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Protolunar Disk Evolution and the Depletion of Volatile Elements in the Moon

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Abstract
We explore how the evolution of the protolunar disk could lead to a depletion in K, Na, and Zn in the Moon relative to Earth even in the absence of escape.

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moon, protolunar disks, potassium, sodium, zinc

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Protolunar disk evolution and the depletion of volatile elements in the Moon. R. M. Canup[1], C. Visscher[2], J. Salmon[1], and B. Fegley, Jr.[3]. [1]Southwest Research Institute (Planetary Science Directorate, 1050 Walnut Street, Suite 300, Boulder, CO, 80302; robin@boulder.swri.edu); [2]Dordt College; [3]Washington University in St. Louis

Overview: Compared to the bulk silicate Earth, the Moon is depleted in moderately volatile elements including potassium, sodium, and zinc [e.g., 1]. The origin of this depletion remains poorly understood. It has been suggested that volatiles were evaporatively lost from an impact-generated protolunar disk prior to the Moon's accumulation [2-3]. However escape may have been minimal for expected disk conditions [4]. A depletion could also result if volatiles were preferentially accreted by the Earth rather than by the Moon [1, 4-5].

We combine results of lunar accretion simulations [6] with estimates of the disk's thermal state [7] and predictions from a chemical equilibrium code [8]. We find that K, Na and Zn condense late in the disk's evolution when the majority of inner disk material is scattered onto the Earth rather than being accreted by the Moon [6]. This would produce depletions in the Moon relative to the Earth even in the absence of escape.

Background: Lunar samples are enriched in the heavy Zn isotopes compared to the BSE, which has been interpreted as evidence of large-scale evaporative loss after the Moon-forming impact [2]. However Jeans escape of Zn would be minimal due to its high atomic weight. Taylor et al. [1] advocated that the Moon's volatile depletion was instead due to incomplete condensation from a high temperature vapor, in which the accretion of material by the Moon was cut-off at temperatures below the condensation temperatures of the depleted species. We explore this concept here.

Disk evolution: After the Moon-forming impact, the two-phase silicate disk may develop a vertically stratified structure, with a mid-plane melt layer surrounded by a silicate vapor atmosphere [7]. Clumps form in the melt due to local gravitational instability. Within the Roche limit ($a_R = 3R_\oplus$), such clumps are sheared apart by planetary tides, producing a viscosity that dissipates energy and spreads the melt [e.g., 6-7]. The balance between radiative cooling and viscous heating causes the Roche interior disk to spread over ~ 10^2 yr [7]. Exterior to a_R viscous heating is likely minimal, and silicate vapor condenses on a timescale $\tau \sim (\sigma_v l)/(2\sigma_{SB} T_P^4) \sim 3$ yr $(\sigma_v/10^6 \text{ g cm}^{-2})(2000 \text{ K}/T_P)^4$, where $l = 2 \times 10^{11}$ erg g^{-1} is the silicate latent heat of vaporization, σ_{SB} is the Stefan-Boltzmann constant, T_P is the disk photospheric temperature, and σ_v is the vapor surface density. In the outer disk, melt present after the impact (or that subsequently condenses) rapidly accretes into moonlets in < 1 yr.

Fig. 1 shows results from a lunar accretion model [6]. The Roche-interior disk is described analytically, and its total mass and outer edge evolve due to viscous spreading and resonant interactions with outer moonlets. Material outside the Roche limit is described by an *N*-body accretion simulation. The latter assumes that outer disk material has largely cooled so that this region may be approximated as a condensate disk. As inner disk material spreads beyond the Roche limit, mass and angular momentum are removed from the inner disk and added to the *N*-body portion of the model in the form of new moonlets. Such spawned moonlets can form rapidly via local gravitational instability just outside a_R.

In "phase 1", material placed into orbits outside the Roche limit by the impact rapidly accretes into a moonlet that in this case contains ~ 40% of the Moon's mass. In phase 2, resonant torques from this moonlet confine the inner disk to within the Roche limit, and the Moon's accretion stalls. The inner disk spreads, and once its edge reaches the Roche limit it spawns moonlets just beyond a_R (phase 3). Initially these spawned moonlets are rapidly driven outward due to resonant interaction with the inner disk, and they are efficiently accreted by the Moon (Fig. 1b). However as the inner disk mass decreases, disk torques weaken, and spawned moonlets are scattered onto high-eccentricity orbits by the Moon. Most are then tidally disrupted as their perigees near the

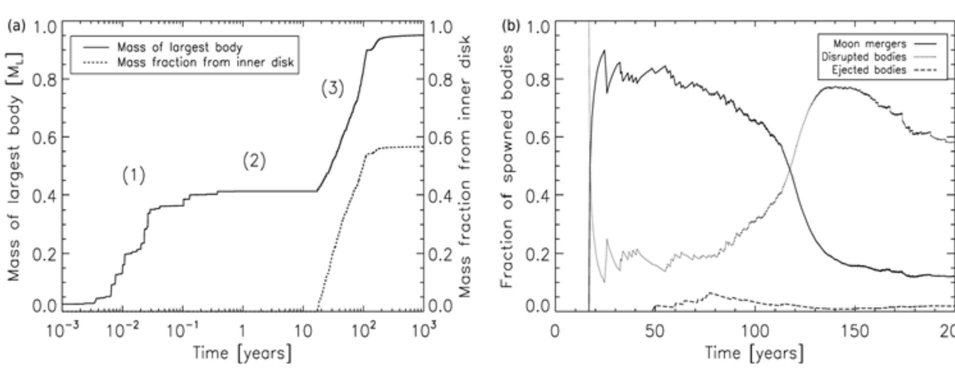

Fig. 1: Lunar accretion model [6]. (a) Moon mass in lunar masses vs. time (solid) and fraction derived from inner disk (dotted). (b) Fate of material spawned from the inner disk. Initially ~ 80% is accreted by the Moon (dark line), but a cut-off occurs at ~ 120 yr.

Earth's surface before they can accrete onto the Moon (Fig. 1b). The result is a transition from an accretionary regime – in which the Moon in this case gains the final ~ 60% of its mass from inner disk melt – to a non-accretionary regime – in which most inner disk melt is ultimately accreted by the Earth [6]. Inner disk elements that condensed subsequent to this transition would be depleted in the Moon relative to the Earth.

To approximate the formation temperature of moonlets spawned from the inner disk, we estimate the disk's mid-plane temperature at the Roche limit (T). Initially, the disk is in silicate vapor-melt equilibrium [7], with T (K) $\approx T_1(\sigma/10^7 \text{ g cm}^{-2})^{\alpha}$. Here σ is the disk's surface density at a_R, $\alpha = 0.055$, and $T_1 = 3700$ K (4000 K) for $x = 0.1$ ($x = 1$), where x is the gas mass fraction of the atmosphere at the mid-plane [7]. Eventually cooling allows all the silicate vapor to condense, and the inner disk is no longer regulated by the silicate two-phase equilibrium. The remaining volatile-rich atmosphere is heated by viscous dissipation in the melt (which decreases with time as the melt spreads) and by the Earth, whose effective temperature is ~ 2000 K [9]. We estimate T in this phase assuming vertical thermal equilibrium and an optically thick atmosphere [10].

Condensation temperatures: We estimate the partitioning of elements between the disk's vapor vs. melt using the MAGMA chemical equilibrium code for a BSE composition disk (e.g., [8]). We derive the partial vapor pressure of each species which, in combination with the total bulk elemental inventory of the disk, is used to estimate the relative fraction of each element in the vapor vs. melt phase as a function of T and σ. Results are shown in Fig. 2 for $\sigma = 10^7$ g cm^{-2} .

Results: Fig. 3a shows the inner disk surface density vs. time for the Fig. 1 simulation. Fig. 3b shows estimated mid-plane temperatures at the Roche limit during the silicate two-phase stage and the subsequent cooling period once the inner disk's silicate vapor has condensed (dashed line). The colored curves show our estimated 50% condensation temperatures (T_{50}) for Zn (grey), Na (orange), and K (green). The formation temperature of inner disk clumps remains above T_{50} for these elements until the Moon has essentially completed its accretion (Fig. 3c) and the efficiency of inner clump accretion by the Moon has decreased to ~ 10% (Fig. 1b). Thus we expect the portion of the Moon derived from the inner disk would be substantially depleted in these elements even in the absence of thermal escape.

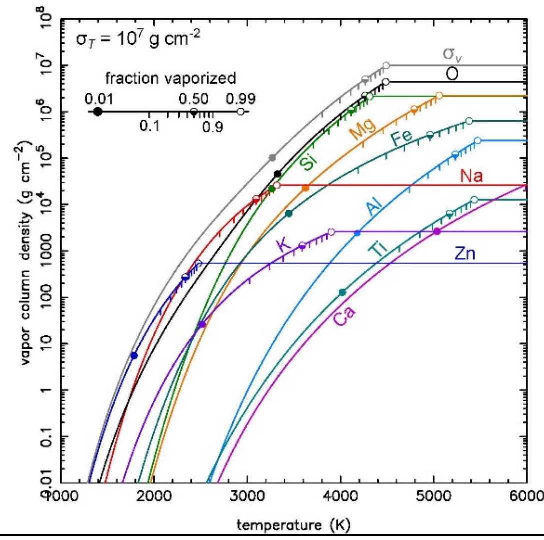

Fig. 2: Fraction of species in a BSE disk in the vapor phase as a function of T for $\sigma = 10^7$ g cm^{-2}.

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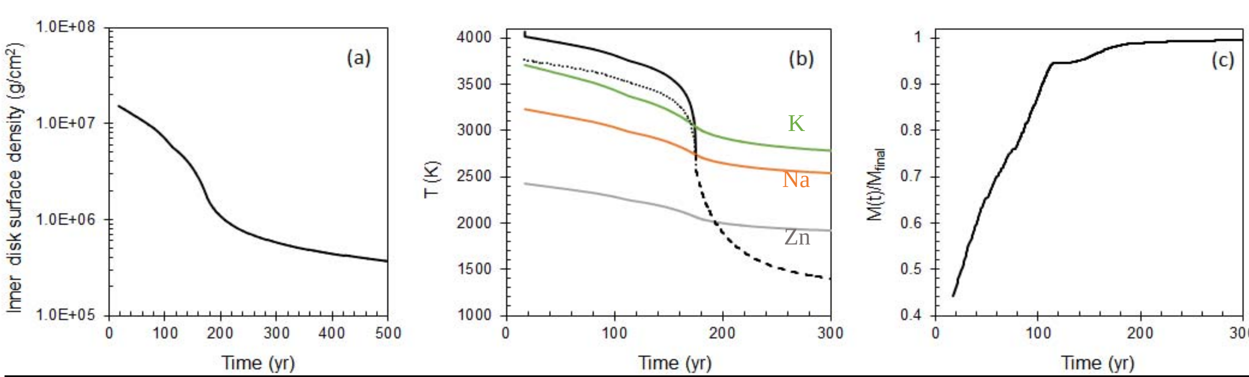

Fig. 3. For the Fig. 1 simulation: (a) Inner disk $\sigma(t)$; (b) Disk mid-plane T at a_R (black lines; solid has $x = 1$, dotted has $x = 0.1$), and T_{50} for Zn (grey), Na (orange), and K (green) vs. time; and (c) fraction of the Moon accreted vs. time.