LUNAR GEOSCIENCE ORBITER AND THE ORIGIN OF THE MOON.

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Introduction

The **Apollo** and **Luna** programs generated a wealth of new information concerning the Moon through *in situ* measurements on the lunar surface and through detailed physical, chemical, isotopic, and petrological studies of returned samples. In view of this wealth of detailed information, it is perhaps surprising that most hypotheses of lunar origin attempt to satisfy just four principal observations, only one of which is a direct result of lunar sample studies. These observations are (i) the rotational angular momentum of the Earth-Moon system, (ii) the orbital characteristics of the Moon, (iii) the low mean density of the Moon which implies at best a small metal core, and (iv) the very low volatile content of the Moon. The relative lack of impact of detailed lunar sample studies on theories of lunar origin results in part from the difficulty in extrapolating from samples collected at nine surface sites and a few *in situ* measurements to global lunar properties. The principal contribution of the **Lunar Geoscience Orbiter (LGO)** to theories of lunar origin will arise from global surface coverage of the X-ray and γ-ray spectrometers, and to the possibility of a positive detection of a lunar core using a combination of the magnetometer and electron reflectance experiments. Global geochemical surface coverage will permit estimates to be made of bulk lunar inventories of elements such as U and of the Mg#, with fewer assumptions than are necessary at present. Such estimates constrain the provenance(s) of proto-lunar material. Determination of core size, coupled with estimates of siderophile element abundances in the lunar mantle, will constrain initial siderophile element abundances in proto-lunar material and, hence, the provenance(s) of that material.

Constraints on Lunar Origin

Refractory Element Abundances in the Lunar Mantle: Direct samples of the lunar mantle are not available. The only "global" estimates of refractory element abundances come from the orbital γ-ray and X-ray analyses of the lunar surface performed during the Apollo 15 and 16 missions. From these experiments, mean highland surface concentrations for K of approximately 600 ppm and for Th of approximately 0.9 ppm are derived [1]. In order to convert these estimates into bulk lunar mantle abundances of a refractory element such as U, for which there is an independent geophysical estimate, various assumptions must be made. The principal assumptions are the mean thickness of the crust, the distribution of these elements in the crust, and the efficiency of extraction of these elements from the differentiated lunar mantle.

For example, if the mean crustal thickness is 75 km, the crust corresponds to 12.4% by volume of the Moon. If K and Th are uniformly distributed throughout a 75-km-thick crust, and if K and Th were quantitatively extracted from the mantle into the crust, the bulk Moon concentrations of K and Th are 75 ppm and 112 ppb respectively. Using a lunar K/U ratio of 2500 and a chondritic Th/U ratio of 3.53, an estimate of approximately 31 ppb U in the bulk Moon is obtained from both K and Th [2]. Within uncertainties discussed below, this value is consistent with the range of 33-44 ppb U derived from heat flow measurements [3].

Mg# of the Lunar Mantle: The Mg# of the lunar mantle may be estimated from petrological and geophysical considerations. Most petrological estimates are based on mare basalts or mare glasses and require assumptions which are not unambiguously provable. Nevertheless, a consistent Mg# for the bulk lunar mantle of about 0.8 is obtained by several authors (see [2] for a discussion). Geophysical estimates based on seismic velocity considerations are consistent with these estimates [4]. This "consensus" is weakened somewhat by petrologic estimates based on the most magnesian terrae rocks, which yield a Mg# of 0.87-0.91 [5], a value indistinguishable from the terrestrial upper mantle value of 0.89.

Mass of the Lunar Core: Newsom [6] has shown that siderophile element abundances inferred for the lunar mantle display the signature of segregation of metal from silicate. Thus a small metal core probably exists. Hood and Jones [4] reach the same conclusion on the basis of seismic velocity considerations, as do other workers using other approaches (see [7] for a discussion). The mass of the lunar core is uncertain and the probable presence of a lunar core does not presently provide significant constraints on the provenance(s) of proto-lunar material.

Principal Uncertainties and LGO Solutions

Refractory Elements: The lunar estimate of 31 ppb for refractory U is significantly higher than the value of 20 ppb U for the Earth, but considerable uncertainties exist. For example, if the mean thickness of the lunar crust were as low as 50 km (corresponding to 8.4 vol. % of the Moon), keeping all other assumptions the same, the bulk Moon concentrations of K and Th would be 50 ppm and 76 ppb respectively, leading to an estimate of the concentration of U of approximately 20 ppb, the same as estimated for the Earth. A spacecraft gravity system on **LGO** would permit detection of gravity anomalies associated with farside features, which in turn can be used to infer crustal thickness. In the absence of this experiment, an improved estimate of crustal thickness is expected because of (i) the

LGO: LUNAR ORIGIN

Drake, M.J.

availability of global topography from the altimeter experiment and (ii) high latitude nearside gravity from Earth-based tracking.

Some K and Th must remain in the mantle since mare basalts derived from the interior with model Rb/Sr ages of less than 4.5×10^9 years contain K and Th, thus raising the estimates of bulk U concentration. **LGO** will indirectly address this issue by providing more complete estimates of the K, Th, and U contents of mare basalts, which in turn may be used to infer mantle inventories of these elements.

Ryder and Wood [8], on the basis of sample studies, and Andre and Strain [9], on the basis of Apollo orbital geochemical measurements, have argued that the lunar crust is heterogeneous and layered. If K, U and Th are not uniformly distributed in the crust, the mean crustal concentrations and, hence, bulk lunar concentrations must be appropriately adjusted. **LGO** will provide considerable information about both the lateral and the vertical distribution of K, U, and Th. The precision of these measurements depends on the concentrations of Th, U, and K, and on the length of measurement time. For example, an anorthositic norite composition typical of terrae contains 0.6 ppm Th, 0.2 ppm U, and 400 ppm K. The precision of measurement (at 30° latitude) for these elements is 7%, 7%, and 5%, respectively, leading to uncertainties for the ratios of two elements on the order of 10%. Such precision is adequate to enable good comparisons between terrestrial and lunar values, as well as to reveal significant differences among different regions of the lunar surface. Although orbital γ-ray experiments analyze only the outer few centimeters of the lunar surface, depth information may be obtained from analyses of large basin ejecta. For example, the Gargantuan Basin (3200 km diameter) and the Big Backside Basin (1900 km diameter) may have penetrated to the lunar mantle [10]. Ejecta close to the basin rims represent excavated, deep-seated rocks. Thus, global orbital geochemical maps created by **LGO** will remove the considerable uncertainty that exists concerning crustal heterogeneity and hence global lunar U concentration, and might provide direct measurement of excavated mantle materials.

The apparent agreement between U abundances obtained by geochemical mass balance and from heat flow may be misleading because deductions from heat flow are also model dependent. For example, both heat flow probes were located at mare/terrae boundaries and several authors (most recently [11]) have argued that this geological setting will lead to an overestimate of global U concentration. The microwave radiometer experiment may permit the global mean heat flow to be estimated to ±20%, a significant improvement over the two Apollo measurements, and may resolve the uncertainty in lunar heat flow arising from the unfortunate siting of both Apollo probes at mare/terrae boundaries.

Mg# of the Lunar Mantle: **LGO** will enable the Mg# of individual regions of high Mg and Fe concentrations to be determined to within about ±3%, and averages over broader regions of lower concentrations to that precision or better. If the largest lunar craters really did penetrate into the lunar mantle, we may be able to measure the Mg# in the ejecta from the mantle, providing us with a more direct determination than the model dependent petrological and geophysical estimates discussed above.

Mass of the Lunar Core : The combination of the magnetometer and electron reflectance experiments may permit positive detection of a lunar core and raises the possibility of determining the mass of the core and, hence, constraining the provenance(s) of proto-lunar material through use of siderophile trace element abundances as discussed above.

Two Spacecraft?

A second simultaneously operating spacecraft, perhaps launched by the USSR, ESA, or Japan, could augment the capabilities of **LGO** and raise its probability of achieving significantly enhanced scientific goals if it, say, (i) served as a relay for farside gravity data, thus improving the estimates of lithospheric thickness; (ii) provided a second magnetometer for deep electromagnetic sounding and determination of the radius of the core; and/or (iii) installed a seismic network using penetrators, thus permitting direct determination of the thickness of the lithosphere and the radius of the core.

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