



Inefficient volatile loss from the Moon-forming disk: Reconciling the giant impact hypothesis and a wet Moon

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ABSTRACT

The Earth's Moon is thought to have formed from a circumterrestrial disk generated by a giant impact between the proto-Earth and an impactor approximately 4.5 billion years ago. Since this impact was energetic, the disk would have been hot (4000–6000 K) and partially vaporized (20–100% by mass). This formation process is thought to be responsible for the geochemical observation that the Moon is depleted in volatiles (e.g., K and Na). To explain this volatile depletion, some studies suggest the Moon-forming disk was rich in hydrogen, which was dissociated from water, and it escaped from the disk as a hydrodynamic wind accompanying heavier volatiles (hydrodynamic escape). This model predicts that the Moon should be significantly depleted in water, but this appears to contradict some of the recently measured lunar water abundances and D/H ratios that suggest that the Moon is more water-rich than previously thought. Alternatively, the Moon could have retained its water if the upper parts (low pressure regions) of the disk were dominated by heavier species because hydrogen would have had to diffuse out from the heavy-element rich disk, and therefore the escape rate would have been limited by this slow diffusion process (diffusion-limited escape). To identify which escape the disk would have experienced and to quantify volatiles loss from the disk, we compute the thermal structure of the Moon-forming disk considering various bulk water abundances (100–1000 ppm) and mid-plane disk temperatures (2500–4000 K). Assuming that the disk consists of silicate (SiO₂ or Mg₂SiO₄) and water and that the disk is in the chemical equilibrium, our calculations show that the upper parts of the Moon-forming disk are dominated by heavy atoms or molecules (SiO and O at $T_{\text{mid}} > 2500\text{--}2800$ K and H₂O at $T_{\text{mid}} < 2500\text{--}2800$ K) and hydrogen is a minor species. This indicates that hydrogen escape would have been diffusion-limited, and therefore the amount of lost water and hydrogen would have been small compared to the initial abundance assumed. This result indicates that the giant impact hypothesis can be consistent with the water-rich Moon. Furthermore, since the hydrogen wind would have been weak, the other volatiles would not have escaped either. Thus, the observed volatile depletion of the Moon requires another mechanism.

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1. Introduction

It is widely accepted that the Earth's Moon formed by a collision between the proto-Earth and an impactor approximately 4.5 billion years ago (Hartmann and Davis, 1975; Cameron and Ward, 1976). This impact created a partially vaporized disk around the planet, from which the Moon accreted. In the standard version of this hypothesis, the impactor was approximately Mars-sized and the impact velocity was close to the escape velocity (Canup and Asphaug, 2001). This model has been favored because it can explain several observed aspects of the Earth–Moon system, such as

its angular momentum, the lunar mass, and the small iron core of the Moon. However, the model cannot easily explain the observation that the Earth and Moon have identical or strikingly similar isotopic ratios (e.g., oxygen and tungsten, Wiechert et al., 2001; Herwartz et al., 2014; Young et al., 2016; Kruijer et al., 2015; Touboul et al., 2015) given that the impact simulations indicate that most of the disk materials originate from the impactor, which presumably had different isotopic ratios from the Earth. It may be, however, possible that the impactor happened to have similar isotopic ratios to those of Earth because the inner solar system may have been well-mixed (Dauphas, 2017). This idea might bolster the standard model, but it still requires an explanation for the identical tungsten isotopic ratios.

Alternatively, Čuk and Stewart (2012) suggest that a small impactor hit a rapidly rotating Earth while Canup (2012) suggests

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that two half Earth-sized objects collided. In these models, the composition of the disk is similar to that of the Earth, and therefore, the isotopic similarities could be naturally explained. These new models are promising alternatives, but they may predict that the Earth's mantle becomes mixed by the energetic impact (Nakajima and Stevenson, 2015). This appears to contradict observed anomalies of short-lived isotopes indicating that the Earth has never been completely mixed (e.g., ^{182}Hf – ^{182}W , Willbold et al., 2011; Touboul et al., 2012; Rizo et al., 2016; Mundl et al., 2017 and noble gases, Mukhopadhyay, 2012). A recent suggestion that the Moon could have formed as the outcome of merging of smaller Moons and multiple impacts (Rufu et al., 2017) revives an old idea requiring some specific, perhaps unlikely dynamical conditions to be acceptable.

In addition to the isotopic ratios of the Earth–Moon system, the chemical compositions provide further essential information. The giant impact has been thought to be at least partly responsible for the observation that the Moon is depleted in volatiles, such as K, Rb, Na, and other volatile elements (e.g., Krähenbühl et al., 1973; Ringwood et al., 1987). Smaller K/Th and K/U ratios of the Moon than those of the Earth also indicate that the Moon is depleted in volatiles (K is more volatile than Th and U) (Tera et al., 1974). The Moon-forming disk was hot and partially vaporized (up to 4000–5000 K and 20–30% for the standard case and 6000–7000 K and 80–90% for the recent models, Nakajima and Stevenson, 2014). Hydrogen, which would have been dissociated from water at this high temperature, may have escaped from the hot Moon-forming disk as a wind (hydrodynamic escape) together with heavier atoms and molecules (Genda and Abe, 2003; Desch and Taylor, 2013).

This model predicts that the Moon also lost a significant amount of water, but this appears to be inconsistent with some of the measured lunar water abundances. Determining the bulk lunar water abundance is an active area of research; based on these measurements and modeling of the lunar interior evolution (e.g., Boyce et al., 2010; McCubbin et al., 2010; Hauri et al., 2011; Hui et al., 2013; Saal et al., 2013), the bulk water content of the Moon has been estimated to range from <10 ppm (Elkins-Tanton and Grove, 2011) to a few hundred ppm (Hui et al., 2013; Hauri et al., 2011, 2015; Milliken and Li, 2017). Lin et al. (2016) suggest that the crustal thickness estimated by GRAIL (34–43 km, Wieczorek et al., 2013) can be consistent with an initially deep (~700 km) lunar magma ocean with presence of water (270–1650 ppm). On the other hand, work using Cl and F in addition to H in apatite suggests that the water content of the Moon can be much lower (e.g., Boyce et al., 2014). These results cover a wide range: the Moon could be “wet”, which indicates here that the Moon is as water-rich as Earth (Earth's bulk water abundance is estimated as a couple of hundred ppm, McDonough and Sun, 1995) or could be drier (<100 ppm). Needless to say, the possibility that water is heterogeneously distributed within the Moon (Robinson and Taylor, 2014) makes it even more difficult to estimate the bulk lunar water abundance based on a small set of samples.

If a significant amount of water escaped from the disk, the lunar D/H ratios should be more enhanced than that of the Earth because H is lighter and would have escaped more efficiently than D. However, analyses of pristine lunar water suggest that lunar D/H ratios may be comparable to the terrestrial values, which may indicate that water loss was insignificant (e.g., Saal et al., 2013). It should be noted that measuring the bulk content of the indigenous water and D/H ratio is a very challenging task because the available lunar samples are limited and because a number of processes, including fractional crystallization, degassing solar wind irradiation, and cosmic-ray spallation, would likely alter the original values.

Thus, the Moon is depleted in some volatiles, but it may or may not be depleted in water. To understand the history of the

lunar volatiles, we propose to reevaluate the water loss mechanism. Desch and Taylor (2013) suggest that hydrodynamic escape could have occurred and blew off the disk atmosphere when the disk temperature is 2000 K and the mean molecular weight of the disk is $\bar{m} = 6 \text{ g mol}^{-1}$ (i.e., water in the disk was dissociated to 2H and O). Conventionally, hydrodynamic escape from a planetary atmosphere occurs when the Jeans parameter $\lambda \equiv GM_{\oplus}\bar{m}/RT r'$ is smaller than ~ 2 (Parker, 1963) (the exact number of this criterion can vary depending on the atmospheric composition, Volkov et al., 2011, and the geometry, Desch and Taylor, 2013). Here, G is the gravitational constant, M_{\oplus} is the Earth mass, R is the gas constant, T is the temperature, and r' is the distance from the planet. The work done by Desch and Taylor (2013) is certainly insightful, but an important aspect here is that this criterion of λ has been developed for a gas that behaves as a material with a single molecular weight (for example the solar wind, which is primarily hydrogen), and it is necessary to understand if this model is applicable to the specific system of interest. If the disk were dominated by heavier elements that were gravitationally bound (i.e., the escape fluxes of the heavy elements were negligible), the hydrodynamic escape model is no longer valid. For hydrogen to escape from a disk dominated by heavier elements, it must diffuse out from the heavy elements that are gravitationally bound to the planet-disk system. Thus, the hydrogen escape rate is limited by this diffusion process and this is called diffusion-limited escape, which is much slower than the “blow off” hydrodynamic escape. This type of hydrogen escape likely occurred from early planetary atmospheres (e.g., Hunten, 1973; Zahnle et al., 1990).

As an example, consider a disk that is dominated by a light element i and heavy element j . We assume here that i and j are hydrogen and oxygen, respectively, and that their mole fractions are $f_i = \frac{n_i}{(n_i+n_j)} = f_H = 0.1$, where n_i and n_j are the number densities of the element i and j , respectively. The upper limit of the diffusion-limited escape rate is described as (Hunten, 1973),

$$\phi_l = b_{ij} f_i \left(\frac{1}{H_j} - \frac{1}{H_i} \right) \sim b_{ij} f_i / H_j, \quad (1)$$

where b_{ij} is the binary collision parameter between elements i and j , f_i is the mole fraction of the element i , $H_i (= RT/m_i g$, where m_i is the molecular weight of the element i) is the scale height of the element i . The subscripts i and j represent the elements of i and j , respectively. R is the gas constant, and g is the gravity. The last approximation is valid when $H_i \gg H_j$. Here, we are assuming that the heavy element j is not escaping from the system.

Under the hard-sphere approximation, b_{ij} is described as (Chamberlain and Hunten, 1987),

$$b_{ij} = \frac{3}{64Q} \left(2\pi RT \frac{m_i + m_j}{m_i m_j} \right)^{\frac{1}{2}}, \quad (2)$$

where

$$Q = \frac{\pi}{16} (\sigma_i + \sigma_j)^2. \quad (3)$$

σ is the collision diameter. Assuming i is atomic hydrogen and j is atomic oxygen, the hydrogen escape flux becomes $1.83 \times 10^{15} \text{ atoms m}^{-2} \text{ s}^{-1}$ ($\sigma_i = 2 \times 53 \text{ pm}$, $\sigma_j = 2 \times 60 \text{ pm}$, $m_i = 1 \text{ g mol}^{-1}$, $m_j = 16 \text{ g mol}^{-1}$, $T = 2000 \text{ K}$, $f_i = 0.1$, $r = 3R_{\oplus}$, $z = 3R_{\oplus}$, $r' = \sqrt{r^2 + z^2} = 4.2R_{\oplus}$ where r is the horizontal distance from the planetary spin axis and z is the vertical distance from the disk mid-plane, and $g = GM_{\oplus}z/r'^3$). The choices of these parameters are discussed in Section 3.3). Assuming the surface area of the disk is $2\pi((5R_{\oplus})^2 - R_{\oplus}^2)$ and the disk life time is 1000 yrs, the total amount of lost hydrogen is $5.86 \times 10^{14} \text{ kg}$ and the equivalent amount of water is $5.86 \times 10^{14} \times (18/2) = 5.27 \times 10^{15} \text{ kg}$. It

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