

EFFICIENT EARLY MOON DEVOLATILISATION JUST AFTER ITS FORMATION, THROUGH TIDALLY ASSISTED HYDRODYNAMIC ESCAPE.

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Introduction : Most lunar rocks are depleted in volatile and moderately volatile elements including Na, Zn and K by a factor 10 to 100 [1,2,3,4,5]. This volatile depletion points toward a volatile depleted lunar interior compared to the Earth. The origin of this volatile depletion was unknown until the discovery of a heavy isotope enrichment of the Moon compared to the Earth for several moderately volatile elements including Zn and K pointing toward a loss by evaporation during/following the formation of the Moon [6,7]. Several subsequent studies have suggested that the volatile loss must have occurred rather during the early history of the Moon via magma ocean degassing rather than during the giant impact [8]. The recent discovery of the enrichment of the Moon in the lighter isotope of Cr compared to the Earth argues in favor of a devolatilization under low temperature (<1800 K) further confirming volatile loss by degassing of a magma ocean.

Despite all these chemical evidence for volatile loss from the early Moon, there are presently no physical mechanisms that could account for this loss. Whereas it is suspected for a long time that devolatilization would be a natural consequence of the Moon Forming Giant Impact (as it is the preferred mechanisms today, whereas different versions exist [9,10,11]), it was not chemically proved until the discovery of Zn isotopic fractionation in lunar samples [6] and the physical mechanism by which volatile may escape the system has never been clearly elucidated and is still not understood. Simple evaporation from the protolunar disk has been invoked, in particular for Zinc [5] but the disk or the early Moon is not hot enough for the thermal velocity to become comparable to the system's escape velocity (11 km/s, that is Earth's). Alternative models based on the dynamics of the protolunar disk [12,13,14] suggest that heavier elements were preferentially incorporated in the protomoon, and that volatiles elements were implanted on the Earth leading to a depletion of heavier species. These models suffer from the complexity of the physics required to model the protolunar disk, whose structure is still uncertain. In particular, whether or not the vapor can decouple from the gas is unclear, as well as the energy budget [15,12,16] and viscosity sources may efficiently heat up the system regularly [17]. Finally the lack of

hydrogen in the system prevents efficient dragging of heavier species by escaping hydrogen [18] to space.

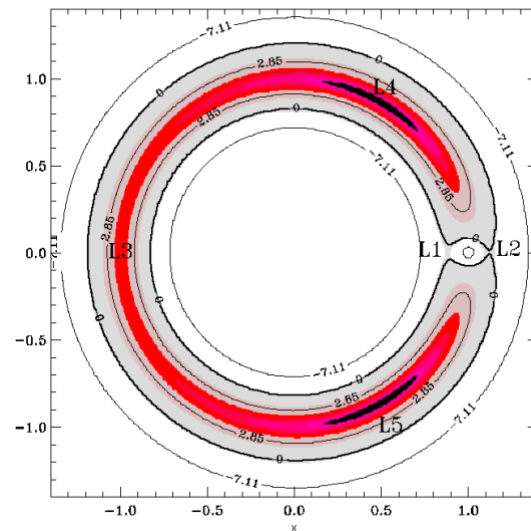


Figure 1 : *Contours of the Potential Energy field in the frame rotating with the Moon in the restricted 3-bodies problem. The Earth is in the Center (not represented), the Moon is between the L1 and L2 Lagrange points. Colors stand for the value of the Potential Energy. The Hill sphere is in white around the Moon, colored regions correspond to Horseshoe regions. X-Y axes are normalized distances to Earth's center.*

Method: Here an alternative model inspired by the physics of binary stars and evaporating exoplanets has been developed. We consider the physics of gas escaping from a magma ocean at the surface of the protomoon, inside the gravitational tidal field of Earth and the Moon. The Earth gravitational field limits the extent of the Moon gravitational domination to a small region called the “Hill Sphere” (or the Roche Lobe) with approximate size $R_h = a(M_m/3M_e)^{1/3}$, with a , M_m , M_e standing for the Earth-Moon distance, the Moon mass and the Earth Mass, respectively

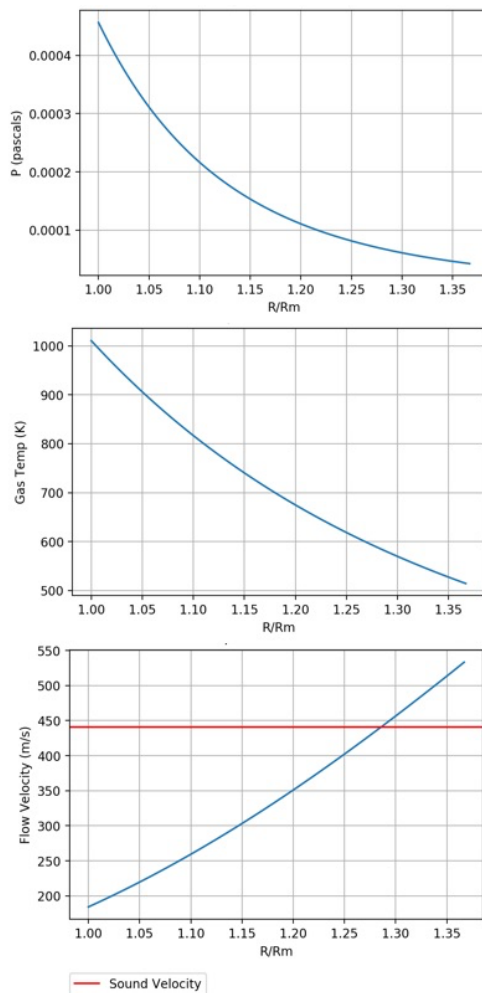


Figure 2 : Flow solution for a moon surface temperature=1000 K. top : pressure, Middle : Temperature, Bottom: velocity. X axis is the distance to the Moon's surface (in units of Moon radius).

When the protomoon is located at the Roche Limit, the size of its Hill Sphere is comparable to its physical radius, meaning that the kinetic energy necessary for a particle to leave the Moon is much lower than for the traditional definition of the escape velocity (loss of a particle to an infinite distance from the body). In this dynamical configuration, any gas leaving the Moon's surface will leave either from the L1 or L2 Lagrange point (see Figure 1). Due to 3-body effect, it will be difficult for the escaping gas to return to the Moon's surface, because any dissipative mechanism (radiative loss, viscous forces) will lower the gas potential energy (in the frame rotating with the Moon) and circularizing the gas orbit, and thus will repel the gas from the Moon (because of angular momentum conservation). As such,

the escaped gas will enter circular orbits around the Earth but will have been lost from the Moon.

So the main question is: is-it the possible for the vapor atmosphere, that may have topped the molten Moon, to escape from the Moon's surface?

Results: Using the formalism of hydrodynamical escape [19] we have computed the pressure, velocity, and temperature profile of the vapor above a magma ocean at the proto-moon surface, and under the Earth's tidal field (Figure 2). We assume the temperature and pressure at the Moon surface corresponds to the liquid/gas equilibrium at a given temperature. We find the gas evaporated from the magma escapes the Moon's surface at high velocity and is lost to the Earth. This allows an extensive and efficient escape of volatile species. Under some conditions, Zn can be depleted by a factor 100, for cooling time less than 10^4 years.

Conclusion: We conclude that Earth tidal fields promotes an efficient escape of the vapour generated by the early molten proto-moon, resulting in removal of more than 99% of the zinc. Even though the material cannot escape the Earth, it can escape the Moon and eventually be lost (through radiation pressure [20]) or be reaccreted onto the Earth. This is an alternative model to proposed protolunar disk escape models [12,13,14] but based on simpler and better-understood physics.

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