MERCURY IMPACT ORIGIN HYPOTHESIS SURVIVES THE VOLATILE CRISIS: IMPLICATIONS FOR TERRESTRIAL PLANET FORMATION.

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Introduction. The end stage of terrestrial planet formation is characterized by chaotic impacts between planetary embryos. Such giant impacts have been invoked as an *ad hoc* explanation for a wide range of observations in the Solar System, from the large metal core of Mercury [1] to removal of a hemisphere of crust on Mars [2]. The most detailed studies of giant impacts have focused on the giant impact hypothesis [3, 4] for the origin of the Moon.

The depletion of moderately volatile elements in the Moon (relative to Earth and chondrites) but not in Mercury has led to a ‘volatile crisis’ for the various impact hypotheses to explain the size of Mercury’s core. Here, we discuss the survival of the impact hypotheses for Mercury’s origin in light of a new lunar origin model that successfully explains the observed chemical and isotopic characteristics of the Moon [5] and implications for the role of impact events in modifying the volatile content of a planet.

Volatile Depletion of the Moon but not Mercury. Compared to Earth and chondrites, the Moon is depleted in the moderately volatile element K and all elements with higher volatility than K [6]. The ratios of K to the refractory elements Th or U provide insight into variations in volatile abundances in a planet. The K/Th ratios are 3000-3600 for Venus and Earth and about 7000 for Mars [7, 8]. The lunar value is about a factor of 5 lower than Earth (K/Th ~ 650) [9]. Because giant impacts have sufficient energy to melt and vaporize substantial portions of the growing planets, the observed volatile depletion in the Moon has led to a widespread qualitative association between giant impacts and volatile loss.

A single, disruptive giant impact that ejected most of Mercury’s mantle would have been accompanied by widespread melting and vaporization of the remaining planet [10]. Thus, the observation by the MESSENGER mission of a K/Th ratio on Mercury that is similar to the other terrestrial planets (8000±3200 [11]) was initially taken as evidence against the giant impact hypothesis [12], using the volatile depletion on the Moon as an analogy for the post-impact composition of Mercury.

The association between Mercury and the volatile-depleted Moon, rather than Mercury and the Earth (the body that suffered the Moon-forming giant impact) reflects the lack of coupled physical-chemical models that can predict changes in composition after different classes [13] of giant impact events. Such coupled models have only recently been developed to address the differences in the abundance of volatile elements between the Earth and Moon [14]. However, the canonical giant impact model [15-17] has not yielded a satisfactory explanation for the observed chemical and isotopic composition of the Moon [18].

In an attempt to address the unique isotopic similarity between the Earth and Moon, high-angular momentum giant impact scenarios for lunar origin were shown to mechanically mix the mantles of the colliding bodies in equal proportions between the Earth and moon-forming disk [19, 20]. However, the narrow range of impact parameters that led to perfect mixing raised questions about the generality of the solution [20].

A more general solution [5] for the observed chemical [21] and isotopic composition [22] of the Moon has been found. In this high-energy, high-angular momentum giant impact model, the lunar composition is imparted by equilibration between a partial condensate and the bulk silicate Earth (BSE) vapor at a pressure determined by the mass of vapor in the disk (10’s bar) and a temperature dictated by the onset of substantial vaporization of silica (3500-3800 K). At these pressures and temperatures, the majority of the moderately volatile elements remain in the BSE vapor [21], which is gravitationally bound to the Earth. These elements condense with silicates as the planet cools.

The Earth does not fractionate the abundances of moderately volatile elements (compared to the composition of the impacting bodies) during the Moon-forming giant impact because bulk ejection of the rocky mantles does not separate volatile and refractory components (also see discussion in [23]). Thus, the remaining, gravitationally bound mantle material after the giant impact has a similar composition as the original condensed mantles. The cooling time for the silicate vapor atmosphere is fast [5]; thus thermal escape is limited. Indeed, after the Moon-forming impact, there is no prediction or evidence for significant isotopically fractionating thermal escape from the transient temperature excursion of the event [5].

The new physical-chemical model for lunar origin has implications for the interpretation the presence of the moderately volatile and volatile elements observed on Mercury (e.g., K, Na, S, Cl [24, 25]). The Earth, not the Moon, is the correct comparison body for a mantle stripping impact event (disruption [10] or hit-and-run [26, 27]) on Mercury. Mercury did not accrete and equilibrate in the vapor atmosphere of another body, which is the origin of lunar volatile depletion. In the impact hypothesis, Mercury is a gravitationally bound remnant after bulk ejection of a portion of the mantle. Moderately volatile elements recondense as silicates as the planet cools and there is no expected fractionation between condensing elements.

Thus, the different Cl/K ratios on Mercury and Mars vs. Venus and Earth [24] does not appear to be simply related to the occurrence or lack of impact events. We will discuss possible alternative explanations: e.g., the duration of steam atmospheres on Venus and Earth compared to Mercury and Mars may be an important factor.

Impact Modification of Terrestrial Planets. Impact-induced changes in the composition of a planet is dependent on the pre-impact chemical differentiation (core, mantle, crust, ocean, atmosphere) of the bodies and the details of the impact parameters (size ratio, angle, and velocity). Impact-induced removal of small portions to substantial fractions of atmospheres and oceans is possible by both giant and smaller impact events [28-30]. Such events could separate atmophile and hydrophilic elements from the silicate composition, which is supported by geochemical data from Earth [31].

In contrast to atmospheric impact erosion, separating components within the condensed silicates is much more difficult. As discussed above, transient heating during an impact event does not lead to substantial chemical fractionation of the condensed phases because the mechanics of the loss process is bulk ejection followed by rapid cooling and recondensation of the post-impact gravitationally bound material. Recently, ‘collisional erosion’ of crustal components, in preference to the mantle, has been invoked widely in the literature. However, significant physical separation of the thin crust and mantle is unlikely during expected planetary impacts. Giant impacts that could eject substantial portions of the crust would also remove a significant amount of mantle. Smaller impacts encompass a wider range of outcomes, from net accretion to net erosion. An impactor population that is especially tuned in size and velocity to sandblast away the crust without addition or removal of other material is not expected in our solar system.

Net ejection of significant condensed planetary layers (e.g., mantle vs. core) is possible, as demonstrated in Mercury mantle stripping calculations [10, 26, 27]. Thus, the thickness of the layer is an important factor in the efficiency of possible impact-induced separation of the condensed portions of a planet. The Mercury giant impact hypothesis must still overcome the problem of re-accretion of the ejected silicates. The recent hit-and-run style impact events may be a solution [26, 27], because the ejecta could be accreted to the other body. However, the planetary context for such a style event still needs to be quantitatively assessed.

Conclusions. Giant impacts may contribute to loss of atmosphere and oceans. However, for the range of impact conditions considered for terrestrial planet formation, giant impacts do not lead to significant fractionation of condensed silicate components. The observation of moderately volatile and volatile elements (K, Na, S, Cl) and the chondritic ratio of Cl/K on Mercury are consistent with a giant impact hypothesis to explain Mercury’s large core.

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