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Volatile Depletion from the Protolunar Disk

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Abstract

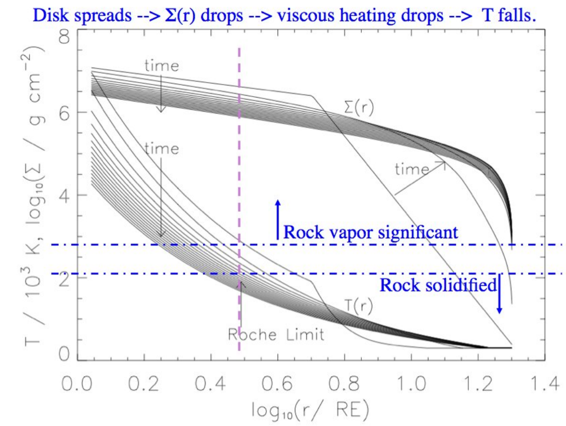
Despite forming largely from the terrestrial mantle, the Moon is depleted in several volatiles relative to Earth, especially water. We hypothesize that the magma in the protolunar disk outgassed volatiles that were lost by hydrodynamic escape and not incorporated by the Moon. Here we present preliminary results of our modeling efforts to quantify the volatile depletions.

1 The Moon's Volatile Depletion

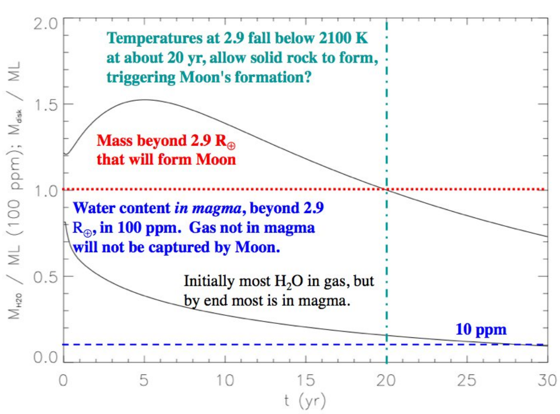
The Moon is widely accepted to have formed from a protolunar disk formed after the impact of a Mars-sized body with the proto-Earth [1]. This material derives from both the Earth ($\sim$ 80%) and impactor ($\sim$ 20%) [2,3], yet the Moon's isotopic composition very closely matches the Earth's in O [4], Ti [5] and Si [6], implying that the Moon and Earth exchanged substantial material. Volatiles are presumably as mobile, yet the Moon's bulk abundances of Na ($\approx$ 600 ppm [7]) and K ($\approx$ 80 ppm [7]) are much lower than the Earth's bulk abundances of Na ($\approx$ 2500 ppm [8]) and K ($\approx$ 240 ppm [8]). The Earth's water abundance ($\approx$ 500 ppm [9]), in particular, far exceeds the Moon's. The Moon's water abundance appears heterogeneous, with bulk water abundances inferred to be higher in mare basalts than in the KREEP component [10-14]. The uniformity of volatile depletions with respect to CI abundances led [11,12] to infer that the mare basalts record a late addition to the Moon's inventory. The bulk abundance of the Moon, as inferred from KREEP glass apatites, appears to be $<$ a few ppm [11,12,15]. The D/H ratio of this water also appears elevated with respect to Earth, by up to a few hundred per mil [11,14]. To reconcile these findings, we hypothesize that the magma in the protolunar disk outgassed an atmosphere of volatiles that was steadily lost by hydrodynamic escape as the disk evolved. Later, the Moon formed from the magma, incorporating only those volatiles still dissolved in it. Here we present a preliminary, quantitative model of the volatile loss from the protolunar disk.

2 Disk Model

Our model builds on previous lunar formation models of the impact and protolunar disk [1-4]. We assume just under $2\,M_{\rm L}$ 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 $2.9\,R_{\oplus}$, which then swept up all material farther than this as it dially migrated outward [Ida et al 1997]. We model the disk with an initial surface density $\Sigma(r) \propto r^{-1}$ out to $5\,R_{\oplus}$, conforming to [2]. We impose a profile $\propto r^{-10}$ beyond that, resulting in a total mass $1.92\,M_{\rm L}$, and $1.13\,M_{\rm L}$ initially outside the Roche limit. We model the temperature $T(r)$ in the disk by balacing radiative losses per area, $2\sigma_{\rm SB}T^4$, 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 $\alpha = 3 \times 10^{-4}$. We evolve the disk using formulas of [16]. Here we impose a reflecting boundary condition at $1\,R_{\oplus}$ (i.e., the disk does not drain onto the Earth nor gain mass from the Earth), but plan to relax this assumption in future work. 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. 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 $P_{\rm H2O}$) and water dissolved in the silicate magma (with mass fraction $x_{\rm s}$) according to the formula of [17], $x_{\rm s} = (6 \times 10^{-7})(P_{\rm H2O}/1\,{\rm dyn\,cm^{-2}})^{0.54}$. Typically $1-15\%$ of the H_2O is dissolved in the magma. Lacking data, we arbitarily assume half of Na and K partition into the melt. Volatiles are lost in proportion to their abundances *in the gas phase*, because the loss mechanism is necessarily hydrodynamic escape. To lose 500 ppm of a Moon's mass of H_2O, from an area $\sim 50\pi R_{\oplus}^2$, in $< 10^2$ yr, implies fluxes $>$



$3 \times 10^{16}\,\mathrm{cm^{-2}\,s^{-1}}$, for which the crossover mass [18] is $\sim 10^7$ amu $= 2\times10^{-17}$ g. Not even silicate droplets $> 100\,\mu\mathrm{m}$ in radius would be lost, and the flow itself does not impose chemical or isotopic fractionation. We calculate loss rates using modified Jeans parameter $\lambda = (GM_\oplus \mu)/(rkT)\ \left[(1+z^2/r^2)^{-1/2} - 1/2\right]$, and the results of numerical simulations including λ and Knudsen number, by [19]. We consider the chemical state of the gas on the mean molecular weight μ, including thermal dissociation of H_2O, and thermal ionization of Na and K. Figure 2 shows the total disk



mass beyond $2.9\,R_\oplus$, as well as the total mass of H_2O dissolved *in the magma* beyond $2.9\,R_\oplus$, as functions of time. Figure 1 shows that after 20 years material at the Roche limit cools to the point that magma can solidify, which [1,4] suggest is what triggers the Moon's formation. Accretion and subsequent outward migration at 20 years, taking decades, will allow the Moon to accrete $1.0\,M_\mathrm{L}$ of material, with a bulk water content dissolved in the magma in the range 10-15 ppm, possibly decreasing over time.

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