Initial Water Abundance of the Bulk Silicate Moon. M. Nakajima and E. H. Hauri, Department of Terrestrial Magnetism, Carnegie Institution for Science, 5241 Broad Branch Rd NW Washington, DC 20015, USA (mnakajima@carnegiescience.edu).

Summary: Analyses of lunar rock samples indicate that the Earth's Moon is depleted in volatiles, such as potassium and sodium, while the Moon may or may not be depleted in water. The Moon may have lost volatiles while it accreted from a partially vaporized disk generated by a giant impact between the Earth and an impactor. The behavior of water may have been different from other volatiles because some amount of water would have been present in the liquid phase in the disk. Here, we perform numerical simulations to track the evolution of water within the disk and find that indeed a large portion of water would have been in the liquid phase, most of which eventually would have accreted onto the Moon. Moreover, our calculations suggest that the initial water abundance of the Bulk Silicate Moon (BSM) may be similar to that of the Earth.

Introduction: The Moon likely formed by a collision between Earth and an impactor approximately 4.5 billion years ago [e.g., 1, 2]. This impact formed a hot and partially vaporized disk around Earth from which the Moon accreted. This process may be partly responsible for the geochemical observations that the Moon is depleted in volatiles, such as potassium and sodium [e.g., 3, 4]. The Moon-forming disk would have had high temperatures (4000-6000K [5]) and some volatiles must have been present in the vapor phase in the disk. Water may not have hydrodynacamically escaped to space [6] because the disk vapor would have been dominated by heavy elements, which would have supressed such escape. Rather, it is possible that some water was lost to Earth. Salmon and Canup [7] and Canup et al. [8] perform dynamical simulations to track the evolution of the Moon-forming disk and suggest that the Moon accreted through multiple stages. Initially, disk materials outside the Roche radius quickly accrete and form a proto-Moon (here, the Roche radius is the distance within which a self-gravitating body becomes disrupted by the tidal force from the planet). The proto-Moon continues to grow as the inner disk materials viscously spread out to the outside of the Roche radius and accrete to the proto-Moon. An important factor here is that the liquid in the disk spreads out more rapidly than the vapor because it has a larger viscosity. Before all the silicate vapor in the disk condenses, the proto-Moon becomes massive enough to scatter materials coming from the inner disk. These materials that are rich in volatiles accrete onto the Earth instead of accreting into the Moon. As a result, the deep lunar interior may have formed from volatile-rich materials that were initially located outside the Roche radius, and the shallow lunar interior may have formed from volatile-poor materials that originated from the inner disk liquid [7, 8].

A unique aspect of water is that a significant amount of water may have dissolved in the liquid and therefore water may have behaved differently from other volatiles. Here, we track the evolution of the Moon-forming disk by combining results from previous work [7, 8] with our calculations on the disk structure in order to estimate of the initial water abundance of BSM.

Model: We assume that the Moon-forming disk has a liquid layer at the mid-plane and a vapor layer exists below and above the liquid layer (Figure 1). The vapor layer has a convective region at small z, where z is the vertical distance from the mid plane, and a radiative region at large z. The disk is assumed to consist of SiO_2 and water. As the disk cools, silicate vapor condenses and falls into mid-plane as silicate melt rain. The solubility of water is expressed as H_2O_{melt}=9.3744 $(X^{vapor}{}_{H2O}P)^{0.4264}$ [9] where H_2O_{melt} is the water abundance in a silicate liquid (melt) in ppm and $X^{vapor}{}_{H2O}P$ is the partial pressure of water vapor in Pa. This formula indicates that the amount of water that is partitioned into the liquid phase depends on the local pressure and mole fraction of H_2O in vapor. In this study, for simplicity, we assume that silicate liquids are re-equilibrated at the mid-plane, therefore the amount of water contained in the silicate liquid is determined by the pressure, temperature and vapor composition at the mid-plane.

To track the evolution of the disk, we take the time evolution of total disk surface density and disk temperature at the Roche radius from the previous studies [7, 8] as inputs. We assume that only liquid crosses the Roche radius and it becomes a fragment that retains the water abundance determined at the Roche radius. The fragment eventually accretes into the proto-Moon without losing any materials. Thus, by tracking the pressure and temperature evolution at the Roche radius, the water content of the growing Moon is calculated. We assume that the bulk water content of the disk is fixed to 500 ppm.

Result and Discussion: Figure 2 (a) shows the inputs of this study: the mass of the growing proto-Moon normalized by the final Moon's mass (black line) and the mid-plane temperature (grey dashed line). The Moon accretion is nearly completed within the first 120 years (up to ~ 95%) while the disk temperature remains high (3800-4200K) [8]. The total surface density as a function of time is shown in the black line in Figure 2 (b) [8]. Based on the total surface density and mid-plane temperature, we computed the amounts of water that are partitioned into the liquid (sky-blue line) and vapor (blue line) phases in Figure 2 (b). Throughout the disk evolution, approximately ~ 70 wt.% of the water remains in the liquid phase. Figure 2 (c) shows the water abundance in ppm these phases. As the temperature decreases, the vapor phase becomes more water-rich while the surface density of the vapor continues to decrease.

These results indicate that the disk materials accreted later (~40 wt.% of the lunar mass) to the Moon are more depleted in water (as small as ~300 ppm) while the disk materials that are initially located outside the Roche radius and accrete onto the proto-Moon in the beginning (~60wt%) are more water-rich (500 ppm). Combining this result with the proto-Moon accretion rate (Figure 2a), our calculations suggest that the initial water abundance of BSM is slightly smaller (~465ppm) than the bulk water abundance of the Moon-forming disk (500pm), but the difference is not significant. If the lunar interior has never mixed, it is possible that an outer layer of the Moon, which accreted later, is more depleted in water than the interior.

It should be noted that this study is based on simplifications and further studies will be required to estimate the initial water abundance of BSE more accurately. For example, we assume that all the materials outside the Roche radius eventually accrete onto the Moon. This may be a reasonable assumption because these materials would not escape from the disk to space, but the physics of this process needs to be understood.

In this presentation, we will further discuss behavior of volatiles as well as predictions of isotopic signatures of the Moon.

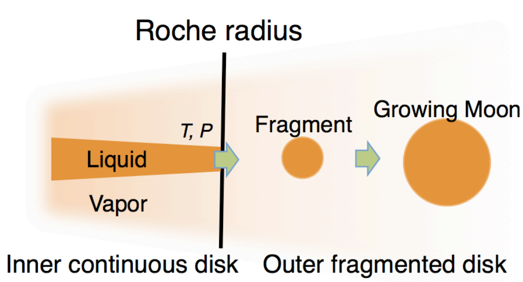

Figure 1: Schematic View of the disk evolution model inspired by previous studies [7, 8].

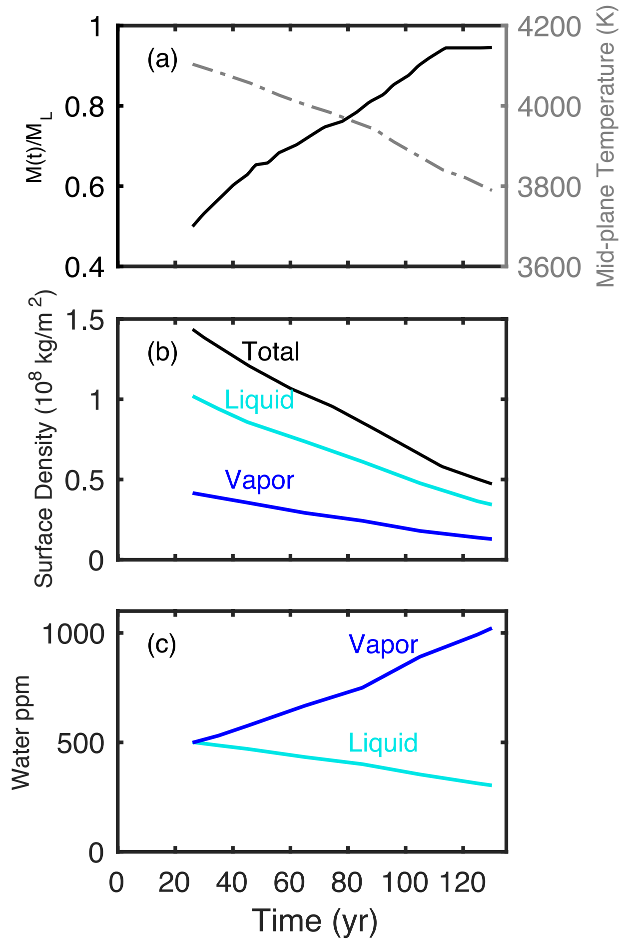

Figure 2: (a) Time evolution of the Moon's mass shown in the black line and the mid-plane temperature at the Roche radius shown in the grey dashed line [8]. (b) Time evolution of the total, liquid, and vapor surface density at the Roche radius. The surface densities of the liquid and vapor are computed based on the vertical disk structure. (c) The water abundances between the liquid and vapor phases at the Roche radius.

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