RESONANCES AND THE ANGULAR MOMENTUM OF THE EARTH-MOON SYSTEM. Matija Ćuk[1, 2], Sarah T. Stewart[2], [1] SETI Institute, Carl Sagan Center, 189 N Bernardo Ave, Mountain View, CA 94043, [2] Harvard University, Department of Earth and Planetary Sciences, 20 Oxford St, Cambridge, MA 02138.

Lunar Formation Problems:

1. The Moon appears to be derived from Earth's mantle, but Earth was never spinning fast enough to lose material to orbit.

2. The Moon has significant orbital inclination, but should have none.

3. The impactor must have had very low v_{inf} to form the Moon

4. Earth's post-giant-impact obliquity was low, but it should have been random.

Our Solution:

We simulated lunar tidal evolution starting with a fast-spinning Earth, including the interaction between Earth's core and the Moon. We find that multiple resonances of the Moon with both the Sun and Earth's core drained angular momentum from the system. Resonances also tilted Moon's orbit and lowered Earth's tilt. If post-giant-impact Earth was spinning very fast, the Moon could form from Earth's mantle in an impact-triggered fission.

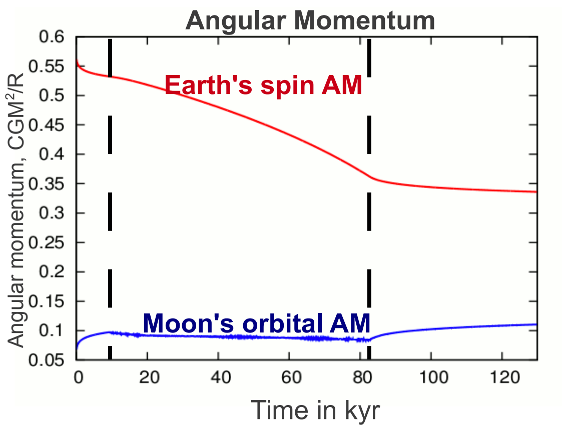
Moon-Sun Resonances: The Moon appears to be made from Earth's mantle material [1], while the Giant Impact theory predicts that the Moon was derived from the impactor [2]. It has been suggested that an initially faster spinning Earth could explain this discrepancy [3], but the system would later need to lose excess angular momentum (AM).

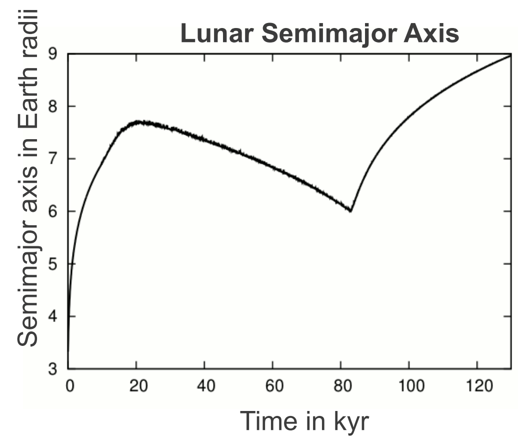
Here we explore the possibility that the early Earth had faster spin and higher obliquity than predicted by AM conservation. We made a symplectic integrator based on work by Touma and Wisdom [4, 5, 6, 7] that includes rotating Earth (mantle and core), the Moon and the Sun, with both tidal and CMB dissipation. Tidal Q values for Earth and the Moon were set to ~100. Initial spin period of Earth was 2.5 hr and initial obliquity was 40°.

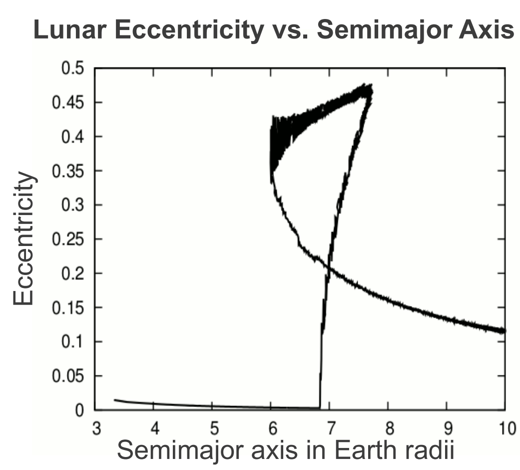
We find the Moon meeting "tiltover resonance" $[2\lambda_{Sun}+\Omega_{Moon}-3\Omega_{Sun}]$ at 5.9 Earth radii (R_E) , which excites lunar inclination to 2°.

At 6.8 R_E the Moon gets captured in the evection resonance $[2\lambda_{Sun}-2v_{Moon}]$. This capture is more robust than in [6], as faster Earth rotation (larger J_2) moves the resonance out. At 6.9 R_E tidal evolution is slower and solar perturbations stronger than at 4.5 R_E [6]. Eccentricity first rises and then levels out as the Sun drains AM from Earth. Eventually the lock is broken and the Moon's outward tidal evolution resumes.

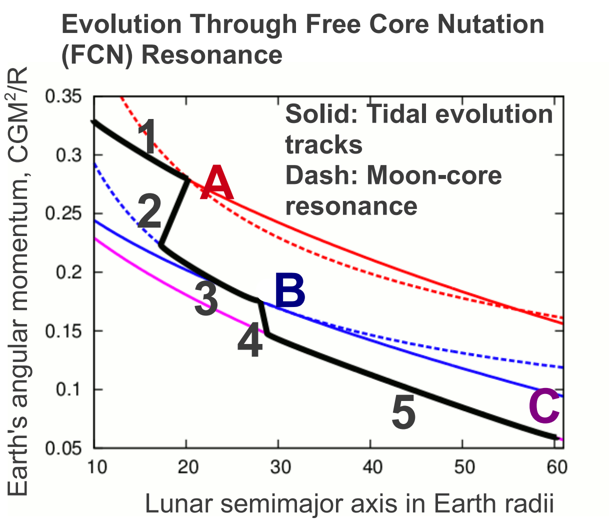
Right after evection, the Moon passes through a mixed eccentricity-inclination resonance $[2\lambda_{Sun}-2v_{Moon}+W_{Moon}-W_{Sun}]$ ("eviction" in [6]) which increases lunar inclination to 2.5°.



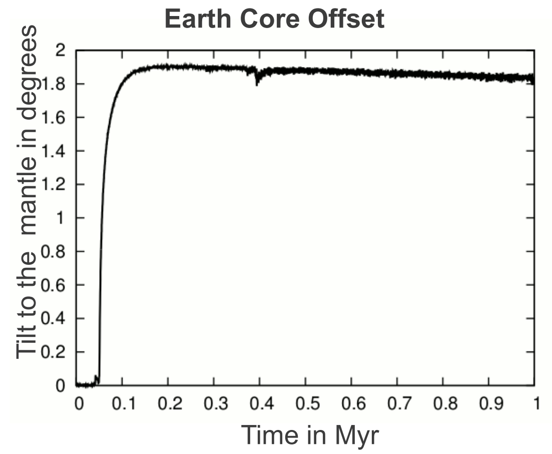


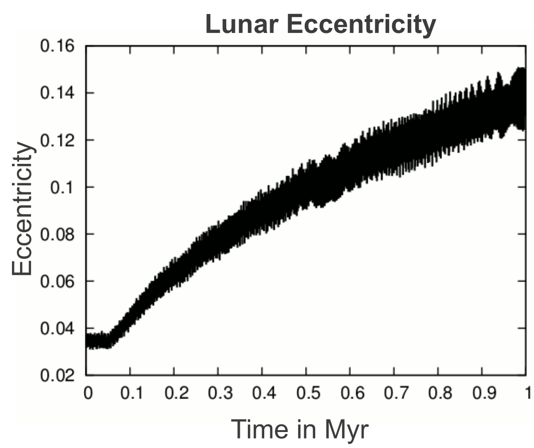


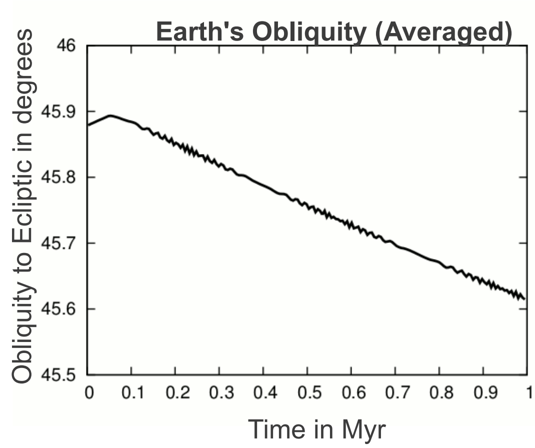
Earth's Core-Moon Resonances: Early Moon-Sun resonances always leave the Moon with inclination too low and Earth with obliquity and spin rate too high to match the present. However, additional resonances between the Moon's mean motion and the Free Core Nutation (FCN) of Earth are likely. Since early Earth's mantle was not solid, FCN must have swept a range of periods during mantle solidification (assumed to happen over ~10 Myr), trapping the Moon in an eccentric FCN resonance [λ_{Moon}-ν_{Moon}+W_{Core}-W_{Moon}]. FCN resonance lowers Earth's obliquity and increases lunar free inclination and eccentricity. Simulating FCN resonance is very expensive, and only the initial capture is shown. We expect that the Moon will exit the resonance once it reaches the present angular momentum, but with e=0.45, which is lowered by tides and planetary resonances [8].



A - FCN resonance capture (this simulation)
B – FCN resonance escape (estimate)
C – Present state of the Earth-Moon system
1, 5 – Ordinary tidal evolution
2 – Mantle solidification shifts resonance
3 – Tidal evolution within resonance
4 – Eccentricity damping after resonance







References: [1] Touboul, M., et al. (2007). *Nature* 450, 1206-1209. [2] Canup, R. M. (2004). *ARA&A* 42, 441-475. [3] Melosh, H. J. (2009). *MPS Sup.* 72, 5104. [4] Touma, J., Wisdom, J. (1994). *AJ* 108, 1943-1961. [5] Touma, J., Wisdom, J. (1994). *AJ* 107, 1189-1202. [6] Touma, J., Wisdom, J. (1998). *AJ* 115, 1653-1663. [7] Touma, J., Wisdom, J. (2001). *AJ* 122, 1030-1050. [8] Ćuk, M (2007). *Science* 318, 244-244.