EVOLUTION OF THE LUNAR INCLINATION. B. G. Downey[1], F. Nimmo[1] and I. Matsuyama[2], [1]Dept. Earth and Planetary Sciences, University of California Santa Cruz, CA 95064, USA (bgdowney@ucsc.edu, fnimmo@ucsc.edu), [2]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85719, USA (isa@lpl.arizona.edu)

Introduction: How the Moon got its present-day orbital inclination has long been a mystery [1, 2]. In the canonical Moon-forming giant impact scenario (e.g., [3]), the Moon would have formed in the Earth's equatorial plane, i.e., a zero-inclination orbit. However, tides raised on the Earth and Moon always act to damp the Moon's inclination [4], so the Moon had to start its outwards evolution with an inclination of >10° in order for it to decay to the present value of 5.2° [1, 5, 6]. Furthermore, obliquity tides in the ancient lunar magma ocean would have accelerated the inclination damping, which makes it difficult for a primordial inclination to survive to the present-day [7]. The purpose of this work is to reconstruct the thermal-orbital history of the Moon in order to reconcile the current inclined orbit with the Moon-forming giant impact theory.

We build on past thermal-orbital models [7]; in our work the most significant addition is that we account for a fossil figure and for second order eccentricity and obliquity effects on the Moon's tidal-rotational bulges [8]. We use our coupled thermal-orbital model to match the present-day inclination and degree-2 gravity observations to answer the questions of how the Moon got its inclination and where the Moon's fossil figure froze in.

Thermal-Orbital Evolution: The thermal-orbital model evolves the lunar orbit in response to tidal dissipation in the Earth, in the lunar magma ocean, and in the lunar lower crust. The biggest unknowns are the lifetime of the lunar magma ocean, the early migration rate of the Moon away from the Earth, and where the Moon's fossil bulge froze in. These quantities affect whether the magma ocean had solidified before the Cassini state transition occurred (a period of large obliquity and hence rapid inclination damping).

Orbital Evolution: We use the Mignard equations, which describe the evolution of the Earth-Moon system and take into account tidal effects among the Earth, Moon, and Sun [9, 10, 6]. There is a time lag, Δt, between when the Moon is directly overhead on the Earth and when the Earth's high tide actually occurs [9]. We assume that tidal dissipation in the early Earth was much weaker than the present-day [11], so we create an exponential expression for $\Delta t(t)$ that has a variable initial condition, Δt_0, and that matches the observed Δt and semi-major axis at the present-day.

Lunar Figure: We assume the Moon is always in a damped Cassini state, which means that for a given orbital state and degree-2 gravity, the Moon will have a specific obliquity value (e.g., [12]). We use the formulation in [8] for the Moon's degree-2 gravity coefficients to include the second-order effects from obliquity and eccentricity and to include the effects of a fossil figure. Where the fossil figure froze in is a variable in our model. Comparing our model to the degree-2 gravity observations in [8] allows us to provide an estimate of the orbital state when the fossil figure froze in.

Lunar Magma Ocean Solidification: After the Moon-forming giant impact, the Moon would have had a global magma ocean 100 – 1000 km deep. We track the solidification of the magma ocean and growth of an overlying crust. The timescale of complete solidification is treated as a variable in our model, although there are data that suggest a 100-200 Myr lifetime (e.g., [13, 14] and references therein). The survival of a primordial inclination is sensitive to obliquity tides in the lunar magma ocean, and the thickness of the solidified crust affects solid-body tidal dissipation and how well the Moon can maintain the lithospheric stresses of a fossil figure.

Results: The goal of our model is to vary the lifetime of the lunar magma ocean, the early migration rate of the Moon (Δt_0), and the orbital distance where the fossil figure freezes in (X^* in units of Earth radii), to determine which configurations match the present-day observations for the lunar inclination and degree-2 gravity field (J_2 and C_{22}).

Fig. 1 shows that of the three potential constraints on the model (a long-lived magma ocean, the present-day inclination, and the present-day J_2 and C_{22} observations), only two can be satisfied at the same time. As the Moon approaches the Cassini state transition, obliquity tides in a long-lived magma ocean cause enough tidal dissipation to completely damp any initial inclination (as observed in [7]). This can be avoided if a large fossil figure component is frozen in because then the Cassini state transition will happen at a greater orbital distance (as observed in [8]) and there are no strong obliquity tides while the long-lived magma ocean survives. The problem is that this last scenario would require a fossil figure component that is much larger than that observed at the present-day. On the other hand, a short-lived magma ocean (< 10 Myr) consistently preserves a primordial inclination, and to match the J_2 and C_{22} observations, a fossil bulge would have to freeze in between $X = 9$ and $X = 13$. The problem with this scenario is that most lunar chronology data point to a long-lived magma ocean [14].

The J_2 and C_{22} observations are the strictest constraint because of the uncertainty in the source of the inclination and the exact lifetime of the magma ocean. This leads to only two evolution possibilities for the Moon: either the magma ocean lasted < 10 Myr and the lunar inclination is primordial (consistent for a range of Δt_0 and X^*) or the magma ocean lasted > 100 Myr and the lunar inclination is the result of a late excitation mechanism.

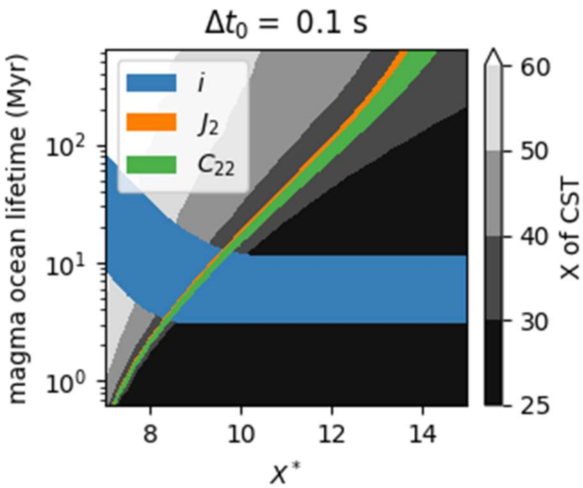

Figure 1: For $\Delta t_0 = 0.1$ s, the colored bands are the regions of parameter space that match the present-day inclination (blue), J_2 (orange), and C_{22} (green). The $J_2$and C_{22} observations come from [8] and include the tidal-rotational and fossil figure components (excludes contributions from the South Pole-Aitken basin). The gray contours in the background show where the Cassini state transition (CST) occurred in the model runs. To match the present-day J_2 and C_{22} observations, the CST happened between 30 and 40 Earth radii.

Inclination excitation mechanisms: Various theories have been developed to explain excitations of the lunar inclination, which can be grouped into early [15, 16] and late [17, 18] excitation theories. If the inclination is primordial, any early theory will suffice, but if the excitation happens late, then it has to at least happen after the solidification of the magma ocean.

An example of a late inclination excitation is to posit a high obliquity (60-80°), high angular momentum Earth that excited the lunar inclination to >30° during the Moon's Laplace plane transition at 16-22 Earth radii [17]. A second theory is that during the period 10-100 Myr after Moon formation, at around 20-40 Earth radii, a few planetesimals passed near enough to the Earth-Moon system to excite the inclination of the lunar orbit [18]. Because planetesimals are removed with time, the second theory is hard to reconcile with a long-lived lunar magma ocean (100-200 Myr), so we focus on the first.

For the angular momentum of our Earth-Moon system set by the initial configuration, the Laplace plane transition occurs at $X = 15$. To ensure that the Laplace plane transition occurs after the magma ocean solidifies (> 100 Myr), the Δt_0 of the early Earth has to be < 0.1 s, consistent with [11]. Then to match the present-day J_2 and C_{22} observations in [8], a fossil figure freezes in at X^*= 12.

Summary: The current inclination of the lunar orbit can be explained by one of two possible evolution histories. (1) The inclination is primordial and was acquired soon after the Moon-forming giant impact in which case the lunar magma ocean had to be short-lived (< 10 Myr). (2) The inclination was excited during the Laplace plane transition at $X = 15$, and for this point to be reached after the solidification of a >100 Myr magma ocean, $\Delta t_0 < 0.1$ s. To match the J_2 and C_{22} observations in [8], a fossil figure freezes in at X^*= 12.

Future Work: Since the location of the Laplace plane transition is dependent on the angular momentum of the early Earth-Moon system, we will explore the effects of a high angular momentum starting point on the predicted lunar evolution.

References: [1] Goldreich, P. (1966) *Reviews of Geophysics 4(4)*, 411-439. [2] Touma, J. & Wisdom, J. (1994) *AJ, 108*, 1943-1961. [3] Canup, R. M. & Asphaug, E. (2001) *Nature 412*(6848), 708-712. [4] Chyba, C.F. et al. (1989) *A&A 219*, L23-L26. [5] MacDonald, G. J. (1964) *Science*, 881-890. [6] Mignard, F. (1981). *The Moon and the Planets, 24*(2), 189-207. [7] Chen, E. M., & Nimmo, F. (2016) *Icarus, 275,* 132-142. [8] Matsuyama, I. et al. (2021) *PSJ 2*(6), 232. [9] Mignard, F. (1979). *The Moon and the planets, 20*(3), 301-315. [10] Mignard, F. (1980) *The Moon and the planets, 23(*2), 185-201. [11] Zahnle, K. J. et al. (2015) *EPSL, 427,* 74-82. [12] Ward, W. R. (1975) *Science, 189*(4200), 377-379. [13] Elkins-Tanton, L. T. et al. (2011) *EPSL, 304*(3-4), 326-336. [14] Maurice, M. et al. (2020) *Science advances*, *6*(28), eaba8949. [15] Ward, W. R. & Canup, R. M. (2000) *Nature, 403*(6771), 741-743. [16] Touma, J. & Wisdom, J. (1998) *AJ, 115*(4), 1653. [17] Ćuk, M., et al. (2016). *Nature, 539*(7629), 402-406. [18] Pahlevan, K., & Morbidelli, A. (2015) *Nature, 527*(7579), 492-494.