HOW EARLY COULD THE GIANT IMPACT HAVE TAKEN PLACE?

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Introduction: The Moon is widely accepted to have formed from a Giant Impact (GI) between proto-Earth and Theia, but the timing of this event is unclear [1]. If the collision was triggered by the outer Solar System dynamical instability involving Jupiter's migration, this must have occurred in the first 100 Myr of the Solar System, or the inner planets' orbits would have been excited [2] and Trojan binaries like Patroclus disrupted [3]. Defining t=0 to be the birth of the Solar System at 4568.4 Myr ago [4], the GI must have occurred before the impact suffered by Haumea at $t \approx$ 77-82 Myr [5], and the most probable time is at $t \approx$ 37-62 Myr [6]. It is expected that the lunar magma ocean (LMO) would have solidified ~10 Myr after that [7].

This timing is difficult to reconcile with the ages of the oldest Moon rocks, ferroan anorthosites like FAN 60025, reliably dated by multiple systems to have crystallized from a lunar magma ocean (LMO) much later, at 208±3 Myr [8]. This is consistent with inferred formation of urKREEP at 201±19 Myr [8], and basalts, Pb-Pb dated to 192±18 Myr [9]. Similarly, the oldest terrestrial zircons, when Earth had crust and oceans, date to 218 Myr [10], following Earth's crust-mantle differentiation at 168 ± 30 Myr [11]. Yet other evidence suggests an earlier origin of the Moon: lunar zircons Pb-Pb dated to 108±31 Myr [12], some lunar zircons Lu-Hf dated to 58±10 Myr [13] and Hf-W evidence suggesting the Moon's core formed at $t \approx$50 Myr [14; but see 15]. We compile these constraints in **Figure 1**.

Reconciling these dates would require an early impact at time $t_{\rm GI}$ ~50 Myr, and crystallization of an initial LMO ~10 Myr later (forming some zircons), followed by melting of a *second* LMO by tidal heating, at ~200 Myr. Here we present new interpretation of Rb-Sr data consistent with this scenario, explore physical conditions necessary to have a second LMO crystallize after 150 Myr, and propose a testable timeline of events.

Rb-Sr dating: From Rb-Sr isochrons, the initial ^{87}Sr/^{86}Sr ratio of FAN 60025 =0.699050±0.000010 [8] or 0.699078±0.000002 [16]. Because ^{87}Rb decay ($t_{1/2}$ = 49.603 Gyr; [17]) increases ^{87}Sr/^{86}Sr monotonically, this dates the GI, if we knew the starting ^{87}Sr/^{86}Sr and ^{87}Rb/^{86}Sr values in the materials comprised by FAN 60025. We adopt the following parameters.

We assume the planetary embryos of proto-Earth and Theia and the planet-sized [18] angrite parent body (APB) formed similarly, at the same time ($t \approx$ 2-3 Myr), and from similar materials (devolatilized chondrites), resulting in nearly-identical ^{87}Rb/^{86}Sr and ^{87}Sr/^{86}Sr. We re-analyze the data of [19] and find 0.698984±0.000002 for the initial ^{87}Sr/^{86}Sr of the APB. Because Rb and Sr are not lost from the Earth-Moon system in the impact, ^{87}Rb/^{86}Sr in proto-Earth and Theia must match the value of bulk silicate Earth (BSE) today, ^{87}Rb/^{86}Sr = 0.0725±0.0145 [20]. This model predicts ^{87}Sr/^{86}Sr = 0.704±0.001. We assume the lowest allowed value in Earth today, ^{87}Rb/^{86}Sr = 0.058, yielding ^{87}Sr/^{86}Sr = 0.703, because that is consistent with mid-ocean ridge basalts, which have the lowest ^{87}Sr/^{86}Sr and also presumably best sample BSE [21]. The Moon today has a lower value, ^{87}Rb/^{86}Sr= 0.0154±0.0017 [20], because Rb did not fully condense into lunar materials from the protolunar disk. Across this range, we find FAN 60025's initial ^{87}Sr/^{86}Sr = 0.699050±0.000010 if **$t_{\rm GI}$ = 33 ± 17 Myr,** or 0.699078±0.000002 if **$t_{\rm GI}$ = 77 ± 8 Myr,** implying the Moon formed early, at about 50 Myr

Formation and Evolution of the Moon: Following [22,23], we assume the Moon formed at r = 3 R_E, then tidally evolved outward as its first LMO crystallized in < 10 Myr, until the Moon entered the evection resonance at 8 R_E, which increased the Moon's inclination and eccentricity e (to 0.7) as it migrated to 11 R_E. The Moon then entered "quasi resonance" (QR) and migrated inward as e dropped to 0.2. The evection resonance extracted angular momentum from the Earth's spin, which was lost to the Earth's orbit around the Sun during this stage, even as tidal heating kept the Moon molten. After the Moon escaped QR at 5 R_E, e dropped to 0, at which point tidal heating was limited and the second LMO crystallized. The Moon would have taken a time 0.26 ((Q/k_2) / 410) Myr to evolve to this point [23]. To preserve primordial inclination, the Moon must have then completely solidified as it approached the Cassini transition at r = 30 R_E [24]. Later constraints on the Moon's position at different times come from terrestrial rhythmites [25].

Discussion: Delaying crystallization of the second LMO to t ~195 Myr, long after an impact at $t_{\rm GI}$ ~50 Myr, would require 0.26 ((Q/k_2) / 410) Myr = 145 Myr, or (Q/k_2) ≈ 2.3 x 10^5. This is high but possible, but only if Earth were completely molten [26]. Maintaining a terrestrial magma ocean for this long is not possible with a traditional greenhouse atmosphere: hundreds of bars of CO_2 and H_2O prolong Earth's magma ocean stage only by ~2 Myr [26,27]. H_2 atmospheres are much more effective: a similarly thick H_2 atmosphere can maintain a magma ocean for > 10^8 yr [27]. A key aspect of the model for low-D/H reservoirs in the Moon [28] is that Theia (mass ≈0.4 M_E) ingassed solar nebula hydrogen from a thick (20 bar) H_2 atmosphere; proto-Earth (≈0.6-M_E) would have 30 bars of H_2. About 25% of this would be retained during the GI [29], leading to ~10 bars of H_2 around early Earth, adding to tens of bars of CO_2 and > 260 bars of H_2O. It should be tested whether such a greenhouse atmosphere could keep Earth completely molten for 145 Myr, and if $(Q/k_2) = 2 \times 10^5$ would result.

Once Earth's crust starts to form at ≈195 Myr , $(Q/k_2) \approx 100$ would result [26], dropping to ≈40 after water oceans form by 215 Myr, accelerating the Moon's outward migration. Still, using standard formulas for the Moon's outward migration [22], the Moon would only reach 25 R_E as it solidified at 215 Myr, and the Cassini transition at 30 R_E at 240 Myr.

Delaying crystallization of the final LMO to 145 Myr after the impact would allow a slow (> 10 Myr) crystallization duration. The GI not only creates the protolunar disk and Moon, but ejects a Moon mass of debris into heliocentric orbit. Over ~10^8 yr this material impacts the Moon [30], which can drastically decrease LMO solidification time [31,32].

Proposed Timeline: We propose the following timeline for the Moon's evolution and suggest it be tested.

t = 0 Myr: Solar System forms, 4568.4 Myr ago
t < 2.5 Myr: Accretion of proto-Earth and Theia
t ≈ 50 Myr: **Giant Impact!**
Earth completely molten ($Q/k_2 \sim 2 \times 10^5$)
Moon forms at 3 R_E with e=0
t ≈ 60 Myr: Moon starts to crystallize
t = 63 Myr: Moon enters evection resonance at 8 R_E
t = 75 Myr: Moon enters QR with e=0.7 at 11 R_E, melts
t = 190 Myr: Moon exits QR at 5 R_E, with e=0.2
Minerals start to crystallize as e drops to 0
t ≈ 195 Myr: Earth's crust-mantle differentiation
(Q/k_2) drops to ~100 as crust forms
t ≈ 205 Myr: Moon's anorthosite crust starts to form
t ≈ 215 Myr: Moon completely solidified, at 25 R_E
t ≈ 215 Myr: Earth's crust and oceans form
(Q/k_2) drops to ~40
t ≈ 240 Myr: Moon passes Cassini transition at 30 R_E
t ≈ 1400 Myr: 15-hour day, Moon at 46 R_E
t ≈ 2200 Myr: 17-hour day, Moon at 50 R_E
t = 4568 Myr: 24-hour day, Moon at 60 R_E

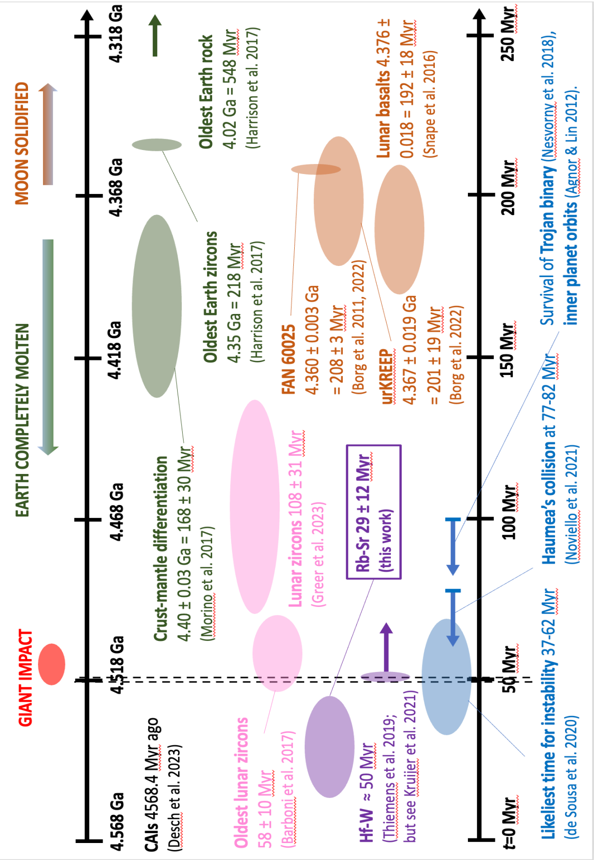

Figure 1. Timeline of events in the Moon's formation.

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