A Model of the Moon's Volatile Depletion

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Recent measurements of lunar apatites and volcanic glasses show the Moon has small but non-trivial amounts of water [1-4]. Inferred bulk water abundances are ~ 0.064 – 5 ppm [5], 2 – 12 ppm [6]. We adopt 10 ppm.,much smaller than bulk water abundance on Earth, ~ 500 ppm [7].

This water may be isotopically heavy, inferred δD ~ 0 permil [5] up to +1000 permil [6].

We present a model to explain how the Moon could have formed from a *wet* Earth and yet lost *most* but *not all* (i.e., ~ 98%) of its water, *and* experienced isotopic fractionation, in the protolunar disk stage.

Volatiles are lost from disk via hydrodynamic escape, and must escape both disk *and* Earth

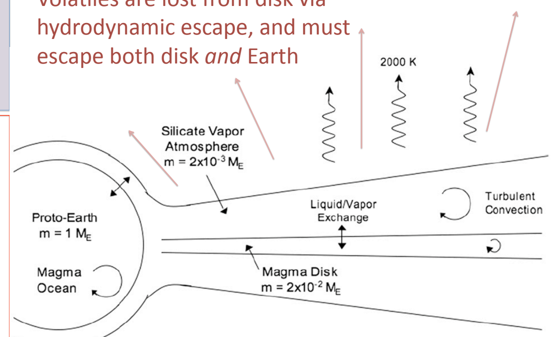
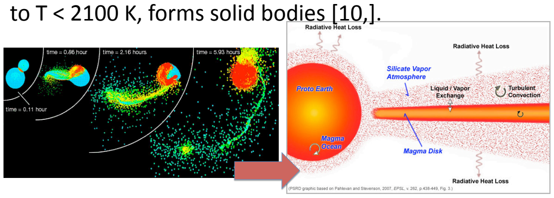


Fig. 3 of [8].

After the Impact

Protolunar disk starts with ~1.6 M_L, T > 4000 K, 20% rock vapor, 1 <r<5 R_E [9]. Moon forms at Roche limit (2.9 R_E) when magma there cools to T < 2100 K, forms solid bodies [10,].



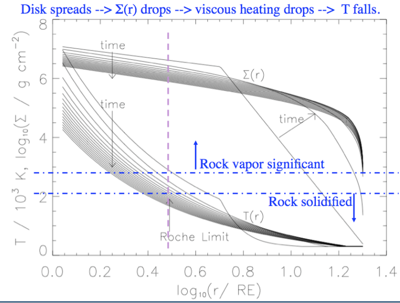
Disk Evolution

Our model builds on protolunar disk model of [8], used to explain match of Earth's and Moon's oxygen isotopes. We calculate viscous evolution and gas loss. Turbulence (α ~ 3 x 10^{-4}, or ν ~ 10^{10} cm^2 s^{-1}) mixes and heats disk. **Magma at 2.9 R_E solidifies when T < 2100 K, after ~20 years.**

$$2\sigma T^4 = \frac{9}{4}\Sigma\,\nu\,\Omega^2 \qquad \nu = \alpha\left(\frac{kT}{\bar{m}}\right)\frac{1}{\Omega}$$

$$\frac{\partial\Sigma}{\partial t} = \frac{1}{2\pi r}\frac{\partial\dot{M}}{\partial r} \qquad \dot{M} = 6\pi r^{1/2}\frac{\partial}{\partial r}\left(r^{1/2}\nu\Sigma\right)$$

Disk spreads --> Σ(r) drops --> viscous heating drops --> T falls.



Disk Atmosphere

Disk material is silicate (Fo91) from Earth mantle, with H_2O ~ 500 ppm, Na ~2600 ppm, K ~540 ppm [11], which outgas into disk atmosphere. Rock vapor pressure from [12]. H_2O solubility in melt from [13]:

Partial pressure in atmosphere

$$x_s = 6\times10^{-7}\left(\frac{P_{\rm H2O}}{1\,{\rm dyn\,cm^{-2}}}\right)^{0.54}$$

weight fraction in magma

We calculate that atmosphere dominated by rock vapor (μ = 39 amu) at T > 2800 K. Na (μ = 23) and H_2O (μ = 18) dominate at T < 2800 K. Thermal ionization of Na, dis-sociation of H_2O yield μ = 11 between 2000 and 2800 K.

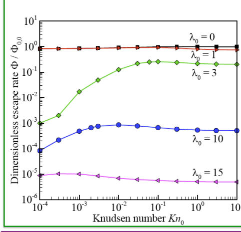
Only ***hydrodynamic escape*** makes dent in Moon's water budget. 500ppm x M_L = 4 x 10^{22} g = 10^{45} molecules. Disk area ~ 2 x 10^{19} cm^2. Time ~ 30 yr. Flux ~6 x 10^{16} molecules cm^{-2} s^{-1}. Atmosphere loss on Earth that fractionated Xe only ~ 10^{14} cm^{-2} s^{-1} [14].

Flow itself does not fractionate elements or isotopes.

Hydrodynamic Escape

Hydrodynamic loss requires low λ < 2:

$$\lambda = \frac{U}{kT} = \frac{GM_\oplus\mu}{rkT}\left[\left(1+z^2/r^2\right)^{-1/2} - \frac{1}{2}\right]$$



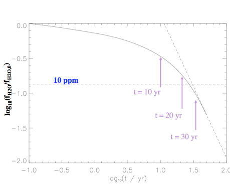
Mass loss rate taken from Monte Carlo molecular dynamics calculations of [15]:

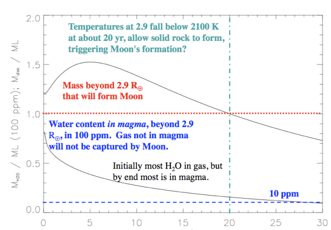
In our model, gas lost from ~2 scale heights, Kn ~ 10^{-8}, Φ/Φ_{00} ~ 10^{-3}.

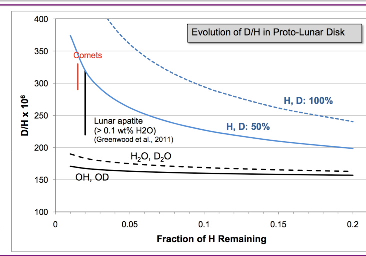
$$dM/dt/A = \left(\frac{\Phi}{\Phi_{00}}\right) n_{\rm base}\left(\frac{kT}{2\pi\mu}\right)^{1/2}(1+\lambda)\exp(-\lambda)$$

Most gas lost from 3 – 6 R_E, where μ lowest. At r<3 R_E, T>2800 K, rock vapor too heavy, r too small. At r>6 R_E, T too low, μ too high.

Results







References: [1] Saal et al 2008; [2] Hauri et al. 2009; Hauri et al. 2010; [4] Boyce et al. 2010; [5] McCubbin et al. 2010; [6] Greenwood et al. 2010; [7] Mottl 2007; [8] Pahlevan & Stevenson 2007; [9] Canup et al 2004; [10] Ida et al. 1997; [11] McDonough & Sun 1995; [12] Nagahara et al 1994 ; [13] Fricker & Reynolds 1966; [14] Hunten et al. 1987; [15] Volkov et al. 2011; [16] Zhang 2011

Conclusions: All species not dissolved in magma are lost during hydrodynamic escape. Gas loss draws water out of magma. When disk material solidifies at 2.9 RE, at ~ 20 yr, water fraction ~ 10ppm. Water fraction <<10 ppm would require formation time >> 10^2 yr. Water loss from protolunar disk substantial but incomplete.

If fO_2 < IW-2, H escapes as H_2, large isotopic fractionations possible between magma and gas [16]. δD of H_2O left in magma can rise up to +1000 permil.

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"Wet" moon (water ~10 ppm) with high D/H can form from impact, as water outgasses from magma into protolunar disk atmosphere, which undergoes hydrodynamic escape.