

DEVOLATILIZATION MECHANISM FOR A MOON OF FISSION ORIGIN;
 A. B. Binder, Institut für Geophysik, Neue Universität,
 D-2300 Kiel, W. Germany

While the lack of any significant ($\gg 1\%$ of the lunar mass) Fe or FeS lunar core (1,2,3) and the general similarities between the bulk composition and density of the moon and the terrestrial mantle (4,5,6,7) have always been strong points in support of the fission origin of the moon, the depletion of lunar volatile elements (e.g. Na, K, Pb, Rb, Bi) and compounds (e.g. H_2O) with respect to terrestrial materials has been regarded by many researchers as a fundamental difficulty with this mode of origin (8,9). However, it was pointed out by Binder (4) in his initial discussions of the petrological and selenochemical properties of a moon of fission origin that fission must have occurred from an essentially totally molten proto-earth. Hence the moon was also initially completely molten and most probably had super-liquidus temperatures for some time after fission. During this time the hot, newly formed moon would have lost some or most of its volatile components. The mechanism for this proposed devolatilization of the moon has been studied in more detail (10) and it can explain not only the loss of the volatile elements, but also the apparent differences in the olivine to pyroxene and iron to magnesium ratios between the moon and the earth's mantle (3,5).

As discussed by Ringwood (11) and others, the gravitational energy released during the accretion of the earth was most probably sufficient to raise at least the outer parts of the earth to $2000^\circ C$ or higher. Ringwood further points out that the potential energy released during core formation is sufficient to raise the temperature of the earth by another $2000^\circ C$. As a result, it seems rather certain that the proto-earth had temperatures in its outer parts in the range of 2000° to $4000^\circ C$. It then follows that the initial temperature of a fissioned moon must also lie in this range.

At temperatures near or above $2000^\circ C$ most materials are (at low pressures) in a vapor state. Therefore, both the moon and earth would have had primitive atmospheres of evaporated elements and compounds similar to the type Ringwood envisions for the earth as the basis of his precipitation hypothesis (11). It is, of course, obvious that the more volatile elements and compounds would be enriched in these hot primitive atmospheres and if an effective loss mechanism were acting on the lunar atmosphere (but not on the earth's) the moon would have been able to lose a large part of its volatile elements. The existence of such a loss mechanism can be readily found in the model for mass exchange between contact binary stars (e.g. 12).

Briefly, mass exchange between binary stars separated by only a few radii is as follows. As one of the pair begins to form an extended atmosphere late in its life time, the atmosphere becomes large enough to fill the Roche lobe of that star. At that point, matter passes freely through the lagrange (L_1) point connecting the Roche lobes of the star and is largely captured by the second star. The same process must have acted in

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the early earth-moon system.

A first order model of the conditions in the earth-moon system just after fission can be obtained as follows. First, fission of the proto-earth, which had a Poincare figure (13), resulted in an original lunar orbit at three earth radii ($\sim 19,000$ km) from the earth's center (just outside the Roche limit at 2.7 earth radii) (13). Using the solution to the restricted three body problem (14) and treating the earth and moon as point masses, L_1 was about 3000 and 16,000 km from the center of the moon and earth, respectively. The rotation rate of the earth after fission was only slightly less than that the proto-earth had before fission (~ 2.6 hr) (13). Therefore, the figure of the earth was a triaxial Jacobian ellipsoid with a polar radius of 4200 km, with equatorial radii of 5200 km and 12,000 km (13) and the apparent acceleration of gravity was about 300 cm/sec^2 and 1200 cm/sec^2 at the ends of the long and short equatorial axes of the earth, respectively. The moon's figure (for an orbital period of 7.3 hr (4) and neglecting tidal effects), would have been a MacLaurin oblate sphere with an equatorial radius of 1800 km and g at the lunar equator was about 150 cm/sec^2 . Based on these lunar and terrestrial radii, the L_1 point was only 1200 km from the surface of the moon, while the distance from the surface of the earth to L_1 varied from 4000 km to 11,000 km as the earth rotated.

As a first order approximation, it is assumed that the primitive atmospheres of the earth and moon were isothermal. Using the bulk composition for the moon as given in (4) and the fact that the major silicate forming oxides are dissociated into SiO , O_2 , Mg , Fe , Al_2O and Ca at temperatures greater than 2000°C , one can derive the scale heights (H) of the primitive atmospheres of the earth and moon for the range of temperatures given above (see Table 1).

Considering the case with $T=3000^\circ\text{C}$, the distance from the lunar surface to L_1 would have been only about $3H$. Thus, the density and pressure at L_1 would have been e^{-3} or 5% of that at the surface. However, for such small distances (in terms of H) between the surface (where $g=150 \text{ cm/sec}^2$) and L_1 (where $g=0$), the approximation used is very poor since the local scale height goes to infinity in the vicinity of L_1 . Thus the calculated 450 km scale height leads to an underestimation of the actual pressure and density at L_1 . It is more likely that the distance between the lunar surface and L_1 was equivalent to only about 1 "isothermal" scale height, i.e. the pressure and density were reduced only to values of about 30% of those at the lunar surface. In any case it is clear that a hot, primitive lunar atmosphere would have filled the lunar Roche lobe, would have poured through L_1 , and, for the most part, would have been captured by the Earth.

The reverse is not the case. Even in the most favourable configuration, i.e. when the long axis of the triaxial earth was pointed towards the moon, the distance between L_1 and the surface was 4000 km or $18H$ ($H=225 \text{ km}$). Thus, the pressure or density of the earth's atmosphere at L_1 was only e^{-18} or 10^{-8} of that at the surface. Thus, unlike the lunar case, the primitive terrestrial atmosphere was confined to the near surface of the

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earth as compared to the L_1 distance. It is clear that the earth's primitive atmosphere was not sufficiently expanded to have allowed terrestrial matter to pass into the lunar Roche lobe; the loss process worked only for the moon.

Extrapolation of the partial pressure vs temperature curves given for SiO and Mg (11) indicate that at 2000° to 3000°C the atmospheric pressure at the surface of the earth and moon would have been on the order of 10^2 to 10^4 atmospheres. Further, in cooling from 3000°C to solidus temperatures, the moon lost about 1.5×10^{30} ergs/gm of energy. Since the heat of vaporization is a few $\times 10^9$ ergs/gm (15), then, even if only 10% of the available energy went into heat of vaporization, a large fraction of the original mass of the moon would have been evaporated into the atmosphere. Thus, if the pressure and density of the lunar atmosphere at L_1 were about 30% of those at the surface, large quantities of the evaporated material, enriched in lunar volatiles, would have poured through L_1 as long as the moon was hot. Also, since a large fraction of the mass evaporated from the original moon, then, due to the relative high volatility of Mg and SiO as compared to Fe, Al_2O_3 and Ca, the ratio of Fe to Mg and olivine to pyroxene in the moon should be higher for the moon than for the earth, as is indicated by other lines of evidence (3,5).

Table 1
Isothermal scale height, H

Temp. °C	H (km) at lunar equator	H (km) at end of earth's a axis	H (km) at end of earth's b axis
2000	300	150	37
3000	450	225	55
4000	600	300	75

References: 1) Nakamura et al., 1974, Geophys. Res. Lett., 1, 137-140. 2) Wiskerchen and Sonett, 1977, Proc. 8th Lunar Sci. Conf., 515-535. 3) Binder and Voß, 1978, Lunar Planet. Sci. IX, 97-99. 4) Binder, 1974, The Moon, 11, 53-76. 5) Binder, 1976, The Moon, 16, 159-173. 6) Rammensee and Wänke, 1977, Proc. 8th Lunar Sci. Conf., 399-409. 7) Ringwood, 1978, Lunar Planet. Sci. IX, 961-963. 8) Taylor, 1975, Lunar Science: A Post-Apollo View, 335, Pergamon. 9) Smith, 1977, Proc. 8th Lunar Sci. Conf., 335-370. 10) Binder, 1978, Earth Planet. Sci. Lett., 41, 381-385. 11) Ringwood, 1970, Earth Planet. Sci. Lett., 8, 131-140. 12) Gyldenkerne and West (Eds), 1970, Proc. IAU Coll. No. 6, Copenhagen University Publ.. 13) Wise, 1963, J. Geophys. Res., 68, 1547-1554. 14) McCuskey, 1963, Introduction to Celestial Mechanics, 92-118, Addison and Wesley, 15) Ringwood, 1975, Composition and Petrology of Earth's Mantle, McGraw-Hill, Inc..