GEOPHYSICAL CONSTRAINTS ON THE LUNAR INTERIOR: STATUS AND REMAINING ISSUES.

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Since the immediate post-Apollo period, a series of developments has led to significant refinements of geophysical constraints on lunar internal structure and bulk composition. These refined constraints, if they are valid, would impose new limits on models of lunar origin and early evolution.

Seismic Constraints:

Nakamura (1) originally reported the first analysis of the complete five-year, four-station Apollo seismic data set. The resulting P and S-wave mantle velocity model was characterized by a large velocity increase at a depth of approximately 500 km. This velocity increase was assumed to mark a transition from the lunar upper mantle to the middle and lower mantle. A recent application of a more computationally intensive inverse Monte Carlo technique to the same arrival time data has obtained a similar large velocity increase near 550 km depth (2). In addition, the latter analysis has reported evidence for a more inhomogeneous velocity structure in the middle and lower mantle than in the upper mantle. (However, this more inhomogeneous structure could also reflect increased arrival time errors at larger distances and/or model insensitivity at these depths.) Following the publication of the Nakamura velocity model, several attempts to synthesize available petrological, seismic, and other geophysical constraints on lunar bulk composition and structure were reported (3,4). These analyses showed that the magnitude of the inferred velocity increase at the base of the upper mantle (1.0–1.5 km/s for P-waves) could not easily be explained by a phase change alone in a compositionally homogeneous mantle (e.g., from the spinel to the garnet stability field for Al-bearing silicates). Rather, a composition change (an increase in aluminous phases and/or an increase in Mg# from the upper to the middle and lower mantle) was probably required.

In general, lunar bulk composition and evolutionary models that assume differentiation of the upper mantle only, that are more aluminous than the terrestrial mantle, and that are characterized by an increase in Mg# in the middle and lower mantle are most successful in matching the Nakamura seismic velocity model. The more inhomogeneous velocity structure of the middle and lower mantle that characterizes the more recent Khan et al. (2) velocity model is also consistent with melting and differentiation of the upper mantle only; the middle and lower mantle would consist of relatively "pristine" and therefore inhomogeneous material.

Moment of Inertia:

The variation of mass density in the Moon is constrained primarily by the moment of inertia value together with the mean density (3.3437 ± 0.0016 g cm^{-3}) (5), mean crustal thickness (~ 61 km) (6) and models for the thermal structure of the mantle. Recently, an improved determination of the polar moment of inertia factor (C/MR^2) as 0.3932 ± 0.0002 has been derived from Lunar Prospector Doppler gravity data (7). The upper bound of 0.3934 is only slightly larger than that (0.3928) adopted in previous detailed density modeling of the mantle using seismic velocity models as an added constraint (3,4). These studies found that mantle density increases alone were insufficient to match this adopted upper bound for plausible thermal, compositional, and evolutionary models of the lunar interior. The addition of a small dense (Fe or FeS) core was generally required to match all available constraints. However, the core radius was not strongly constrained.

Magnetic Sounding:

An alternate approach toward investigating the existence and size of a metallic core takes advantage of the core's high electrical conductivity relative to that of the mantle. One method uses time-dependent magnetic fields and requires data from at least two magnetometers (8). An alternate method requires data from a single magnetometer in low-altitude lunar orbit. Specifically, time intervals are identified when the Moon is exposed for prolonged periods in a nearly spatially uniform magnetic field in a near-vacuum environment. Conditions that approximate this idealized situation occur occasionally each month when the Moon passes through a lobe of the geomagnetic tail in the Earth's magnetosphere. Exposure of the Moon to such a steady field induces electrical currents in the interior with an associated negative induced magnetic dipole moment. After currents in the lunar mantle have decayed ($\sim$ 5 h or less), any residual induced moment is expected to be due to currents near the surface of a possible highly electrically conducting core. A recent application of this method using Lunar Prospector magnetometer data has yielded an estimate for the core radius of 340 ± 90 km (9). For an Fe-rich composition, such a core would represent 1 to 3% of the lunar mass. However, the magnetic sounding technique does not determine the core composition: A molten silicate core would have an electrical conductivity high enough to explain the observed negative induced moment. The inference that the implied core is metallic in composition comes entirely from the moment of inertia constraint and density modeling.

Laser Ranging:

Lunar laser ranging measurements of physical libration parameters have shown that the lunar rotation axis is advanced by about 0.2 arcsec from the Cassini alignment, indicating significant internal dissipation. In addition to solid-state friction in the lunar mantle, friction at the boundary between a possible fluid (molten silicate or metallic) core and a solid silicate mantle appears to be necessary to explain the magnitude of this advance. The most recent analysis of all available laser ranging data together with an improved gravity field from LP Doppler tracking data has yielded a 1σ upper limit of 352 km on the core radius for an assumed Fe composition (10). For an Fe-FeS eutectic composition, the upper limit is increased to 374 km.

Gravity / Topography Data:

Recent analyses of Clementine and Lunar Prospector gravity and topography data have yielded new constraints on lateral variations of crustal thickness and/or density as well as on the rigidity of the lunar lithosphere at the time of loading by surface topography or density variations (6,11). In general, the gravity and topography data indicate large lateral variations in crustal thickness ($\sim$ 20 - 110 km) and a range of compensation states that imply a more complex near-surface thermal history than had previously been considered.

Summary and Interpretation:

The available seismic velocity models of the lunar mantle are most consistent with initial melting and differentiation of the upper mantle only ($<$ 550 km depth), representing roughly two-thirds of the lunar volume. The middle and lower mantle must consist of more aluminous and MgO-rich phases in order to be consistent with an inferred large velocity increase (1.0–1.5 km/s for P-waves) at the base of the upper mantle. As pointed out by Mueller et al. (4), such a refractory-rich deep interior could be a consequence of fractional condensation of an impact-produced vapor cloud. These condensates may have accreted to form a small proto-Moon that would have remained unmelted because of smaller accretional energy deposition, a larger surface area to volume ratio, and a somewhat higher mean melting temperature. Later addition of less refractory material at higher impact velocities on a larger body may have melted the outer 500 km of the final proto-Moon, producing the upper mantle and crust.

The combination of gravity, magnetic field, and laser ranging data described above appear to be most consistent with a small metallic core representing 1 to 3% of the lunar mass. Such a small core is generally consistent with the giant impact model for lunar origin, which predicts formation of the Moon mainly from mantle silicates in both the Earth and the impactor (12,13).

Remaining Questions:

The conclusion that the deep lunar interior (below 500-550 km depth) remains undifferentiated and is composed of more aluminous and/or MgO-rich phases depends heavily on the inferred large velocity increase at the base of the upper mantle. Although Khan et al. (2) have recently supported the reality of this increase using the arrival time data published by Nakamura (1), a completely independent determination of the mantle velocity structure using either the original Apollo seismic time series or a new seismic data set would greatly strengthen this inference. A new data set can only be acquired if a new, more widely distributed seismic network is deployed on the Moon. Until such a network can be deployed, further analysis of the Apollo seismic data could be useful for verifying the reality of the positive velocity increase near 500 km depth.

The inference of a small metallic core existing at the bottom of an undifferentiated lower mantle raises the question of whether core formation is possible under these circumstances. Specifically, would a metallic liquid cumulate at the base of the melted upper mantle have successfully migrated to the lunar center if the middle and lower mantle had remained mostly unmelted? Or, could such a core have accreted heterogeneously from the impact vapor cloud? If the above inference is correct, then the answers to these questions would bear directly on models of lunar origin and earliest evolution.

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