EVECTION RESONANCE IN THE EARTH-MOON SYSTEM.

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Summary: The evection resonance can remove angular momentum from the Earth-Moon system, transferring it to the Earth's orbit. However, previous studies have found contradicting outcomes (*e.g.,* early vs. late resonance escape), and varied angular momentum (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, we study the system's evolution using the Mignard tidal model. Our results show that both early and late resonance escape are possible in different parameter regimes. In either case, AM is removed, although through different mechanisms. 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. Moreover, our results do not show a preference for obtaining a final AM similar to that in the current Earth-Moon system (L_{EM}).

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, 2; see also 3] without requiring an Earth-like impactor [4]. In such impacts, the Earth-Moon system's initially high AM (i.e. $> 2L_{EM}$) must be greatly reduced after the Moon forms. A possible AM removal mechanism is the evection resonance with the Sun [1], 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. For an initial 5-hr terrestrial spin (corresponding to a total AM of $\sim 1\ L_{EM}$), evection is encountered at 4.6 Earth radii (R_E) and only limited AM removal was found [5]. However, with a more rapidly spinning Earth (total AM $> 2L_{EM}$), the resonance location shifts outward due to Earth's increased oblateness, and large-scale AM removal was found [1]. Notably, there also appeared to be a preference for a final AM near $\sim 1\ L_{EM}$, independent of the starting AM [1].

Ćuk & Stewart [1] used a simplified approximation of a constant-Q tidal model. Later studies with a full constant-Q model found that 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., $< 1L_{EM}$; [6]). 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 [6, 7]. Understanding such behaviors is important for assessing the likelihood of high-AM lunar origin scenarios [8].

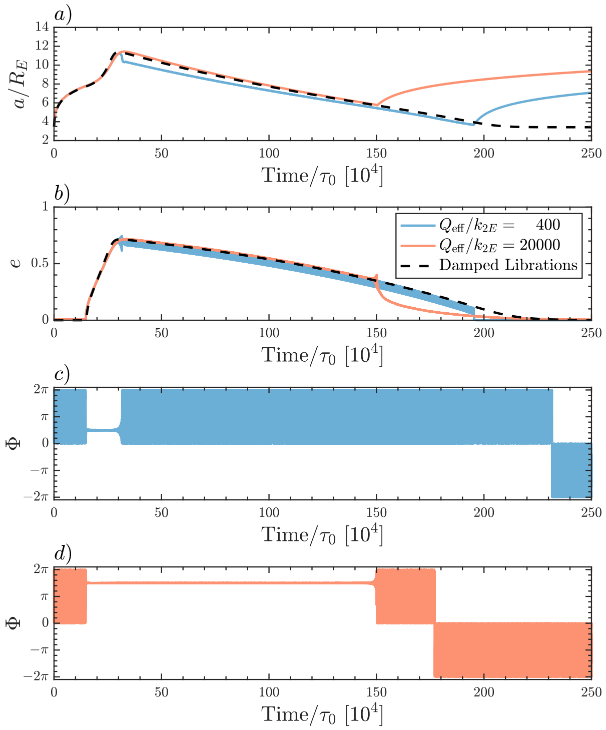

Fig 1 – Earth-Moon tidal evolution with Mignard model, assuming $A = 10$ and two $Q_{\rm eff}/k_{2E}$ values (red and blue curves), compared with a damped-libration approximation in which the system is locked in resonance (dashed curve; [9]). a) Semi-major axis, normalized to R_E; b) eccentricity; c) evection resonance angle for $Q_{\rm eff}/k_{2E} = 400$; and d) evection resonance angle for $Q_{\rm eff}/k_{2E} = 2 \cdot 10^4$, as functions of time, with time normalized by the tidal time-scale $\tau_0 = \left(6k_{2E}M_M/M_E\Omega_\oplus^2\Delta t_E\right)^{-1}$, where $\Omega_\oplus$ is the orbital frequency at R_E.

Methods: We examine the Earth-Moon evolution in evection using the Mignard tidal model [10, 11], which assumes a constant lag-time, Δt, between the tide-raising-potential and the body's response. The result is a frequency-dependent tidal force that evolves smoothly near the synchronous orbit and is valid for high lunar eccentricities. The lag-time may be related to a tidal dissipation factor

$$Q_{\rm eff} \sim [2(s-n)\Delta t]^{-1}$$

where s is the Earth's spin rate and n is the Moon's mean motion. The relative strength of tides on the Moon vs. those on the Earth can be expressed by:

$$A = \frac{k_{2M}}{k_{2E}} \frac{\Delta t_M}{\Delta t_E} \left(\frac{M_E}{M_M}\right)^2 \left(\frac{R_M}{R_E}\right)^5$$

where k_{2M} (k_{2E}), $\Delta t_M(\Delta t_E)$, $M_M(M_E)$ and R_M (R_E) are the Moon's (Earth's) Love number, lag time, mass and radius. The definition differs from the constant-Q model by a (varying) factor of $(s-n)/n \sim O(10)$ (e.g., [12]). For ease of comparison with other works, we express results as a function of Earth's Q_{eff}, with Q_{eff} calculated for the initial spin rates (described below).

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 [13], evolved using an adaptive step, 4th 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 2.2 L_{EM}.

Results: Initially tides control the lunar orbit expansion until capture into resonance occurs (a~7.8 R_E; Fig. 1a), causing e to increase rapidly (Fig. 1b) and Φ to librate about a constant value (Fig 1c, 1d). 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 $Q_{\text{eff}}/k_2 < 10^4$, 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 e oscillates about a value smaller than the stationary resonance eccentricity (blue vs. dashed lines in Fig. 1b; [13, 14]) and Φ does not librate about a fixed value (Fig. 1c). 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 [6] 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 ~1 L_{EM}, and in many cases, the QR phase removes AM until the system reaches the dual-synchronous state with ~ 0.6 L_{EM} (Fig. 2). This state is ultimately unstable, resulting in the eventual loss of the Moon due to slow-down of Earth's spin by the Sun.

A different behavior occurs for slow tidal evolution ($Q_{\text{eff}}/k_{2E} > 10^4$). The system remains in resonance during orbit contraction (Fig. 1d), with e tracking the stationary resonance eccentricity (dashed line in Fig. 1b; [13]). AM removal is controlled purely by evection, the type of evolution found in Ćuk & Stewart [1]. However, similarly to the QR cases, we do not find a preference for resonance escape at a minimum AM near 1 L_{EM}, in contrast to [1]. As long as evection is occupied, the system approaches the co-synchronous state, independent of the initial AM. In the case shown by the red curves in Fig.1, chosen parameters allow the Moon to exit evection when the final AM is $L_F = 1.25\ L_{EM}$.

We find that resonance escape depends on both Q_{eff}/k_{2E} and A (Fig 2). For a given A, increasing Q_{eff}/k_{2E} in either the QR or pure evection mode leads to greater AM removal. For a given Q_{eff}/k_{2E}, 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_{eff}/k_{2E}. Large Q_{eff}/k_{2E}values > 10^4 may be preferred for a fluid-like post-impact Earth [15].

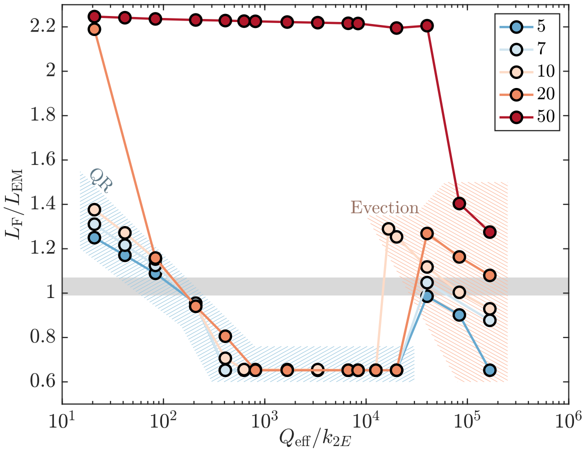

Fig 2 – The final AM as a function of the initial terrestrial tidal dissipation factor, Q_{eff}, for different relative tidal strength values, A (colors in legend). The horizontal grey area shows values consistent with the current Earth-Moon, accounting for later AM change due to late accretion and solar tides [16, 17]. AM removal by a quasi-resonance (QR) vs. formal evection is marked by the shaded blue/red areas.

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