Origin of the Martian Moons and Their Water Abundances. M. Nakajima[1] and R. M. Canup[2], [1]Department of Terrestrial Magnetism, Carnegie Institution for Science, 5241 Broad Branch Rd NW Washington, DC 20015, USA (mnakajima@carnegiescience.edu), [2]Southwest Research Institute, 1050 Walnut St #300, Boulder, CO 80302, USA.

Summary: The origin of the Martian moons, Phobos and Deimos, has been actively debated. Initially, it was thought that these moons were gravitationally captured asteroids, but recent studies investigate the possibility that they formed from a disk generated by a giant impact. These moons' chemical and isotopic compositions, spectra, and densities may offer important clues to their origin. In order to understand the connection between their origin and observable parameters, we perform numerical simulations to estimate the amount of water that would have escaped from the Martian moon-forming disk if these moons formed by an impact. We find that water loss from the Martian moon-forming disk may have been significant. This suggests that impact-induced Phoboes and Deimos may have smaller water abundances and higher D/H ratios than gravitationally captured moons might have. This may prove important in interpretting data from planned future exploration of these objects, e.g., the Martian Moons eXploration Mission (MMX) in 2022.

Introduction: Based on their sizes, densities and spectra, Phobos and Deimos were thought to be gravitationally captured asteroids [e.g., 1]. A capture origin is still not ruled out, but recent observations of thermal infrared spectra of the moons [2, 3] and the high porosity of Phobos cast doubt on this hypothesis [4]. Another issue is that gravitationally captured moons would tend to have high eccentricities and inclinations, but this prediction is inconsistent with their nearly circular and low inclined orbits, especially because Deimos's orbit is too far from Mars to be tidally circularized. Alternatively, as is thought the case for Earth's Moon, these satellites could have accreted from a disk generated by a large impact [5, 6, 7], which could naturally explain their regular orbits.

In order to determine origin of these moons, it is important to understand the connection between such models and observable properties. One potential key observable is the volatile content of the moons. For the Earth's Moon, the geochemical observation that the Moon is depleted in volatile elements may be explained if the Moon formed by a giant impact. Canup et al. suggest that some volatiles would have been preferentially accreted by the Earth instead of by the Moon as the Moon accumulated from the impact-generated disk [8]. More generally, Nakajima and Stevenson suggest that water and other volatiles would likely not have escaped from the disk to space, partly due to the Earth's large gravity and partly because the disk would have been dominated by heavy elements, which would have prevented such volatile escape [11]. Thus, at least for the Earth's Moon-forming disk, the Earth-disk system may be considered a closed system. Indeed recent measurements of some lunar materials suggest substantial initial water abundances in the Moon [12].

Here we address whether water and other volatiles would have more readily escaped from a Martian moon-forming disk. The Martian moon-forming disk appears more susceptible to volatile loss to space given that its escape parameter λ ($=GMm/kTr$) is much smaller than that of the Earth's Moon-forming disk. Here, G is the gravitational constant, M is the planetary mass, m is the mean molecular weight of vapor, k is the Boltzmann constant, T is the disk temperature, and r is the distance from the planet. The parameter λ is the square of the ratio of the local escape velocity at distance r to the mean vapor thermal velocity, and so describes the vulnerability of vapor to escape from the system, with smaller λ implying increased likelihood for escape. For $\lambda > 3$, escape is slow, evaporative, and occurs molecule by molecule, while for smaller values rapid loss in bulk can occur via hydrodynamic escape. For a Martian moon-forming disk (m=18 g/mol assuming that the vapor phase is dominated by water, T=2000K, and $r \geq 5R_p$ where R_p is the planetary radius), $\lambda \leq 2.7$, while this parameter is ≈ 14 for the Earth's Moon-forming disk. This small value of λ for the Martian moon-forming disk is mostly because of the smaller planetary mass. To summarize, it is possible that the Martian moons lost volatiles to space during their formation even though that was likely not the case for the Earth's Moon forming disk. If a significant amount of water and other volatiles escaped from the Martian moon-forming disk, impact-induced Martian moons would be water-poor, in contrast with gravitationally captured moons, which could have been water-rich.

Model: We determine the thermal profile of the disk based on results of impact simulations [13] using a method called smoothed particle hydrodynamics (SPH) that describes a fluid as a collection of spherical particles. SPH simulation output provides the mass, entropy, and angular momentum of the disk, from which the thermal structure of the disk is reconstructed (for details, see [14]). Once the structure of upper parts of the disk (where the vertical distance from the mid-plane, z, is large) is determined, we compute the escape rate of water. The Jeans escape flux ϕ_J is expressed as $\phi_J = n_c U(1+\lambda_c)\exp(-\lambda_c)/2\sqrt{\pi}$, where n_c, λ_c, U are the number density, escape parameter, and the thermal velocity at the exobase where the scale height is the same as the mean free path. It should be noted that this flux likely underestimates the escape flux from the disk given that the disk tends to have a small λ (<3) and therefore the escape likely would be in the hydrodynamic escape regime. In this regime, the escape flux is approximately expressed as $\phi_H \sim 4\pi n_c U r^2$ [e.g. 15]. We assume that the disk consists of water and SiO_2 and that the vapor phase in the disk is in a convective regime. The bulk water abundance is set to 1000 ppm. Larger or smaller values are possible, but this parameter does not significantly affect the disk structure.

Results and Discussion: Figure 1 (a) shows an example of the disk surface density and temperature using outputs from an SPH simulation where the impactor mass is 0.001 Mars masses and the impact velocity is 20 km/s. In this specific case, the disk mass is ~5 × 10^{-5} Mars masses. To convert SPH simulations to the surface density, we assume that disk particles settled into circular orbits while conserving angular momentum. The reduction in potential energies as the disk relaxes is released as heat. The disk temperature at the mid-plane is then ~ 2200 K, which indicates that the disk is likely molten and the vapor phase is dominated by water because the partial pressure of silicate vapor is much smaller than that of water vapor. Figure 1(b) shows the vertical profiles of the pressure and density of the vapor at $r'=4R_p$ where r' is the horizontal distance from the planetary spin axis. The disk is highly extended in the vertical direction due to the small gravity of Mars. The disk's local thermal velocity reaches the escape velocity at $z>10R_p$ before the disk reaches its exobase. At this location, $T\sim$ 1800 K, $U\sim$1500 (m/s), $\rho\sim10^{-6}$ (kg/m^3), and $n = 3.3\times10^{19}$ (molecules/m^3). When $r'=4R_p$ and $z=10R_p$, λ is 1.4. Assuming that the surface area of the disk is ~ $\pi(5^2-1^2)R_p^2$, the escaping mass by Jeans escape in a day is 1.9×10^{16}kg. If the escape is hydrodynamic, the escaping mass per day is 2.2×10^{18}kg. Given that the disk has a small λ and that upper parts of the disk are not gravitationally bound, a hydrodynamic escape would be the more probable escape mechanism. When the Martian moon-forming disk contains $10^{3\text{-}5}$ ppm of water, the water mass in the disk is $3.3\times10^{16\text{-}18}$ kg. Since the disk lifetime would be longer than 1 day, a large fraction of water may have escaped from the disk. Thus, if the Martian moons formed via an impact, their water abundances would be smaller and their D/H would be enhanced compared to captured moons if the latter had compositions similar to those of carbonaceous chondrites, even though it is also possible that the captured asteroids happened to be water-poor. It should be noted, however, that these estimates are based on simple approximations and further investigation is needed to estimate a more accurate amount of lost water.

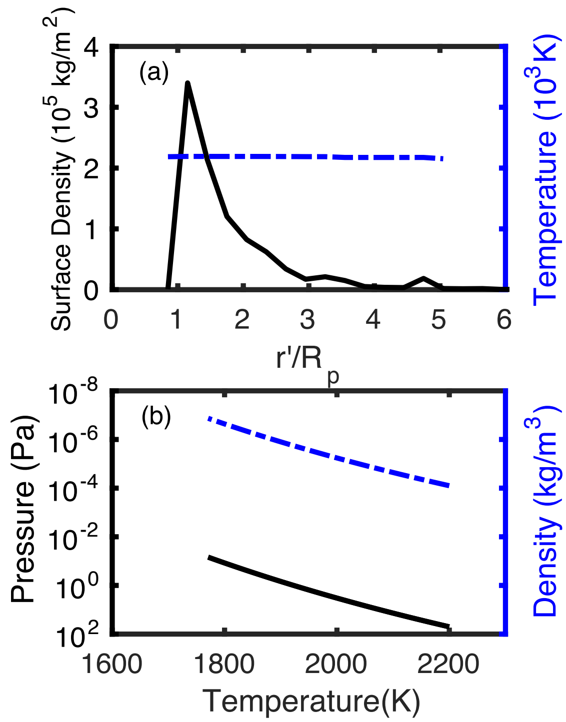

Figure 1: (a) Surface density (black) and disk temperature (blue) for the Martian moon forming disk as a function of r'/R_p. (b) Vertical pressure (black) and density profiles (blue) of the disk at $r'=4R_p$.

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