LUNAR ORIGIN BY GIANT IMPACT: AN EVOLVING LEGACY OF APOLLO.

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Background: A primary scientific objective of *Apollo* was to determine how the Moon formed. The giant impact theory, first proposed in the mid-1970s [1-2], envisions that the Moon formed from a disk of ejecta produced by a collision with the Earth. The idea initially met with skepticism and concern that only a very limited range of impacts might yield a satellite. Nonetheless, origin via impact became the leading hypothesis subsequent to the 1984 "*Origin of the Moon*" conference, based primarily on its perceived ability to account for Earth's rapid early spin, the Moon's lack of iron, and the initial lunar magma ocean [3]. The first generation of 3D hydrodynamic simulations established that many giant impacts produced iron-poor, Earth-orbiting disks [4-7]. Later works showed that the Earth-Moon's current angular momentum (L_{EM}), as well as the Moon's mass and bulk density, could be explained by a low-velocity, oblique impact by a Mars-sized body [8-10], in what has become known as the canonical Moon-forming impact.

"Isotopic crisis" for the impact theory: In the past decade, the nature of a Moon-forming impact has become highly debated, due to difficulty in explaining isotopic similarities between the Moon and Earth's mantle. In most impacts that produce massive disks, including a canonical impact, the disk originates primarily from the impactor ("Theia") rather than from the protoearth. Meteorites from Mars, and most of those from parent bodies in the asteroid belt, have different isotopic compositions than the Earth. If Theia were similarly non-Earth like, and the disk originated mostly from Theia, one would expect measurable Earth-Moon differences. Instead, data increasingly show that the silicate Earth and Moon are isotopically indistinguishable in O and other lithophile elements [e.g., 11].

It was argued that Theia would have been isotopically Earth-like if it formed near 1 AU, so that a disk originating from Theia would yield an Earth-like Moon [12-13]. This seemed plausible because canonical impacts required Theia to have a low relative velocity at infinity, consistent with an Earth-like orbit [8-9]. However, in 2007, Pahlevan & Stevenson [14] used impact statistics from an *N*-body planet accretion model to estimate that the probability of Theia being appropriately Earth-like in O was ≤ a percent. New data also indicated that the Earth and Moon had equal initial tungsten isotopic compositions [15-17]. Theia's core and mantle W isotopic compositions would have been sensitive to the timing and conditions of its core's formation. Thus even if Theia were Earth-like in elements like O, by virtue of having formed near Earth, an additional coincidence would be needed for Theia's W composition to be consistent with an Earth-Moon W match, compounding the isotopic crisis.

New concepts: These results have motivated a diverse array of impact scenarios (Table 1) that strive to better account for Earth-Moon isotopic similarities.

Table 1: Current impact scenarios (References in superscript)	$M_{Theia}/M_{\oplus}$	Velocity (v_{esc})
1) Canonical$^{8-10}$ + Earth-like Theia^{18,19}	0.13 to 0.2	1 to 1.2
2) Canonical$^{8-10,}$ + equilibration^{14}	0.13 to 0.2	1 to 1.2
3) High-AM: Fast-spinning Earth^{20,23}	0.03 to 0.1	1.5 to 3
4) High-AM: Half-Earth^{22,23}	0.4 to 0.5	1 to 1.5
5) High-AM/-Energy + equilibration^{23}	0.03 to 0.5	1 to 3
6) Hit-and-run^{25}	0.2 to 0.3	1.2 to 1.4
7) Multiple-impact^{26}	0.01 to 0.1	1 to 3

Scenarios 1-2: Modified canonical impacts. Recent work [18] implies a substantial likelihood that Theia had an Earth-like isotopic composition in most elements. The exception is W, which seems to require an improbable Theia-protoearth compositional relationship [17]. Alternatively, an initially non-Earth like disk may have become Earth-like as it diffusively mixed with vaporized portions of Earth's mantle [14]. Such an "equilibration" process is appealing because it could account for a wide range of Earth-Moon isotopic similarities, including W [19], but whether it would operate sufficiently in the immediate post-impact conditions before the Moon formed remains unclear.

Scenarios 3-5: High-AM impacts. An important discovery made by Ćuk and colleagues was that dynamical interactions with the Sun could have transferred substantial angular momentum (AM) from the Earth-Moon system to Earth's heliocentric orbit after the Moon formed [20-21]. This implies that the Earth-Moon AM just after the Moon-forming impact could have been much higher than previously assumed, up to ~ 2 to 3 L_{EM}. A variety of high-AM impacts have been proposed, including those that can directly produce a disk and planet with nearly equal isotopic compositions in O and other lithophile elements [20,22], as well as intermediate cases that require modest equilibration [23]. Such impacts produce highly vaporized "synestias" that may lead to distinct lunar accretion conditions [23-24]. Further work is merited to assess the likelihood of required AM modification for varied conditions/parameters.

Scenario 6: Hit-and-run impact. A higher-velocity, less oblique impact produces a disk and planet that are more compositionally similar than in a canonical impact

[25], requiring modest equilibration or a relatively Earth-like Theia. However it appears difficult for a single such collision to yield a sufficiently massive disk.

Scenario 7: Multiple impacts. Rufu et al. modeled Moon formation via ≥ 20 sub-Mars impactors [26]. Each impact creates a moonlet that tidally migrates outward. A later impact produces another moonlet, whose orbital expansion can cause it to merge with the prior outer moon. The Moon can then be built up by many impacts, with the final Earth-Moon compositions approaching that of the mean planetesimal neighborhood. However the merger efficiency between consecutive moonlets may be low [27].

Discussion and open issues: It is now clear that giant impacts are efficient producers of disks and moons. Tremendous creative effort has led to many new ideas for how to form our particular Earth-Moon system, which invoke very different impact histories and energies (Table 1). Distinguishing among such models is crucial for understanding the conditions of lunar formation, and for unraveling what the Moon's origin can tell us about the final stages of terrestrial planet accretion. This will require new modeling efforts to link origin scenarios to testable predictions for the Moon's properties, a better understanding of factors that influence the likelihood of various models, and new data from future sample analyses and lunar exploration. Some key questions include:

- *How did the protolunar disk evolve into the Moon?* The disk's evolution is regulated by both dynamical and thermodynamical processes [28-29]. Prior work finds that < 50% of the disk ends up in the Moon [30], which if substantiated with more detailed models would argue against scenarios that produce lower-mass disks. How pre-lunar material evolves also affects the likelihood of Earth-disk compositional equilibration.
- *What initial Earth-Moon W compositions are implied by realistic late accretion histories?* The most stringent isotopic constraint on all non-equilibration scenarios is explaining the equal Earth-Moon W isotopic compositions inferred by [15-17]. But if late accretion onto Earth after the Moon formed involved large projectiles, the W constraint might be relaxed substantially [31].
- *What is the Moon's endogenic volatile composition?* Recent works account for the lunar depletion in volatile elements via partial condensation, with volatile-rich vapor preferentially accreted by the Earth [23,28,32]. However, the abundance and/or isotopic composition of some lunar volatiles [33-35] may require escape, which appears challenging to explain [36], or a multi-stage process [37].
- *Was the initial Moon partially or fully molten?* Multiple physical constraints, e.g. [38-39], are most easily explained by an only partially molten initial Moon. However scenarios in which the Moon forms in ≤ 1 yr would produce a fully molten Moon [23, 40]. Future lunar exploration may greatly clarify the Moon's initial thermal state.
- *Did multiple impacts contribute to the final Earth-Moon system state?* The feasibility of impact scenarios 3 and 7 depends on how multiple impacts affected Earth's rotation and moonlet retention. This process is not well understood, and prior works reach varied conclusions [26,41].

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