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Precession of the Lunar Core

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Abstract

Goldreich [3] showed that a lunar core of low viscosity would not precess with the mantle. We show that this is also the case for much of lunar history. But when the Moon was close to the Earth the Moon's core was forced to follow closely the precessing mantle, in that the rotation axis of the core remained nearly aligned with the symmetry axis of the mantle. The transition from locked to unlocked core precession occurred between 26.0 and 29.0 Earth radii, thus it is likely that the lunar core did not follow the mantle during the Cassini transition. Dwyer and Stevenson [1] suggested that the lunar dynamo needs mechanical stirring to power it. The stirring is caused by the lack of locked precession of the lunar core. So, we do not expect a lunar dynamo powered by mechanical stirring when the Moon was closer to the Earth than 26.0 to 29.0 Earth radii. A lunar dynamo powered by mechanical stirring might have been strongest near the Cassini transition.

1 Introduction

Paleomagnetic measurements of lunar rocks show magnetic remanence most easily explained by a long-lived early lunar dynamo [2]. Dwyer and Stevenson [1] argued that the only plausible driving force for an early lunar dynamo is mechanical stirring of the liquid core due to the relative motion between the core and mantle. This driving mechanism is only an option if the core of the Moon does not precess along with the mantle.

The Moon is in Cassini state 2 [4], so the spin axis of the mantle precesses along with the orbit of the Moon. Goldreich [3] showed that a liquid lunar core of low viscosity would not precess with the mantle. The inertial coupling mechanism, active on the Earth [5, 6], fails for the Moon because the ellipticity of the core-mantle boundary is smaller than required to cause the core to precess with the mantle. We address here whether the lunar core precessed with the mantle at earlier epochs.

If the core is locked to the mantle (as for the Earth), then the spin axis of the core is nearly aligned with the symmetry axis of the core-mantle boundary. If the spin axis of the core is slightly displaced from this configuration then the spin axis precesses about the symmetry axis with the core precession frequency ω_c [8]

$$\omega_c = \omega \, f_c \, (C/C_m), \tag{1}$$

where ω is the rotation frequency of the Moon, f_c is the core flattening, and C/C_m, the ratio of the polar moment of inertia of the Moon to that of the mantle (the Moon excluding the core), is approximately 1 for the Moon.

Whether the core is locked to the mantle depends on the relative frequencies of the precession of the core and the mantle [5]. If the mantle precesses faster than the core $\omega_m > \omega_c$, as is the case today, the core will not follow the mantle. However, if the precession frequency of the core is larger than that of the mantle $\omega_c > \omega_m$, the core and mantle will precess together, with the core oscillating around the symmetry axis of the mantle with the frequency ω_c.

Goldreich argued that the lunar core flattening is too small today for the inertial coupling mechanism to lock the core to the mantle. But earlier in the lunar history, the Moon was closer to the Earth, and rotated more rapidly, so the Moon was subject to greater tidal and centrifugal forces. Thus the lunar core flattening was larger in the past. Here, we model the past ellipticity of the lunar core-mantle boundary and compare the estimated precession rate of the core to that of the mantle to determine when the lunar core was locked to the mantle.

2 Model and Results

For the history of the lunar orbit, we use the Mignard model of Touma and Wisdom [7]. We approximate the density in the Moon by a two layer model, with constant density in the mantle and in the core. The core is presumed to be fluid.

The origin of the shape and moments of the Moon is still discussed. It is unclear when the current fossil bulge of the Moon was established. We consider two models: the non-hydrostatic mantle model has a mantle with the current shape of the Moon and the hydrostatic mantle model has a mantle in hydrostatic equilibrium with the rotation state, which should be applicable at an early epoch. Given one of these mantle shapes, we compute the shape of the core-mantle boundary assuming it is in hydrostatic equilibrium.

The potential acting on a particular mass element in the Moon includes the rotational potential, the tidal potential, and the potential due to the mass distribution in the Moon. We find the surface on which this potential is constant both numerically and analytically, to first order in the shape parameters, as the Moon evolves in semimajor axis, inclination, and obliquity.

Figure 1 shows the periods of precession for the mantle and for a core with 350 km radius. We see that at large semimajor axes the precession of the fluid core is not coupled to the precession of the mantle, but at small semimajor axes the two precess together. The point of transition is uncertain ($26.0R_e$ - $29.0R_e$, where R_e is the radius of the Earth), because the semimajor axis at which the Moon developed its nonhydrostatic shape is uncertain.

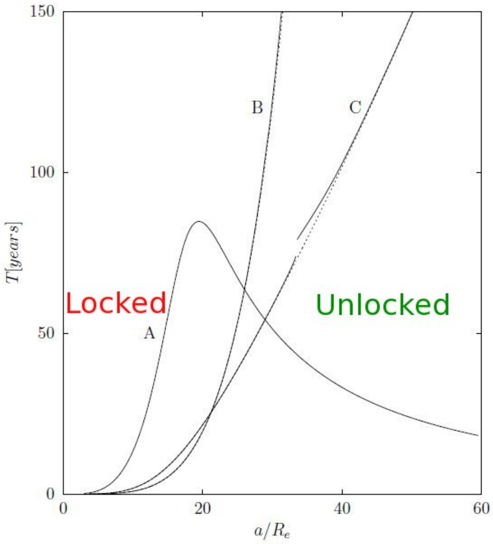

Figure 1: The period of precession of the lunar orbit and lunar mantle (curve A), of the lunar core in the "hydrostatic mantle" model (curves B), and of the lunar core in the "non-hydrostatic mantle" model (curves C), plotted as a function of lunar semimajor axis in Earth radii. The gap in the non-hydrostatic mantle model occurs at the Cassini transition.

The Cassini transition occurs at around $33.4R_e$. We see that it is likely that the core did not follow the mantle during the Cassini transition. Since the obliquity of the Moon is large during the Cassini transition, we may speculate that there was a large magnetic field during the transition because of the large stirring. So we might expect nonzero lunar paleomagnetic measurements to cluster near the time of the Cassini transition, perhaps allowing us to constrain that time. At present there are not enough paleomagnetic data to assess this hypothesis.

3 Conclusion

The fluid core of the Moon does not precess with the mantle of the Moon. We have shown that this is also the case for much of lunar history. But when the Moon was close to the Earth the core followed the mantle. The transition occurred at $26.0R_e$ - $29.0R_e$.

Dwyer and Stevenson [1] suggested that the lunar dynamo needs mechanical stirring to power it. The stirring is caused by the lack of locked precession of the lunar core. So, we do not expect a lunar dynamo powered by mechanical stirring when the Moon was close to the Earth.

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