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Tidal pull of the Earth strips the Moon of its volatiles from a surface magma ocean

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Abstract

Prevailing models for the formation of the Moon invoke a giant impact with the proto Earth, causing extensive depletion of lunar volatiles. Current models favour devolatilisation of Moon-forming material *via* thermal processing in an Earth-Moon disk prior to its accretion. However the physics of this disk are poorly understood and thermal escape of gas is inhibited by the Earth's strong gravitational field. Here we show that a proto-Moon located at the Earth's Roche Limit undergoes atmospheric loss from a surface magma ocean through hydrodynamic escape assisted by tidal pull from the Earth. Thermodynamic equilibrium between vapour and liquid at the evaporating molten surface reproduces the observed depletion of Na, K and Zn and isotopic composition of K and Zn measured in the present-day lunar mantle, at temperatures ≈1500 K. Moon formation was therefore likely much simpler than initially thought, forming by mechanisms similar to evaporating double-stars or exoplanets.

1. Introduction

It is widely accepted that the Moon formed after a giant-impact, however, the modes and mechanisms that led to its physical state and composition remain debated [1,2]. Lunar mare basalts are depleted in volatile elements by a factor of 5 (for alkalis) to 50 (highly volatile elements like Zn, Ag and Cd) relative to their terrestrial counterparts [3]. This depletion is coupled with enrichment in the heavy isotopes of Zn [4] and K [5], attesting to an evaporative origin for volatile element loss from the Moon. Current models attempt to explain these observations by processing of Moon-forming material in a proto-lunar disk. In this disk, volatile depletion by incomplete condensation may occur *via* mechanical separation of vapour from liquid [6] or gravitational torque from the proto-Moon exerted on the vapour [7]. However,

these scenarios are dependent on the disk structure, which remains poorly understood. Here we present an alternative scenario based on more robust physics, derived from that used to describe the atmospheric structure of double-stars or close-in exoplanets.

2. The Lagrange points

The radius of the Moon's gravitational attraction sphere, called the Hill Sphere, is

$$R_H = a(M_m/3M_\oplus)^{1/3} \tag{1}$$

where a is the Earth-Moon distance, and M_m and $M_\oplus$ are the masses of the Moon and Earth, respectively. Airborne particles (liquid or gas) have sufficient kinetic energies to exit the Hill Sphere and escape from the Moon's gravitational reach, even at low temperatures (Fig. 1). The escaping particles pass through either the L1 and L2 Lagrange points and are ejected into orbit around the Earth. The lost gaseous molecules do not re-accrete onto the Moon because any dissipative process (gas viscosity and/or radiative cooling) prevent re-entry to the Hill Sphere.
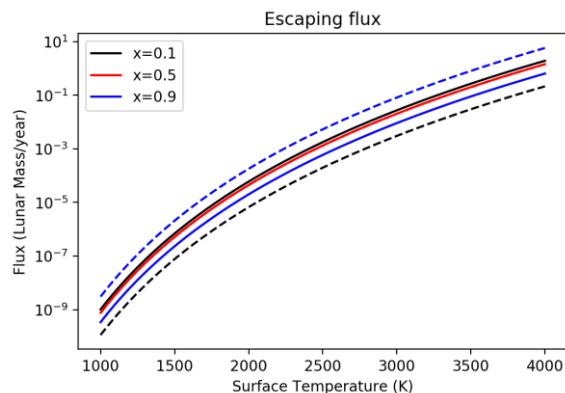

Fig. 1. Flux at the surface of the moon as a function of surface temperature (K). X corresponds to the liquid fraction in the atmosphere.

3. Atmospheric Structure

We have developed a 1D non-isothermal model of hydrodynamic escape along the line joining the Earth-Moon center including (1) evaporation from a magma ocean at temperature T_s (2) gas re-condensation into droplets (3) gravitational fields of the Earth and Moon. The atmosphere's radial velocity increases with the distance to the Moon, and always reaches a sonic point (at distance R_c from the Moon center) where the gas-liquid mixture velocity equals the two-phase gas-liquid sound velocity V_c, given by:

$$V_c{}^2 = \frac{\alpha}{\beta} \frac{\partial P_s(T)}{\partial T} \tag{2}$$

Where $P_s(T)$ is the equilibrium partial pressure at temperature T, and α and β are variables that account for the latent heat and heat capacity of vaporisation, respectively. A few percent of the proto-Moon's mass can escape hydrodynamically in $< 10^4$ years for $T_s >$ 1400 K due to the intense tidal pull from the Earth at the Roche limit. This timescale is smaller than the lunar tidal orbital expansion timescale. The Moon's outward orbital expansion increases the Hill sphere radius, thereby inhibiting hydrodynamic escape; which shuts down between 10^2 and 10^4 years depending on the Moon's tidal Q value.

4. Vapour and Moon composition

We set the initial bulk composition of the Moon to that of the bulk silicate Earth (BSE), and that the composition of the escaping vapour to that of the vapour at the liquid-gas interface. We compute the partial pressures of major metal-bearing volatile species and the effect of their resultant loss from the lunar atmosphere on the composition of the residual lunar magma ocean, considering both (i) equilibrium evaporation and (ii) fractional evaporation at the fayalite-magnetite-quartz (FMQ) buffer. For $T_s >$ 1500 K, near-complete Zn depletion for minor K and particularly Na loss is observed. However, fractional vaporisation at 1200-1400 K yields lunar-like Na/Zn and K/Zn ratios. Here, the liquid and gas phase equilibrate at infinitesimally small increments before being removed. Because the gas escapes hydrodynamically (which imparts no additional isotopic fractionation), the fractionation factor reflects that at equilibrium. Under these conditions, isotopic data for K and Zn may be reproduced by vaporisation ≈1000 K (Fig. 2).
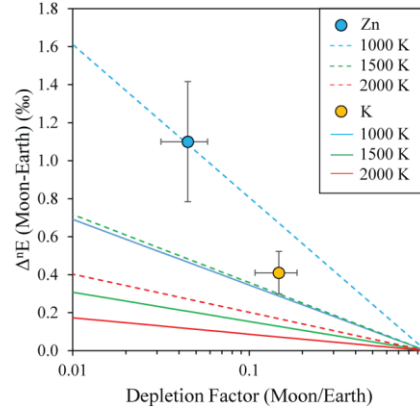

Fig. 2. The difference in stable isotope composition of an element, E (Zn, blue or K, orange) in delta notation, where 'n' denotes the isotope ratio (n = 66/64 for Zn and 41/39 for K) in the Moon relative to the Earth's mantle, against the elemental depletion factor. Lines represent the calculated isotopic fractionation produced by evaporation.

5. Implications and Conclusions

We show that 0.05 to 0.15 % of a lunar mass must have evaporated in order to reproduce the chemical and isotopic composition of the Moon, starting from an Earth's mantle-like composition. The temperatures at which dynamical timescales produce sufficient lunar volatile loss via hydrodynamic escape are in agreement with those deduced from equilibrium thermodynamic calculations, near 1500 K, implying that the Moon was degassed very rapidly ($<10^4$ years). Our work provides a mechanism for volatile loss on small satellites accreting around larger bodies (*e.g.* sun-proximal exoplanets).

References

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