TIDAL EVOLUTION OF THE MOON FROM A FAST-SPINNING HIGH-OBLIQUITY EARTH.

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Introduction: Origin of the Moon by a giant impact [1, 2] is the leading theory explaining the Moon's large relative size and small iron core. In the canonical scenario [3], which is constrained by the present day system angular momentum (L_{EM}), a ~0.1 Earth-mass body obliquely impacts the proto-Earth near the escape velocity to generate a disk predominantly composed of projectile material from which the moon accretes. However, since the original formulation of the Giant Impact hypothesis, improved analytical techniques have revealed that the Moon and Earth have nearly identical isotopes [4], with the simplest explanation for the isotopic similarity being that the Moon was formed from Earth's mantle [5]. As the impactor is expected to have a different isotopic signature than Earth, the giant impact hypothesis has had an “isotopic crisis” [6, 4].

Ćuk and Stewart [7] presented a new model for the origin of the Earth-Moon system. A late erosive impact onto a fast-spinning proto-Earth produced a disk that was massive enough to form the Moon and was composed primarily of material from Earth, but the system had more angular momentum (AM) than at present day. Subsequently, the excess AM was lost during tidal evolution of the Moon via a resonance between Earth's orbital period and precession of the Moon's perigee. Canup [8] presented a different impact scenario, a slow collision between two similar mass bodies, that leads to Earth’s mantle and disk having similar source materials. This scenario, which produces a fast-spinning Earth, invoked the angular momentum loss mechanism in [7]. Wisdom and Tian [9] showed that the evection near-resonance can despin the Earth for a wider range of tidal parameters than explored by Ćuk and Stewart [7] and reproduce the current AM of the system.

Furthermore, Lock et al. [10,11,12] show that after a high-energy, high-angular momentum giant impact, the Earth’s mantle, atmosphere and circumplanetary disk would not be isolated from each other, enabling rapid mixing that would lead to a lunar isotopic composition resembling that of Earth's mantle. Robust post-impact mixing also alleviates the need for special impact conditions, and a wider range of impacts than the so-called successful cases in [7,8] can generate an isotopically similar Moon. Lunar accretion from a high-energy, high-angular momentum post-impact state also predicts a pattern of volatile element depletion of the Moon relative to Earth that matches the observations [12]. However, the AM loss through the evection resonance is confined to a subset of possible tidal parameters of Earth and the Moon, and its robustness is still under question.

Lunar Inclination: A major issue left unresolved by existing theories is the origin of lunar orbital inclination. It is currently about 5 deg and studies of the Moon's tidal evolution [13, 14] found that the inclination would have been at least 12 deg at lunar formation, assuming it was primordial; this is at odds with lunar formation from a flat disk in the equatorial plane of Earth, which should result in the Moon with no inclination. Hypotheses that have been proposed to explain the lunar inclination include a complex sequence of luni-solar resonances [15] and the Moon's resonant interaction with the protolunar disk [16]; both require special conditions and unlikely tidal evolution histories. More recently, Pahlevan and Morbidelli [17] found that encounters between large planetesimals and the Earth-Moon system following lunar formation can generate substantial lunar inclination. However, this mechanism [17] requires implausible tidal properties of Earth and neglects lunar inclination damping by lunar obliquity tides, as well as lunar eccentricity excitation by Earth tides. We find it unlikely that such encounters explain the present lunar inclination.

Chen and Nimmo [18] found that lunar obliquity tides affected lunar inclination more strongly than previously realized. Past studies of lunar tidal history [11, 12, 7] ignored lunar obliquity tides, despite the fact that the Moon had large obliquity when it was between 30 and 40 Earth radii (R_E) due to the lunar spin axis undergoing the Cassini state transition [19, 20]. While Chen and Nimmo [16] considered tides within lunar magma ocean that rely on excitation of Rossby waves [21], here we will be more conservative in our approach and only consider tidal response of the current, “cold” Moon. If we assume long-term average tidal dissipation within Earth and current lunar tidal properties, we find that the orbital inclination of the Moon must have been substantially higher before the Cassini state transition, possibly as high as 30 deg. We now describe a new scenario that can explain this high early inclination.

Tidal Evolution with a High-Obliquity Early Earth: Very large lunar inclinations are reminiscent of studies by Atobe and Ida [22] who explored dynamics of high-obliquity Earth-like planets with large satellites. They found complex dynamics, which included large-scale angular momentum loss from the system.

Dynamics of satellites around high-obliquity planets was later studied by Tremaine et al. [23] and Tamayo et al. [24], who found that the satellite orbits are excited by solar perturbations at the so-called Laplace plane transition if the planetary obliquity exceeds 69 deg.

In order to study tidal evolution of the Moon from a high-obliquity Earth followed by inclination damping at Cassini state transition, we wrote a specialized numerical integrator R-SISTEM that resolves lunar rotation and, therefore, fully models lunar obliquity tides. We will present results for simulations that assume Earth's initial obliquity of 70 deg with a 1.8 L_{EM} post-impact angular momentum, after Ćuk and Stewart [7].

We find that solar perturbations induce significant lunar eccentricity when the Moon reaches the Laplace plane transition at about 17 R_E, triggering strong satellite tides that arrest further tidal evolution. As these solar perturbations are secular in nature [24], they do not affect the lunar semimajor axis but lower the Moon's eccentricity. As a result, AM is removed from the lunar orbit and transferred to Earth's heliocentric orbit; Earth tides in turn transfer AM from Earth's spin to lunar orbit, while satellite tides do not change Earth-Moon system AM. During this prolonged stalling of lunar tidal evolution, the Moon acquires large inclination (over 30 deg), while the obliquity of Earth decreases. In the later part of the Laplace plane transition lunar eccentricity is excited by a complex near-resonance between lunar orbital precession and the precession of Earth's spin axis. Depending on the exact tidal parameters used for Earth and the Moon, Earth's obliquity can reach <20 deg required to match the present value [25], while the AM of the system also matches the present value.

Cassini State Transition: The rotational dynamics of the Moon is strongly dependent on the Moon’s global shape. It is widely expected that the early Moon had little strength and its shape was in equilibrium with tidal forces [26]. While our integrator considers the Moon to be a rigid body, in simulations of the Moon’s earliest history, we periodically reset its figure to match an equilibrium shape at that distance from Earth, assuming synchronous rotation [25]. This assumption of hydrostatic-like shape results in low obliquities in the Cassini state 1 when the Moon is close to Earth [17]. Since the current shape of the Moon matches the order of magnitude of tidal deformation expected at 23-26 R_E [26], we assumed that the Moon is rigid and has the present-day principal moments when modeling lunar tidal evolution beyond 25 R_E. Our results are roughly consistent with the idea that the lunar shape formed at distance 15-17 R_E on an orbit with e~0.2 [27].

We find that the Moon likely spent some time in a non-synchronous rotation state when close to the Cassini state transition, and we find that transition between rotation states can be triggered by various resonances or impacts. Regardless of the Moon's rotation state, lunar obliquity is certain to have been very high during the Cassini state transition and immediately following it, leading to damping of lunar inclination. Using our numerical integrator, we find that the lunar inclination damps roughly to its present value if we assume long-term average tidal properties for Earth and a relatively non-dissipative, solid Moon.

Conclusions: We have discovered a new solution to the lunar inclination problem. Starting with a post-impact high-obliquity, high-angular momentum Earth-Moon system, tidal evolution through the Laplace plane transition leads to reduction in the system angular momentum while generating high inclination. Subsequently, lunar inclination is lowered to the present day value in the Cassini state transition. A single giant impact that generates a high-energy, high-angular momentum, high-obliquity post-impact state initiates a natural sequence of events that imparts the elemental and isotopic composition of the Moon and the present-day dynamical state of the Earth-Moon system.

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