THE LUNAR INCLINATION AS A DOSIMETER FOR TERRESTRIAL LATE STAGE ACCRETION K. Pahlevan., A. Morbidelli, Lagrange Laboratory, Observatoire de la Côte d'Azur, Nice, France (pahlevan@oca.eu)

Introduction: The Moon is generally thought to have formed from the debris ejected by the impact of a planet-sized object with the proto-Earth towards the end of planetary accretion [1,2]. While the "lateness" of this event in the Earth's accretion history has been assumed and/or favored for over a decade [3], it has never been quantitatively demonstrated or precisely defined. Here, we identify a new mechanism – differential momentum transfer during three-body encounters – for tilting the primordial lunar orbit. We show that the inclination of the lunar orbit is a sensitive recorder of dynamical events in the Earth-Moon system and that the smallness of its value (~5 degrees at present) is a reflection of the occurrence of the Moon-forming event towards the very end of Earth's accretion. With this mechanism, we can quantify how dynamically pristine the Earth-Moon system is, constrain the largest post-lunar-formation impacts with the Earth, and limit the angular momentum change of the system via collisional and collisionless interactions with remnant bodies following the Moon-forming impact.

The Moon-forming collision is thought to have generated a compact debris disk (within 10 Earth radii, R_E) from which the Moon rapidly accretes. Like Saturn's rings, the proto-lunar disk is expected to have become an equatorial disk on a timescale rapid relative to its evolutionary timescale. Hence, so long as the proto-lunar material disaggregated into a disk following the giant impact, the Moon is expected to have accreted within ~1 degree of the Earth's equator plane [4]. Tidal evolution calculations suggest that for every two degrees of inclination to the Earth's equator plane at an Earth-Moon separation of 10 R_E, the lunar orbit will exhibit one degree of inclination to Earth's orbital plane at its present separation of 60 R_E [5,6]. Hence, the present ~5 degree lunar inclination – without external influences (external to the Earth-Moon-Sun system) – translates to a ~10 degree primordial inclination relative to Earth equator shortly after lunar formation. This ~10x difference between the modern system and theoretical expectations of primordial dynamical excitation has become known as the lunar inclination problem.

Prior work on this problem has sought to identify mechanisms such as a gravitational resonance between the newly formed Moon and the Sun [7] or the remnant proto-lunar disk [8] that can excite the lunar inclination to its present high value. However, neither one of the proposed mechanisms has been established as having taken place. The former requires particular values of the tidal dissipation parameters while the latter has been shown to be viable only in an idealized system where a single Moon interacts with a single pair of resonances in the proto-lunar disk. Here, we identify three-body encounters as an excitation mechanism that can, in fact, generate inclinations much larger than that which is observed. We then ask a different question: why isn't the inclination of the lunar orbit larger than it is? We then use the *smallness* of its observed value to set constraints on the amount and character of accretion experienced by the Earth-Moon system following its origin.

Context: After the giant impact and lunar accretion, lasting at most ~10^3 years [9,10], the Moon has formed, interacted with [8] and caused the collapse of the remnant proto-lunar disk onto the Earth, passed through the evection resonance with the Sun [7,11], and begun its steady outward tidal evolution. On a timescale rapid relative to the time between large impacts in the final stage of terrestrial planet formation (~10^6-10^7 years) [12], the lunar orbit expands through the action of tides to an Earth-Moon separation of ~20-30 R_E, transitions from precession around the spin-axis of the Earth to precession around the vector normal to its heliocentric orbital plane [5], and its inclination becomes insensitive to the shifting of the Earth's equator plane via impacts [13]. However, the lunar inclination remains sensitive – indeed becomes more sensitive – to excitation via differential momentum transfer as tidal evolution proceeds and the lunar orbit expands. While the lunar eccentricity may be damped via satellite tides, the lunar inclination is largely preserved over geologic time and therefore carries information about dynamical events following lunar origin. The present lunar orbit is therefore a reflection of the environment in the inner Solar System at the time of lunar origin.

Cosmochemical constraints: Existing constraints on the "lateness" of the Moon-forming impact generally rely on observed isotopic similarities between the silicate Earth and silicate Moon. Subsequent accretion, it is argued, would cause a divergence in the isotopic composition of this planet-satellite system. Such cosmochemical constraints, however, rely on assumptions about the composition of Earth-crossing bodies at the end of terrestrial planet accretion and their behavior upon impact. Oxygen isotopes, for example, limit the amount of modern-day asteroidal material that can accrete onto the Earth-Moon system to a few percent [14], unless the accreting body is derived from the same isotopic reservoir as the enstatite meteorites, in which case the oxygen isotope constraint is thoroughly relaxed. Likewise, the tungsten isotope similarity observed between the silicate Earth and silicate Moon [15] is approaching a precision high enough to resolve the contribution of the so-called late veneer, the presumed source of the highly siderophile elements in the Earth's mantle [16,17]. But tungsten and other siderophile elements are strongly concentrated in metallic phases and largely trace the behavior of metals. Hence, using the observed mantle abundances and isotopic compositions of siderophile elements to make statements about the mass of late accretion requires assumptions about the degree of metal-silicate equilibration upon impact, which is currently not a well-known parameter [18]. In summary, while the isotopic similarities have generally been interpreted to be due to the lateness of the Moon-forming impact in Earth's accretion history, such an interpretation is difficult to quantify without additional assumptions. In contrast to such isotopic constraints on the relative timing of lunar formation and Earth accretion, dynamical constraints make no such assumptions about the composition of Earth-crossing populations and/or the extent to which interlopers undergo metal-silicate equilibration upon impact.

Model/Results: We have developed a model tracking the early orbital evolution of the Earth-Moon system subject to tides and gravitational interactions with interloping bodies. We use the model to follow three-body interactions with the nascent Earth-Moon system in the tens of millions of years following its formation. We find that both collisional and collisionless interactions can significantly excite the system dynamically. While the effects of in-plane perturbations that excite orbital eccentricity and may be erased via subsequent tidal dissipation, out-of-plane perturbations will excite the lunar inclination and will be preserved over subsequent history. Importantly, encounters of remnant bodies with the nascent terrestrial planets are expected to be in the "dispersion" regime, that is, isotropic [12]. Given the large number of collisionless encounters before a collisional event, statistical constraints may be placed on remnant bodies, including constraints on the size distribution of remnant populations [19] and on the most massive member (after the Moon-forming impactor). We will present the outcome of simulations that seek to quantify this new dynamical constraint on the amount and nature of accretion experienced by the Earth-Moon system and discuss the dynamical environments which would preserve the lunar inclination at its small observed value.

Implications: There is currently an active, vigorous debate regarding the nature of the Moon-forming impact with ideas ranging from the classic Mars-mass embryo impacting the nearly-formed proto-Earth [2,3], to a nearly symmetric impact of two ~half-Earth-mass bodies [20], to a high-velocity collision with a rapidly-rotating Earth [11], to a Moon-forming event described as a hit-and-run impact [21]. While we do not attempt to determine which – if any – of these scenarios corresponds to the Moon-forming event, we note that distinct scenarios correspond to distinct dynamical environments in the inner solar system that can be identified.

Conclusions: Radioactive chronometers can potentially time the Moon-forming event, to the extent that the giant impact establishes new, chemically distinct reservoirs. For more than a decade [3], a "late" Moon-forming impact has been favored, permitting radioactive chronometers for lunar formation to be used also as chronometers for the termination of Earth formation [15]. However, the "lateness" of the Moon-forming event – in the context of Earth's accretion – has never been quantified. The isotopic similarity observed between silicate Earth and Moon can be used to set some constraints on post-Moon-formation accretion, but this approach requires additional assumptions about the nature of accreting bodies and their behavior upon impact. Here, we have identified a new dynamical constraint – the lunar inclination – that works independent of such assumptions and sets direct constraints on the number and mass of remnant bodies in the terrestrial planet region at the time of the Moon-forming event. The implications of this constraint for the dynamical environment prevailing in the inner Solar System at the time of the Moon-forming event will be discussed.

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