

NEW CONSTRAINTS ON THE SIZE OF THE LUNAR CORE AND THE ORIGIN OF THE MOON; H.E. Newsom, Institute of Meteoritics and Dept. of Geology, University of New Mexico, Albuquerque, NM 87131, USA, and S.K. Runcorn, Physics Dept., Imperial College, London SW7 2BZ, Great Britain, and Geophysical Institute, Univ. of Alaska, College, AK 99775 USA

Recent advances in the physics of core formation, in determining the abundances of siderophile elements in the Earth and Moon, and experimental determinations of metal-silicate partition coefficients are leading to a new understanding of the connection between the size of the lunar core and the origin of the Moon. These results are significantly different than previously assumed [1, 2]. Several years ago the arguments centered around two alternative models for the origin of the Moon. Ringwood and others [3] argued for an origin completely from the Earth's mantle, while Newsom [1] investigated the possibility of the formation of the Moon from chondritic material independent of the Earth. Recently, these models have converged toward a Moon made out of both terrestrial mantle and material from another source, such as a Mars-sized impactor planet.

The original idea of the formation of the Moon largely from the Earth's mantle has run into several problems which are best solved by addition of material from another source. This includes the different FeO contents of the Earth and Moon, the greater depletion of refractory siderophile elements in the Moon compared to the Earth, and the physical difficulty of ejecting mantle material and supplying it with enough angular momentum, without mixing in other material. Theories which form the Moon out of chondritic material have also run into serious difficulties. The co-accretion theory of lunar origin has problems with angular momentum, the low metal content of the Moon and the low abundance of V [4]. Another important constraint is the new realization that large degrees of partial melting are necessary for core formation to occur [5,6]. Early models of Newsom [1] showed that core formation at very low degrees of partial melting under very reducing conditions was required to explain the siderophile depletions in the silicate portion of the Moon, if siderophile abundances were initially chondritic. This model, however, is ruled out by the need for a large amount of melting to achieve core formation. Even the formation of the Moon largely from material in a Mars-sized impactor, by collisional capture, cannot easily explain the depletion of V observed in lunar silicates, because recent metal-silicate partitioning experiments suggest that V is depleted only by partitioning into the O-rich core of an Earth-sized planet [7].

The above arguments have led to a model for the origin of the Moon involving sub-equal amounts of material from the Earth's mantle and another source, probably a Mars-sized planet whose collision with the Earth initiated the formation of the Moon. This theory is dynamically plausible, and numerical simulations suggest that roughly 20% to 50% of the resulting Moon would come from the Earth's mantle [8]. In this model, the depletions of siderophile elements could come from the impactor and the Earth's mantle material, as well as from additional core formation within the Moon [8]. The depletion of V in the Moon is also consistent with a mixture of terrestrial mantle material and material that is not significantly depleted in V [9].

Investigating the nature of the lunar core in terms of the "mixed" model of lunar composition leads to a problem in deciding the initial abundances of siderophile elements as a starting point for geochemical models. One possibility is that the lunar siderophile depletion pattern is simply the result of mixing between the Earth's somewhat depleted pattern and material from a much more depleted mantle of an impactor. In this case the lunar core could be fragments of the impactor core and the chemistry of the lunar mantle would provide no information on the size or chemistry of the core. Several other possibilities could lead to a lunar mantle with siderophile abundances roughly similar to the present terrestrial mantle, including a mixed model where the impactor was depleted similar to the Earth's mantle. Other less likely possibilities include formation of the Moon entirely from the Earth's mantle by fission or impact processes, or formation of the Moon largely from an impactor with a depletion pattern similar to the Earth.

Starting with the assumption of Earth mantle abundances of siderophile elements, early calculations of Newsom [1] suggested that the slightly greater depletions observed in the lunar silicates could be achieved by segregation of only a very small amount of metal ($<< 1$ wt%). Because paleomagnetic data suggested the existence of a relatively large lunar core, Newsom [1] inferred from this calculation that the Moon could not have had an initial siderophile element pattern similar to the Earth's. This conclusion was echoed by Jones and Hood [2], who showed from geophysical considerations, such as the moment of inertia, that a significant lunar core is needed if the Moon has a terrestrial mantle composition. Such a core, they contended, would not be consistent with the observed depletions of siderophile elements.

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The above conclusions must be reevaluated because of two factors: Recent work on the physics of core formation suggests that large degrees of partial melting are necessary to achieve complete segregation of metal, due to the finite yield strength of partially molten systems [5,6]. A new evaluation of the possible oxidation state of the Moon, and the Ni content of the lunar core, suggests that the lunar core may have formed under relatively oxidizing conditions and may be Ni-rich [10].

Figures 1 and 2 represent new calculations of the size of a lunar core required to reproduce the observed depletion of siderophile elements in the Moon, starting out with a terrestrial siderophile pattern. Fig. 1 represents the assumption of an Fe-Ni core, and Fig. 2 represents the results for an Fe-Ni-S core, both assume partition coefficients for an oxygen fugacity of $\log fO_2 = -12$, at a temperature of 1275°C. The calculations assume a Ni content of greater than 15 wt% [10]. Cosmochemical constraints lead to maximum of 15% Ni in a 5 wt% metal core. The calculations show that a maximum size core of 4 wt% to 5 wt% S-rich and Ni-rich metal is consistent with the siderophile element depletions in the Moon. This size core is also consistent with the maximum size core allowed by several geophysical constraints [2]. Another important implication of having a relatively large core, is the possibility of generating a magnetic field. We are currently investigating the possible energy sources for such a magnetic field, including energy from the solidification of a lunar core.

Current data and the model calculations described above lead to the following conclusions regarding the lunar core. Geophysical constraints and the existence of an early magnetic field may require a relatively large lunar core (4 wt% - 5 wt%). Formation of the Moon by coaccretion or capture is unlikely, due to angular momentum problems and the small size of the lunar core. An impact origin of the Moon solves the problem of the small size of the lunar core (< 5 wt%), compared to the Earth's large core (30 wt%). Constraints on the chemistry of the impactor allow a cosmochemically plausible planet [8]. The depletion of V, Cr and Mn in the Moon may indicate a substantial fraction of Earth mantle material was incorporated into the Moon. Assuming the mixture of impactor and mantle material started out with Earth mantle initial abundances of siderophile elements, a 4 wt% to 5 wt% S-rich and Ni-rich core is consistent with the observed siderophile element depletions, if the core was Ni-rich and formed under relatively less reducing conditions than previously assumed [1]. Additional data on siderophile elements in the Moon will provide better constraints on variability of depletions in the Moon, and provide clues to core formation and homogenization of the Moon.

REFERENCES [1] Newsom (1986) in *Origin of the Moon*, Lunar and Planet. Inst., 203. [2] Jones and Hood (1990) in *Origin of the Earth*, Oxford, 85. [3] Ringwood (1986) *Nature* 322, 323. [4] Ringwood (1989) *Earth Planet. Sci. Lett.* 95, 208. [5] G.J. Taylor (1989) *Lunar and Planet. Sci.* XX, 1109. [6] Stevenson (1990) in *Origin of the Earth*, Oxford, 231. [7] Ringwood (1989) *Z. Naturforsch.* 44a, 891. [8] Newsom and S.R. Taylor (1989) *Nature* 338, 29. [9] Newsom (1990) *Lunar and Planet. Sci.* XXI, 875. [10] Seifert et al. (1988) *Geochim. Cosmochim. Acta* 52, 603.

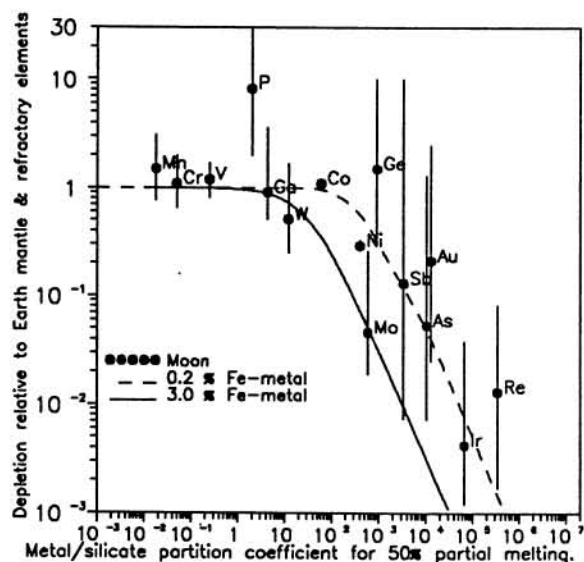


Figure 1

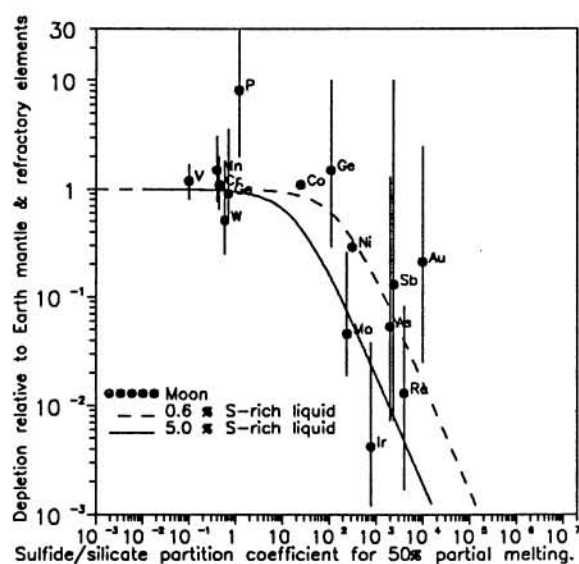


Figure 2