GIANT IMPACTS, VOLATILE LOSS, AND THE K/TH RATIOS ON THE MOON, EARTH, AND MERCURY.
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Introduction. During the end stage of terrestrial planet formation, giant impacts had sufficient energy to melt and vaporize portions of the growing planet [e.g., 1]. These energetic events are expected to shape the final volatile budgets of the planets [e.g., 2], with different effects on each body [3]. Detailed studies of giant impacts have primarily focused on the giant impact hypothesis for the origin of the Moon.

The giant impact hypothesis was partially motivated by the observed depletion of volatile elements on the Moon. Compared to Earth and chondrites, the Moon is depleted in the moderately volatile element K (50% condensation temperature of 1000 K in the solar nebula) and all elements with higher volatility than K [4]. The ratios of K to the refractory elements Th or U provide insight into variations in volatile abundances in a planet. The absolute abundances of these elements vary widely; however, they are highly incompatible and their ratios are preserved during melting processes.

The K/Th ratios are similar for Mercury, Venus, Earth, and Mars (K/Th from 2000 to 7000) [5-7], but about a factor of 10 lower on the Moon (K/Th ~ 360) [8]. The depletion of K on the Moon is widely attributed to a high-temperature origin associated with the Moon-forming giant impact. A giant impact is also proposed to explain the large core mass fraction in Mercury compared to expectations from cosmic abundances of the major elements and to observations of the other terrestrial planets [9]. Because a giant impact that stripped Mercury of most of its mantle would be accompanied by widespread melting and vaporization of the planet [10], Peplowski et al. [5] suggested that Mercury should be depleted in K and that the observed K/Th ratio is inconsistent with a giant impact.

Here we discuss the processes associated with volatile loss during giant impacts. The different loss processes during the formation of the Moon and Mercury led to their distinct K/Th ratios after a giant impact.

Giant Impacts and Volatile Loss. Planetary-scale impact events lead to a great diversity of outcomes [11, 12]. Depending on the specific impact parameters for a collision, the outcomes span perfect merging, graze-and-merge, partial accretion, hit-and-run, partial erosion, and catastrophic disruption events. These myriad categories primarily reflect the final distribution of material that is gravitationally bound to the largest post-collision remnant. The dynamical time scale for a planetary impact event is only several hours. To first order, giant impacts result in a (practically instantaneous) dynamic rearrangement of the bulk material from the colliding bodies.

Compositional fractionation may occur by preferential gravitational ejection of the outer layers of differentiated bodies [13] during partial accretion, partial erosion, or hit-and-run events that erode the outer layers of the smaller body. If the ejecta were not reaccreted at a later time, the bulk core to mantle mass ratio of a planet may be larger than in the original protoplanets [12]. Although not yet quantified in detail, partial accretion, partial erosion, and erosive hit-and-run events may also remove crust and volatiles that are concentrated in the outer layers of a planet [12, 13]. Bulk ejection of outer layers is important for the loss of atmophile elements [3]. What would happen to moderately volatile rock-forming elements such as K?

After a giant impact, the planet would be surrounded by a transient silicate vapor atmosphere of varying mass that depends on the energetics of the specific event. During this period, light elements may be lost from the exosphere by Jeans escape. However, without additional heat flux to the surface (e.g., by more impacts), the silicate vapor atmosphere will quickly cool and condense.

Significant volatile loss by Jeans escape would be accompanied by isotopic fractionation. Yet, K isotope ratios are remarkably homogeneous between planetary bodies (Earth, Moon, Mars) and meteorites (chondrites, HEDs) [14]. Thus, the magma oceans on the Moon, Earth, and Mars did not lead to significant loss of K via escape from a hot atmosphere. Even though substantial vaporization of the Earth is expected during the Moon-forming impact [15, 16], the atmosphere was gravitationally bound and a negligible mass fraction of K escaped before the vaporized silicates condensed.

Incomplete Condensation of the Moon. After the giant impact, the Moon accreted from a circumterrestrial disk of material gravitationally bound to the Earth. Previous simulations of the giant impact obtained the lunar material principally from the impactor [17], which did not constrain the initial volatile composition of the lunar disk. Recently, two different giant impact scenarios both constrain the lunar disk to originate primarily from the bulk silicate Earth (BSE) in order to explain the isotopic identicality between the Earth and

Moon: an impact by a small projectile onto a fully-grown fast-spinning Earth [15] and a graze-and-merge event between approximately equal-mass bodies [16]. Both impact scenarios lead to bulk ejection of a small portion of the silicate material from the colliding bodies (one to several wt%) and generate a vapor-rich (50 to 90 wt%) lunar disk that reaches a stable mass within about 24 hours. Since the initial proto-lunar composition is the BSE, about a factor of five loss of the similarly volatile elements K, Rb and Cs is required to occur during formation of the Moon from the disk [4].

The lack of K isotopic fractionation in the Moon demonstrates that the volatile depletion arose during the recondensation process rather than a vaporization process [14]. The BSE in the lunar disk was vaporized practically instantaneously by the impact shock, which would not produce isotopic fractionation. The volatile depletion in the Moon reflects incomplete condensation of the disk. As the disk cooled, droplets gravitationally clumped into moonlets. Moonlets that migrated beyond the Roche radius were quickly accreted onto the growing Moon [18]. Thus, the addition of moonlets to the Moon must have ended before the lunar disk cooled below the condensation temperature for K, Rb and Cs. Dynamical models of lunar accretion find that half the disk mass or less forms the Moon [18]. The remainder of the disk, carrying the Moon's complement of volatiles, accreted to the Earth.

Hence, the Moon was assembled from volatile-depleted moonlets. Subsequently, the lunar magma ocean led to negligible additional loss of K since isotopic fractionation is not observed [14]. Further, loss of elements from a hot, gravitationally bound disk or atmosphere of silicate vapor is most likely to result in loss of Li (the lightest element after H and He), but the Li/Yb ratio of lunar basalts is similar to that of the Earth and chondrites [19]. The volatile depletion in the Moon is a reflection of its formation from a circumterrestrial disk and does not result from volatile loss during the <24-hour giant impact event.

Gravitational Reaccumulation of Mercury. Impact-driven removal of most of the mantle on proto-Mercury could have occurred via a catastrophic disruption event by a high-velocity small body [9] or via a hit-and-run event where proto-Mercury was the smaller body [13]. Either type of giant impact would have temporarily broken proto-Mercury into a range of fragment sizes. Mercury formed by the gravitational reaccumulation of fragments that did not achieve escape velocity from the center of the potential well.

A planetary mantle-stripping event would be sufficiently energetic to vaporize most of the ejecta and melt and vaporize portions of the reaccreted planet [10]. Vaporized escaping material would have fol-

lowed a recondensation sequence as it expanded and cooled. Melted escaping fragments devolatilized to space by varying degrees before quenching. However, vapor outgassed from gravitationally bound fragments was also bound. Outgassed vapor formed a transient atmosphere around the reaccumulated Mercury, and subsequent volatile loss was limited to Jeans escape before the silicate atmosphere condensed. Thus, substantial loss of moderately volatile rock-forming elements is not expected because the material that reaccumulates to form Mercury was always gravitationally bound, and the observed lack of depletion of K, S, and Na [5, 20] is consistent with a giant impact.

Subsequent reaccretion of devolatilized ejected fragments (on intersecting orbits around the Sun) would lead to a net depletion of volatiles on Mercury; however, such reaccretion would also lower the core mass fraction. Dynamical separation of the ejected fragments from the largest remnant via a separate process is required for the giant impact hypothesis for the origin of Mercury's large core.

Conclusions. Giant impacts do not lead to substantial compositional fractionation during planetary growth (except for ejection of the atmosphere under certain circumstances [3]). Compositional changes may occur by stripping the outer layers of differentiated bodies, but such erosive events are not expected to remove moderately volatile elements from the largest remnant. In contrast, the observed depletion of volatiles in the Moon reflects its formation by incomplete condensation from a circumterrestrial disk. Thus, the observed K/Th ratios for the Moon and Mercury are consistent with their different formation processes driven by the proposed giant impact scenarios.

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