A MODEL OF THE MOON'S VOLATILE DEPLETION. Steven J. Desch[1] and **G. Jeff Taylor**[2].
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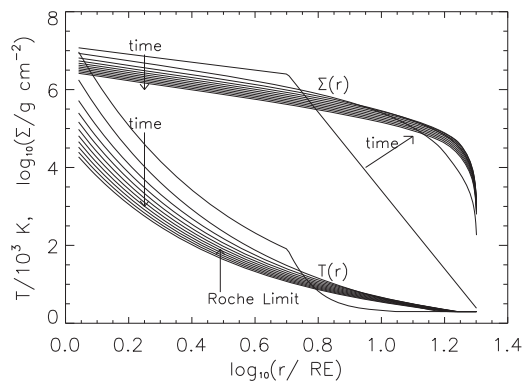[2]Hawaii Institute for Geophysics and Planetology, Univ. of Hawaii, Honolulu, HI. (steve.desch@asu.edu) .

The Moon is widely accepted to have been formed by the impact of a Mars-sized planet with the Earth, causing the ejection of several lunar masses of rocky material into a protolunar disk [1]. This material derived primarily from the impactor's mantle (80%) and the Earth's mantle (20%) [2,3]; barring substantial compositional differences between the impactor and Earth, one would expect the Moon's composition to resemble the terrestrial mantle. The Moon's oxygen isotopic composition very closely matches the Earth's, strongly implying that the protolunar disk exchanged material with the post-impact Earth for an extended period of time, further erasing compositional differences [4]. Since volatiles are presumably as mobile, this exchange should have left the Moon with terrestrial abundances of volatiles like H_2O (≈ 500 ppm; [5]), Na (≈ 2500 ppm; [6]), and K (≈ 240 ppm; [6]). In fact, the Moon is depleted in these and other volatiles. Recent analyses of lunar samples suggest a bulk lunar abundance of H_2O in the range 0.1 - 30 ppm [7-10]; we adopt ≤ 10 ppm, implying the moon retains $< 2\%$ of the total water originally present in the protolunar disk. While some volatiles (e.g., Bi) are depleted by a factor of 10 more, many are depleted by lower factors: the bulk lunar abundances of Na (600 ppm; [11]) and K (80 ppm; [11]) imply depletions by factors of 3-4. Any depletion is difficult to reconcile with the mixing implied by the oxygen isotopic homogeneity, and the magnitude of the H_2O depletion is difficult to explain quantitatively: what process can remove 98% of the water but not 100%? Here we present the first steps in developing a model to quantitatively explain the Moon's volatile depletions.

Our model builds on previous lunar formation models of the impact and protolunar disk [1-4]. We assume just under $2\,M_L$ of material, overwhelmingly liquid silicate magma, is ejected into orbit from $1\,R_\oplus$ to $5\,R_\oplus$, forming a viscously evolving disk that spreads outward for $\approx 20-30$ years, until conditions allow a proto-Moon to form just outside the Roche limit at $2.9\,R_\oplus$ [12]. Outward tidal migration of the proto-Moon then allowed it to sweep up all material beyond the Roche limit. It has been suggested [1] that volatiles (especially H) were lost from the disk during this stage, but this loss has not been quantified. Here, we specifically hypothesize that volatiles were lost as the
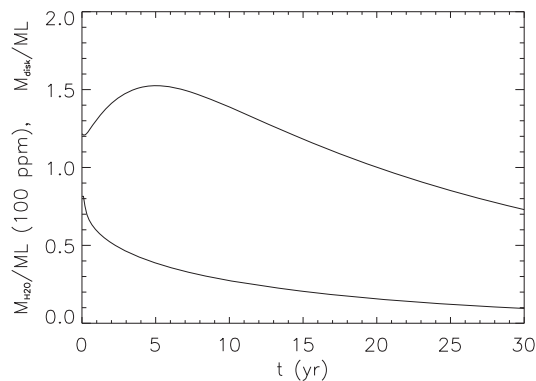
magma outgassed, forming an extended disk atmosphere (mostly Na, H_2O and K) that then underwent incomplete hydrodynamic escape. As volatile loss reduced the partial pressure of volatiles, more volatiles were drawn out of the magma. We assume the proto-Moon could not accrete the disk atmosphere, so the lunar composition reflects the abundances of volatiles dissolved in the magma at the time they cooled and crystallized, or were swept up by the proto-Moon.

We first model the disk, conforming to [2]. The initial surface density is $\Sigma(r) \propto r^{-1}$ out to $5\,R_\oplus$, falling steeply (as r^{-10}) beyond that. The total mass is $1.92\,M_L$ and the mass initially outside the Roche limit is $1.13\,M_L$. The temperature $T(r)$ in the disk is set by balacing radiative losses per area, $2\sigma_{SB}T^4$, against viscous dissipation, $(9/4)\nu\Sigma\Omega^2$, where Ω is the orbital frequency, $\nu \equiv \alpha C^2/\Omega$ is the viscosity, and $C = (kT/\bar{m})^{1/2}$ is the sound speed ($\bar{m} \approx 20$ amu). Following [4] we set $\alpha = 3 \times 10^{-4}$. The surface density evolves (using formulas of [13]), and gases are mixed on the viscous timescale $\sim r^2/\nu \approx 2\,\mathrm{yr}$. We adopt a reflecting boundary condition at $1\,R_\oplus$ (i.e., the disk does not drain onto the Earth nor gain mass from the Earth, although material can be exchanged), and an outflow boundary condition at $20\,R_\oplus$. Figure 1 shows the evolution of $\Sigma(r)$ and $T(r)$ over 30 years at 3-year intervals, illustrating how mass diffuses outward to the outflow boundary so that $\Sigma(r)$, and therefore $T(r)$, in the inner disk slowly decreases. Notable thresholds include $T > 2800\,\mathrm{K}$, reached initially only inside $r < 3\,R_\oplus$, and at $t = 20\,\mathrm{yr}$ inside $2\,R_\oplus$; and $T > 2100\,\mathrm{K}$, the freezing point of the silicate melt with $X_{Fa} = 0.09$ [14], reached initially inside $5\,R_\oplus$, and at $t = 20\,\mathrm{yr}$ inside $3\,R_\oplus$.

At each radius and timestep we calculate the loss of disk atmospheric gas. The total H_2O in each annulus partitions between the atmosphere (parameterized by P_{H2O}) and water dissolved in the silicate magma (with mass fraction x_s) according to the formula of [15], $x_s = (6\times10^{-7})(P_{H2O}/1\,\mathrm{dyn\,cm}^{-2})^{0.54}$. Typically $1 - 15\%$ of the H_2O is dissolved in the magma. Lacking data on solubility of Na and K in silicate melts, we arbitrarily assumed equal partitioning between gas and melt. Volatiles are lost in proportion to their abundances *in the gas phase*, because the loss mechanism is hydrodynamic escape. Loss of 500 ppm of H_2O and 1900 ppm of Na,

from an area $\sim 50\pi R_\oplus^2$, in $< 10^2$ yr, implies fluxes $> 3 \times 10^{16}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, for which the crossover mass [16] is $\sim 10^7$ amu $= 2 \times 10^{-17}$ g. Silicate droplets $> 100\,\mu$m in radius would not participate in the flow, but all other components are lost equally, without isotopic or chemical fractionations; however, partitioning between vapor and liquid can change their relative abundances and loss rates. We note that escape in this context means escape from the Earth; gases leaving the disk but going into orbit around the Earth will return to the disk, at best enhancing the mixing. We thus define the Jeans parameter λ (escape energy per molecule divided by kT) as $\lambda = (GM_\oplus\mu)/(rkT)\left[(1+z^2/r^2)^{-1/2} - 1/2\right]$, where μ is the mean molecular weight, to account for the gas's orbital kinetic energy and for the lower gravitationally binding when at a height z above the midplane. The mass flux of escaping gas is then usually defined as $\rho\,(kT/2\pi\mu)^{1/2}\,(1+\lambda)\exp(-\lambda)$ [17], but recent recent Monte Carlo simulations show that this limit applies only in the limit of large mean free path [18], e.g., at an atmosphere's exosphere. Loss can occur from deeper in the atmosphere, where ρ is greater, but with decreased efficiency; at the high densities and small mean free paths we consider typical (Knudsen number $\sim 10^{-8}$), extrapolation of the simulations by [18] suggest the mass loss rate is $\sim 10^{-3}$ times smaller. Mass loss is also affected by the chemical state of the gas, through the mean molecular weight of the gas. Normally this is 21 amu, but rock vapor (MgO, FeO and SiO$_2$, with a mean molecular weight of 40 amu) can significantly increase this, doubling λ and reducing mass loss exponentially; using the vapor pressure determined by [14], this occurs abruptly above 2800 K. We also include thermal dissociation of H$_2$O, and thermal

ionization of Na and K, both of which can decrease λ, but we find our results are insensitive to these effects.

In Figure 2 we show the total disk mass beyond $2.9\,R_\oplus$, as well as the total mass of H$_2$O dissolved in the magma beyond $2.9\,R_\oplus$, as functions of time. We expect that as temperatures drop below 2100 K at $2.9\,R_\oplus$ at about 20 years, solid particles will grow there and form a proto-Moon. Over the next several decades [1], that proto-Moon will migrate outward and sweep up material farther out in the disk. At this time, Figure 2 shows, the total mass to be swept up is $\approx 1.0\,M_L$, and the bulk water content is ≈ 10 ppm, thus potentially explaining the depletion of water in the Moon.

Further refinements to the model, as well as data on the solubility in olivine melts of Na, K, and other species, can be used in this context to predict the depletions of other volatiles in the Moon.

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