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Our Large Moon Does Not Stabilize Earth's Axis

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Abstract

Obliquity is chaotically unstable if axial precession resonates with perturbations from other planets in a planetary system. Increased tidal forces from a large moon help avoid this by increasing the precession frequency but the associated large tidal drag also slows planetary rotation, and hence precession, thus accelerating evolution towards instability. Modelling of Earth-Moon-like systems with different lunar mass, angular momentum, tidal drag and obliquity indicates that systems with large moons are unstable after 4.5 Gy of evolution. Hence, our Moon does *not* contribute to habitability by stabilizing our axis but, instead, very nearly produced instability! This "near-miss" may imply that large moons benefit habitability for reasons other than axial stability.

1. Introduction

It is frequently speculated that Earth's unusually large satellite contributes to our planet's habitability. More specifically, Laskar et al's classic paper [1] is often misinterpreted as implying that the Moon stabilizes our axis. However, whilst greater tidal forces increase the axial precession rate and hence help avoid chaotic resonance with orbital perturbations, increased tidal drag also slows rotation which reduces precession over time. A large moon therefore ensures that a planet's precession rate is initially far from resonance but it also shortens the time to reach resonance as tidal interactions spin-down the planet. Hence, it is not clear whether, after say 4.5 Gy, a planet with a large satellite is more likely or less likely to have a stable axis. Here, I investigate Earth-Moon-like systems to establish the requirements for long-term axial stability.

2. Assumptions

The effects of four possible changes to the true Earth-Moon system are investigated here. The lunar mass and the total angular momentum would have been substantially altered had the impactor mass or impact parameter of the Moon-forming collision been different [2]. The mean tidal drag strength could differ too on other Earth-like worlds since this is controlled by continent/ocean configuration and by tidal frequency which varies as the planet's rotation slows [3]. Finally, obliquity could also be significantly different on alternate Earths. Analysis of the effects of changing these parameters is based upon three, well-established, relationships.

Firstly, in a coplanar approximation, recession of the Moon is controlled by

$$da/dt = f\, a^{-5.5} \qquad (1)$$

[4] where a is distance, t is time and the tidal drag factor f is given by

$$f = 3kmR^5\mu^{0.5}/QM \qquad (2)$$

with k the tidal Love number, m lunar mass, R Earth's radius, $\mu = G(M+m)$, Q tidal dissipation and M Earth's mass. Note that f increases with lunar mass and can also change through time since k and Q depend upon ocean geometry and upon the tidal frequency [3].

Secondly, Kepler's 3rd Law combined with angular momentum for the Earth-Moon system (neglecting lunar rotation) gives

$$L = a^{0.5}\mu^{0.5}m' + \Omega_e C \qquad (3)$$

where L is angular momentum, $m' = mM/(m+M)$, Ω_e is Earth rotation rate and C is the Earth's moment of inertia.

Thirdly, Earth's precession rate is proportional to tidal forces, the Earth's rotation rate and cosine of the obliquity (e.g. see [1]) and hence

$$k = K\,[\,(m/a^3) + (m_s/a_s^3)]\,\Omega_e \cos\theta \qquad (4)$$

where k is precession rate, K is a constant, m_s is solar mass, a_s is Earth-Sun distance and θ is the obliquity.

3. Calculations

From (1) and (2), Earth-Moon separation at 4.5 Gy is

$$a=a_o F^{(1/6.5)} \tag{5}$$

where

$$F = (\mu^{0.5/}\mu_o^{0.5})\,(m/m_o)\,(<k/Q>/<k/Q>_o) \tag{6}$$

and subscript-o denotes a true Earth-Moon value with $<k/Q>$ the time-average of k/Q. Thus, a after 4.5 Gy of evolution can be found as a function of lunar mass and mean k/Q. Equations (3) and (4) then give the angular momentum, corresponding to any given precession rate at 4.5 Gy, as

$$L=a^{0.5}\mu^{0.5}m' + kC/\{K\,[(m/a^3)+(m_s/a_s^3)]\cos\theta\}. \tag{7}$$

Figure 1 shows equation (7) plotted as a function of lunar mass using the critical precession rate for chaotic resonance of 26"/y and assuming that mean k/Q and obliquity are identical to the true Earth. Axes are normalized by true Earth-Moon system values.

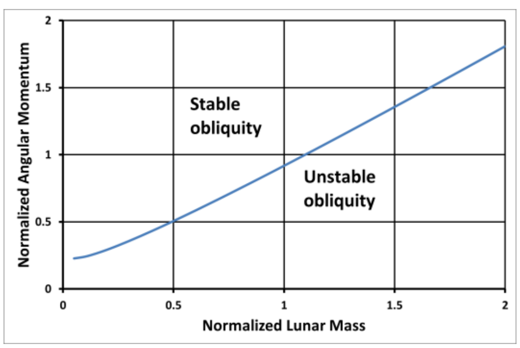

Figure 1: Critical angular momentum for axial stability after 4.5 Gy as a function of lunar mass. Note that increases in lunar mass will change a stable system into an unstable one and that the true Earth-Moon system (L=1, m=1) is almost unstable.

4. Discussion and Conclusions

The key conclusion from Figure 1 is that, given 4.5 Gy of evolution, Earth-Moon-like systems are axially destabilized by larger moons. Hence, the Earth's large Moon does not aid habitability in this way.

Instead, it is intriguing to note that the Earth-Moon system is close to being unstable. An Earth-Moon-like system that emerges from a moon-forming collision with 9% higher lunar mass or 8% smaller angular momentum develops an unstable obliquity 4.5 Gy after moon formation. This conclusion that our Earth-Moon system is almost unstable is unaffected by the assumed mean-k/Q and obliquity which can be varied from their Earth values by factors of two or more without changing this result.

Near-instability may indicate that a large moon and/or low angular momentum are beneficial to habitability for some reason other than axial stability. The Earth could have been "anthropically selected" because it has near optimal values (i.e. as large a moon or as small an angular momentum as is compatible with axial stability). One speculation is that this allows the Earth to have a low rotation rate since the only way to have both a stable axis and slow spin is to have a large moon. Slow rotation, in turn, reduces the temperature contrast between the poles and equator which may play a role in making the Earth's Ice-Ages rare and relatively mild [5]. Furthermore, the slow precession associated with near-instability ensures that obliquity variation and climate-precession are also slow hence reducing the pace of Ice-Age ebb and flow during the occasional glaciations that still occur.

References

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