The "Core" of the Moon: Iron or Titanium Rich? Mark A. Wieczorek and Maria T. Zuber, Massachusetts Institute of Technology, Dept. Earth, Atmospheric and Planetary Sci., Cambridge (markw@quake.mit.edu).

Introduction: The existence, or non-existence, of a lunar iron core has fundamental implications for understanding the Moon's origin and subsequent evolution. As one example, a convecting iron core could possibly have given rise to an internally generated magnetic field that could be the source of the strong surface magnetic fields observed from orbit as well as the paleomagnetic fields measured in the lunar samples. After the moment of inertia of the Moon was first determined, though, it was quickly realized that if the Moon did have an iron core, that it must be small. Many studies have been published over the past 30 years attempting to constrain the size of this putative core, and most researchers are currently in agreement that the Moon probably possesses a liquid metallic core (Fe with some Ni, S, and C) that is less than 400 km in radius. This inference is based upon modeling of the Moon's (1) moment of inertia [e.g., 1], (2) induced magnetic dipole moment [e.g., 2], (3) rotational dissipation as observed in the lunar laser ranging (LLR) data [e.g., 3, 4], (4) combined seismic and moment of inertia data [e.g., 5, 6, 7] and (5) depletion of highly siderophile elements in the mare basalt source region [e.g., 8].

While the above studies are all in rough agreement with each other, the inferences drawn from each are not entirely unique. For instance, the core size inferred from the magnetic data depends upon the assumed electrical conductivity of the "core." Similarly, the core size inferred from the LLR data depends upon the assumed core density and viscosity. In this study we ask how unique the inferences drawn from the above studies are, and whether alternative models of lunar structure could just as easily satisfy the available data. Here we address the specific question as to whether the Moon might possess a molten titanium-rich silicate core.

There are two reasons why one might suspect the Moon to have a titanium-rich core. First, it is widely accepted that when the Moon formed that a large portion of it was initially molten. The crystallization of this magma ocean subsequently gave rise to the anorthositic crust and KREEP-rich rocks [e.g., 9, 10]. Near the terminal stages of magma-ocean crystallization, ilmenite is predicted to crystallize and sink through the lunar mantle. If this dense late-stage magma-ocean cumulate sank all the way to the center of the Moon [e.g., 11, 12], then the Moon might today possess a large "core" of titanium-rich materials [e.g., 13].

A second reason for suspecting that the Moon might possess a titanium-rich core comes from buoyancy considerations of lunar basaltic magmas. Because of the high iron and titanium concentrations that are found in these basalts, Delano [14] realized that these magmas might be negatively buoyant with respect to the deep lunar mantle. Specifically, he showed that if a basaltic melt with a titanium concentration greater than about 16 wt.% was produced deep within the Moon, that this melt would sink. This result has since been confirmd by laboratory experiments [e.g., 15]

Below we briefly review the geophysical evidence in favor of the Moon possessing a metallic core and show that this evidence is equally consistent with having a dense titanium-rich molten silicate core.

Moment of Inertia: The Moon's normalized moment of inertia has been determined to have a value of 0.3931±0.0002 [1]. Since this value is very close to the theoretical value of a homogenous sphere (0.4), it is very easy to construct plausible models of lunar structure that possess either a small iron-rich core (<450 km), or no core at all. For instance, the measured moment of inertia could be easily satisfied by a mantle that was zoned in composition, with the top of the mantle having a composition of Fo_{90}, and the lower mantle having a composition close to Fo_{70}. Thus, if a small titanium rich core was gravitationally stable (i.e., more dense than the mantle), it would likely be consistent with the measured moment of inertia.

Induced Dipole Moment: When the Moon passes through the Earth's geomagnetic tail lobe, a small diamagnetic dipole field is induced within the Moon [see 2]. This is a result of a high electrical conductivity region in the Moon that excludes the ambient field. In Figure 1 we plot the range of core sizes as a function of electrical conductivity that are consistent with this observation. As is seen, if the core of the Moon is made of metallic materials ($\sigma=10^6$ mhos/m), this data implies a core that is between 253 and 431 km in radius [see also 2]. Alternatively, if the conductivity of this core is typical of a basaltic melt, say $\sigma=10$ mhos/m, then the size of this core would be slightly larger with a radius between 361 and 538 km.

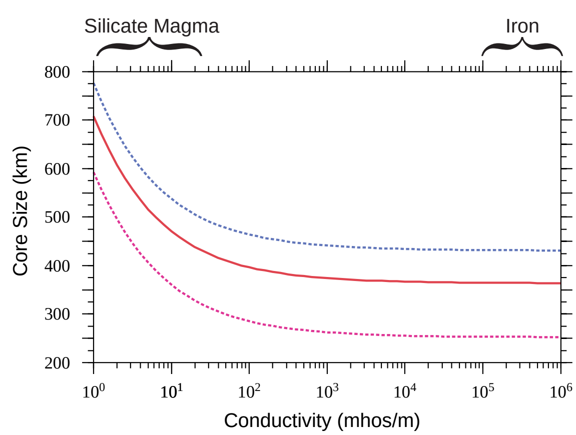

Figure 1. Core size as a function of electrical conductivity. The red, blue and magenta lines represent the values using the average and ±1σ limits of the observed induced dipole moment of the Moon.

Rotational Dissipation: The rotational configuration of the Moon is currently in a Cassini state where the lunar spin axis, orbit normal, and ecliptic normal are all nearly coplanar. Small displacements from this configuration indicate strong sources of dissipation within the Moon. The dissipation signatiures require the existence of both solid-body tidal dissipation, as well as dissipation at a liquid-core/solid-mantle interface [4]. The inferred size of this molten core depends both upon its assumed viscosity and density, and in Figure 2 we plot the dependence of the core size as a function of density. The core size is only slightly dependent upon the assumed viscosity, as an order of magnitude increase in viscosity would only result in a 20 km decrease in core radius. If the core is composed of pure liquid iron, then this core is constrained to have a radius between 313 and 347 km. Alternatively, if the core density is typical of a dense titanium-rich basaltic melt (~3.5 g cm^{-3}) then the core radius is constrained to lie between 372 and 413 km.

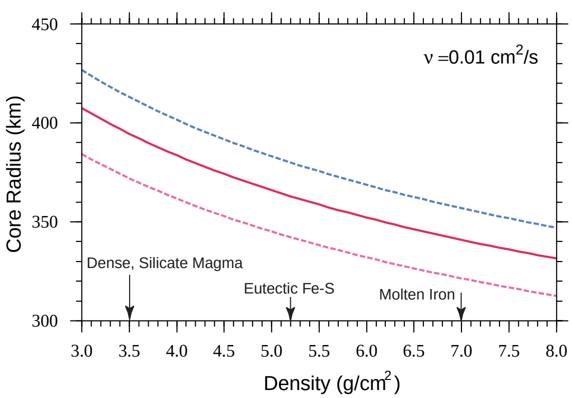

Figure 2. Core size as a function of density as implied by the LLR data. The red, blue and magenta lines represent the values using the average and ±1σ limits of the amount of dissipation occurring within the core. ν is the assumed kinematic viscosity.

Apollo Seismic Data: Khan and Mosegaard [16] have recently placed constraints on the density of the lunar interior by modeling the free-oscillations of the Moon as detected in the Apollo seismic data. They found that the density of the Moon gradually increases from a value of 3.7±0.3 g cm^{-3} at a radius of 500 km to a value of 4.7±0.4 g cm^{-3} at the center of the Moon. This model result is clearly inconsistent with the Moon possessing a pure iron core. Since an Fe-FeS eutectic core should have a density of about 5.2 g cm^{-3} for the range of pressures and temperatures that are expected in the core, this data also appears to be inconsistent with the Moon possessing an iron-sulfur core as well. As noted by Khan and Mosegaard [16], this data is consistent with the "core" of the Moon being composed of dense silicate materials. To account for this relatively "high" density, the core would be required to have a large concentration of both iron and titanium [e.g., 14, 17].

Thermal Considerations: If both the composition of the Moon's core and its thermal history were known, then it would be possible to determine whether it is currently molten or solid. While thermal histories of the Moon's interior possess a wide range of possibilities, it appears that the core temperature was probably somewhere between 1350 and 1750ºC at 4 Ga, and is currently between 1000 and 1400ºC. As the solidus of pure iron is ~1610ºC, a pure iron core would have completely crystallized by the present time. However, if carbon or sulfur were alloyed with iron, then the solidus temperature at the eutectic point would be decreased to about 950ºC [18, 19]. Thus, an Fe-FeS-C core would likely be partially molten today, consistent with the LLR results. While the phase relationships of an iron and titanium-rich silicate melt at core conditions are not well known, the liquidus of the Apollo high-titanium black glass at core pressures is 1570ºC [20]. It thus seems likely that an iron- and titanium-rich silicate core could be partially molten at the present time as well.

Conclusions: While much of the above geophysical data is consistent with the Moon possessing a small Fe-FeS-C core, the recent free-oscillation inversion of Khan and Mosegaard is inconsistent with such a model. As an alternative, we find that all of the geophysical data is consistent with the Moon possessing a dense, titanium-rich, molten silicate core that is slightly larger than the previous iron-core estimates. If this is indeed the case, then one has to reconcile this scenario with the highly siderophile-element data [e.g., 8] which suggests that the Moon did indeed undergo a core forming event. If the Moon formed as a result of a giant impact, we suggest that this "core forming event" may have occurred in the "proto-Moon" before it collided with the Earth. During the giant impact, the core of the proto-Moon would have accreated to the Earth.

References:

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