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Did Evection Greatly Alter the Earth-Moon Angular Momentum?

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Abstract

A possible mechanism to remove significant angular momentum (AM) from the Earth-Moon system is the evection resonance with the Sun. Previous studies have found contradicting outcomes (e.g., early vs. late resonance escape), and varied AM removal efficiency for different tidal models. To explore the origin of such differences and to assess the robustness of evection for removing AM from the Earth-Moon system, we study its evolution using the Mignard tidal model. Our results show that both early and late resonance escapes are possible in different parameter regimes. For early resonance escapes we find that the system may enter a protracted quasi-resonance phase (reminiscent of the limit cycle found by Wisdom & Tian [9]). We find that the final Earth-Moon system AM, set by the timing of resonance/quasi-resonance escape, is a function of both the ratio of physical and tidal parameters in the Earth and Moon (A), and the absolute rate of tidal dissipation in the Earth. Large rates are preferred for a fluid-like post-impact Earth and for these values the AM removal may be controlled purely by evection (late resonance escape). Moreover, our results do not show a preference for obtaining a final AM similar to that in the current Earth-Moon system.

1. Introduction

Moon formation by a high-AM impact may offer a compelling mechanism to create a satellite that is compositionally similar to the silicate Earth [1, 3, 5] without requiring an Earth-like impactor [4]. In such impacts, the Earth-Moon system's initially high AM (i.e. $> 2L_{\mathrm{EM}}$, where L_{EM} is the current Earth-Moon AM) must be greatly reduced after the Moon forms. A possible AM removal mechanism is the evection resonance with the Sun [3], which occurs when the period of precession of the lunar perigee equals one year. Capture into evection excites the lunar eccentricity and AM is transferred from the Earth-Moon pair to Earth's orbit around the Sun. Notably, there also appeared to be a preference for a final AM near $\sim 1L_{\mathrm{EM}}$, independent of the starting AM [3].

Later studies found contradicting outcomes, where the formal evection resonance yields substantial AM loss only for a limited range of A, with final system AM values that are too low (i.e., $< 1L_{\mathrm{EM}}$; [9]). For a post-impact, fluid-like Earth, the Moon exits evection with the Earth-Moon system AM barely altered. Instead, a "limit cycle" was identified, in which appropriate AM can be lost even though the evection resonance angle is not liberating [8, 9]. Given the inconsistencies between previous studies and the importance of the AM removal efficiency to the likelihood of high-AM lunar origin scenarios [2], it is crucial to understand the robustness of AM removal by evection, in particular for other tidal models, and for tidal parameters that are expected after high-AM impacts [10].

2. Model and Results

We examine the Earth-Moon evolution in evection using the Mignard tidal model [6], which assumes a constant lag-time, Δt, between the tide-raising-potential and the body's response. Note that in this model the relative tidal strength parameter, A, differs from the constant-Q model by a (varying) factor of $(s-n)/n \sim \mathcal{O}(10)$ (where s is the Earth's spin rate and n is the Moon's mean motion; [7]).

We use equations for the evolution of the Moon's semimajor axis (a), eccentricity (e), Earth and Moon spin rates, and the evection resonance angle (ϕ, measuring the difference between the solar longitude and the Moon's perigee position as seen from Earth) from Ward & Canup [11], evolved using an adaptive step, 4^{th} order Runge-Kutta integrator.

Our simulations start with a Moon outside the Roche limit on a near-circular orbit around a fast-rotating Earth (2 hr), with an initial AM of $2.2L_{\mathrm{EM}}$. Initially tides control the lunar orbit expansion until capture into resonance occurs ($a \sim 7.8R_{\oplus}$), causing e to increase rapidly and ϕ to librate about a constant value. Lunar orbital expansion stalls at a critical eccentricity for which expansion due to Earth's tides is balanced by contraction due to lunar tides. The Moon then enters an orbital contraction phase, during which large-scale AM may occur.

For $Q_{\mathrm{eff}}/k_{2\mathrm{M}} < 10^4$ (where, $k_{2\mathrm{M}}$ is Earth's Love number), soon after the orbit starts to contract, ϕ librations increase and the system escapes from resonance. If escape occurs to the high-e/low-a side of the resonance, the Moon then enters a protracted quasi-resonance (QR) phase, in which ϕ does not librate about a fixed value. Nearly all AM loss occurs in this QR phase and not in proper evection, which is reminiscent of the limit cycle found by Wisdom & Tian [9] with the constant-Q tidal model. After exiting QR, tides dominate the dynamics and AM is conserved. There is no preference for exiting QR when the system reaches $\sim 1\,L_{EM}$, and in many cases, the QR phase removes AM until the system reaches the dual-synchronous state with $\sim 0.6\,L_{EM}$ (see Figure 1).

A different behavior may occur for slow tidal evolution ($Q_{\mathrm{eff}}/k_{2\mathrm{E}} > 10^4$; dotted markers in Figure 1). The system remains in resonance during orbit contraction. AM removal is controlled purely by evection, the type of evolution found in Ćuk & Stewart [3]. However, similarly to the QR cases, we do not find a preference for resonance escape at a minimum AM near $1L_{\mathrm{EM}}$, in contrast to [3].

In conclusion, we find that resonance escape depends on both $Q_{\mathrm{eff}}/k_{2\mathrm{E}}$ and A (Fig 2). For a given A, increasing $Q_{\mathrm{eff}}/k_{2\mathrm{E}}$ in either the QR or pure evection mode leads to greater AM removal. For a given $Q_{\mathrm{eff}}/k_{2\mathrm{E}}$, increasing A results in a lower peak e and reduced AM loss. Final values consistent with the current Earth-Moon can result for either the QR or pure evection mode, but require particular values for both A and $Q_{\mathrm{eff}}/k_{2\mathrm{E}}$. Large $Q_{\mathrm{eff}}/k_{2\mathrm{E}}$ values $> 10^4$ may be preferred for a fluid-like post-impact Earth [10].

Acknowledgements

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References

[1] Canup, R. M.: Forming a Moon with an Earth-like Composition via a Giant Impact, Vol. 338, pp. 1052-1055, 2012.

[2] Canup R. M. et al: New Views of the Moon II - Origin of the Earth and Moon, in review.

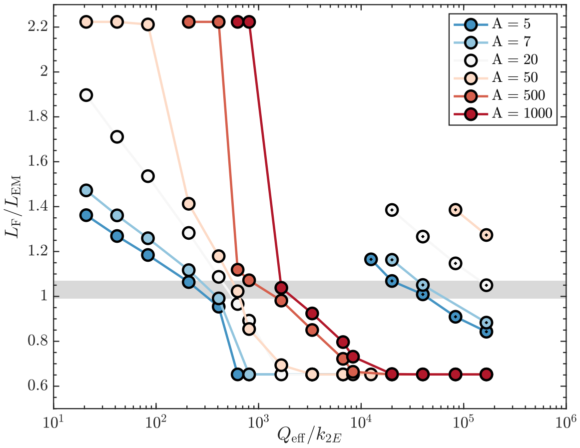

Figure 1: The final AM as a function of the initial terrestrial tidal dissipation factor, Q_{eff}, for different relative tidal strength values, A (colors in legend). The dotted markers represent the simulations where the system remains in evection during the orbital contraction phase and AM is removed during evection proper. The horizontal grey area shows values consistent with the current Earth-Moon, accounting for later AM change due to late accretion and solar tides.

[3] Ćuk, M., and Stewart, S. T.: Making the Moon from a Fast-Spinning Earth: A Giant Impact Followed by Resonant Despinning, Science, Vol. 338, pp. 1047-1052, 2012

[4] Dauphas, N.: The isotopic nature of the Earth's accreting material through time, Nature, 541, pp. 521, 2017.

[5] Lock, S. J., Stewart, S. T., Petaev, M. I., Leinhardt, Z., Mace, M. T., Jacobsen, S. B., and Ćuk, M.: The origin of the Moon within a terrestrial synestia, Journal of Geophysical Research: Planets, Vol. 123, pp. 910– 951, 2018.

[6] Mignard, F.: The evolution of the lunar orbit revisited. I, The Moon and the planets, Vol. 20, pp.301-315, 1979.

[7] Peale S. J. and Canup R. M.: The Origin of the Natural Satellites, Treatise on Geophysics, Vol 10, pp. 559-604, 2015

[8] Tian, Z., Wisdom, J. and Elkins-Tanton, L.: Coupled orbital-thermal evolution of the early Earth-Moon system with a fast-spinning Earth. Icarus, Vol. 281, pp.90-102, 2017.

[9] Wisdom, J. and Tian, Z.: Early evolution of the Earth–Moon system with a fast-spinning Earth. Icarus, Vol. 256, pp.138-146, 2015.

[10] Zahnle, K.J., Lupu, R., Dobrovolskis, A. and Sleep, N.H.:The tethered moon. Earth and Planetary Science Letters, Vol. 427, pp.74-82, 2015.

[11] Ward W. R. and Canup R. M.: The evection resonance and the angular momentum of the Earth-Moon system, LPSC XLIV, 3029, 2013.