compressible layers over a range of reasonable compositions: a solid (γ-Fe-FeS) inner core, a molten (Fe-FeS alloy) outer core and a silicate mantle. Figure 2 shows the mass fraction of each layer versus core radius for the cases that minimized the core mass. The minimum core mass fraction (radius=1800-2000km) is ~60-70% of the total planet mass. If the initial metal-to-silicate rate was chondritic, the maximum reaccretion for these core sizes is ~30% (Figure 1-2), at odds with [2].

For an ejected mass ~4×10^{26}g (comparable to [2]), approximately 3×10^{25} particles of radius 1cm will be produced. Assuming ejection velocities are ~10% of the local Keplerian velocity (47 km s^{-1}, or ~5km s^{-1}).

Using these relative velocities, we estimate the particles will soon occupy a volume of space between about 0.35 and 0.45 AU (i.e., 10% of Mercury's semi-major axis), with inclinations ~0.1 rad, or a vertical extent ±0.04AU. (Initially the particles have similar orbits but are dispersed on timescales $\sim 10^4$ years by gravitational torques.) Within this volume ($\sim 0.02AU^3$), the number density of particles is $\sim 4\times10^{-13}$ cm^{-3}. The geometric mean free path is then ~0.05AU. The cloud of particles is marginally optically thin to sunlight. More importantly, the timescale between mutual collisions of particles is ~0.05 yr. As the collisions occur at relative speeds ~0.1 km s^{-1}, the net effect is to erode the particles and produce a small size distribution, possibly on timescales as short as ~1 yr. This would hasten the PR drag timescale by an order of magnitude. The collisional cascade produced by mutual collisions in the cloud of particles ejected from Mercury could dramatically reduce the predicted reaccretion of ejected material by Mercury.

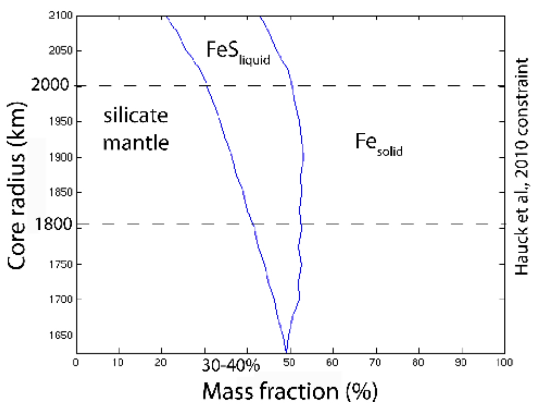

Figure 2: The mass fraction of model layers versus core radius for minimum core mass cases. Dashed lines show the approximate core radii from [4].

3. Silicate composition

The giant impact hypothesis does not directly predict the low-FeO composition of Mercury. However, collisional stripping of Mercury's mantle after magma ocean crystallization has left Fe-rich cumulates perched at the top of the magma ocean cumulate pile but before overturn of the gravitationally unstable cumulate pile (50,000 to 10^6 yrs after accretion), could explain a low-FeO mantle [3]. Since there is no reason to expect iron-poor material to preferentially reaccrete, this hypothesis further limits the amount of material that can reaccrete.

Chemical signatures of a giant mantle stripping impact have not been modeled in detail. However, material that was reaccreted by Mercury would be exposed to high temperatures in a vacuum. Vapors outgassed by the ejecta would be unbound and subject to the solar wind. Thus any material reaccreted by Mercury would be devolatilized. Preliminary measurements of Mercury's surface composition indicate that Mercury is not depleted in volatiles [5]. In addition to possible detection of abundant sulfur, the potassium to thorium ratio (an indication of volatile/refractory elements) suggests volatile abundance on Mercury is consistent with the other terrestrial planets and well above the Moon where low K/Th reflects volatile loss during a giant, moon-forming impact (Figure 3) [5].

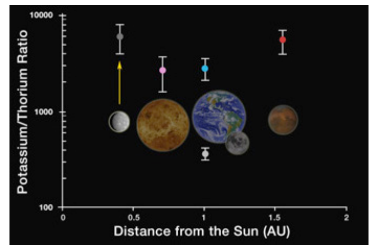

Figure 3: K/Th ratio determined by gamma-ray spectrometer on MESSENGER shows Mercury is not depleted in volatiles [5].

4. Conclusions

If Mercury's iron-enrichment is the result of a mantle stripping impact, reaccretion of ejected mantle material must be lower than previously predicted. Proposed iron-enrichment hypotheses must reconcile new estimates of Mercury's core size and mass, surface volatile abundance and low FeO mantle. At present, none of the existing hypotheses is satisfying. However, significantly reduced reaccretion rates may make the giant impact hypotheses more appealing. Detailed modeling is required to test whether collisional erosion can reduce reaccretion, determine chemical signatures of a giant impact on Mercury, and evaluate the plausibility of preferentially stripping perched Fe-rich magma ocean cumulates.

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