THE LUNAR LATE HEAVY BOMBARDMENT AS A TAIL-END OF PLANET ACCRETION.

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Introduction: The surface of the Moon records an epoch ~3.8–4.0 Gy ago, roughly 0.5 Gy after Solar System formation, when impacts created the youngest lunar basins [1]. The source of the projectiles for this Late Heavy Bombardment (LHB) has been controversial between two hypotheses [as reviewed in 2].

One hypothesis argues that the LHB was created by a terminal cataclysm (i.e. a spike in the bombardment rate) produced by a late dynamical instability in the outer Solar System [3–6]. This impact spike is seemingly supported by impact age distributions from some asteroidal meteorites [7]. Furthermore, evidence for a giant planet instability grew over time [8–10]. However, this evidence and the underlying dynamical models remain agnostic as to the timing of the instability. Both an early instability occurring well before the LHB or a late instability triggering the terminal cataclysm are consistent with the dynamical constraints, and their relative likelihood depends on the unknown properties of the initial outer planetesimal disk [3].

The second hypothesis challenged the cataclysm hypothesis arguing instead that the apparent impact spike reflects collection biases and radiogenic impact-age resetting [11, 12]. According to this hypothesis, the source of the Late Heavy Bombardment projectiles are the leftover planetesimals from the era of planet formation, i.e. the tail-end of planet accretion. This monotonically declining population of impactors surely existed, but was it large enough during the first billion years of solar system history to explain the LHB?

Lunar Crater Record: In Figure 1, we show that a leftover planetesimal population can match the lunar crater record. Here, we use new simulations of the flux of asteroids and comets into the inner solar system from each reservoir [8–10]. We calibrated the number of these objects colliding with terrestrial bodies on the current population of main belt asteroids and Jupiter Trojans. However, the leftover planetesimal population is unconstrained and so is a free parameter, altghough the decay rate of the bombardment that it produces is given by dynamical modeling [6]. This model is consistent with an early giant planet instability seen as a cometary spike near 4.5 Gy. In this case there is no cataclysm and the LHB signature is well reproduced in the model. The lunar bombardment declined monotonically and was dominated by leftover planetesimals until ~3.6 Gy ago, when asteroids from the main belt begin to dominate the flux on the Moon.

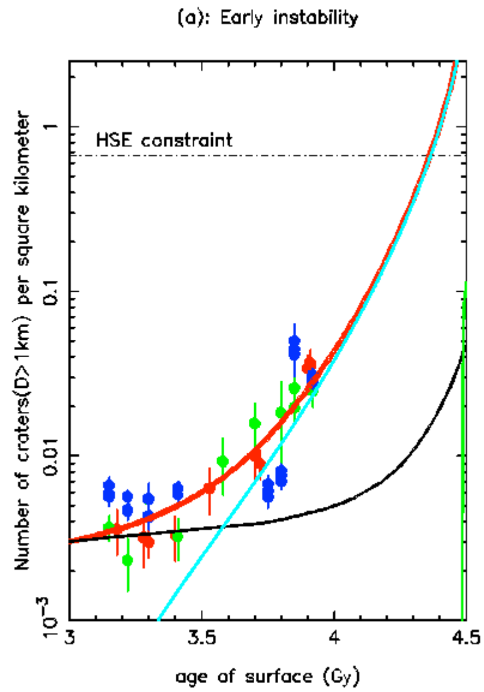

Figure 1: Total (red) density of craters (number per square kilometer) with diameter D>1km as a function of lunar surface age including projectiles from leftover planetesimals from the tail-end of planetary accretion (blue), asteroids (black) and comets (green) compared to measurements reported in [33 (red), 34 (green) and 35 (blue)]. The dash-dotted line shows the density of craters that corresponds directly to the mass of HSE in the lunar mantle.

The results in Figure 1 can be compared to the terminal cataclysm model presented in Figure 2. In this scenario, a late giant planet instability occurs at ~3.9 Gy, which triggers a flux of comets and asteroids into the inner solar system creating the LHB signature. Thus, using the most modern models and constraints, both hypotheses can match the lunar crater record.

Highly Siderophile Elements (HSE) in the Lunar Mantle: In the past [5], the terminal cataclysm hypothesis was preferred [6] due to the small accreted mass inferred from the HSE record of the lunar mantle [13]. HSEs in the lunar mantle are found in chondritic relative abundances indicating that they were delivered by projectiles of chondritic composition after the last major core formation event. Core forming events sequ-

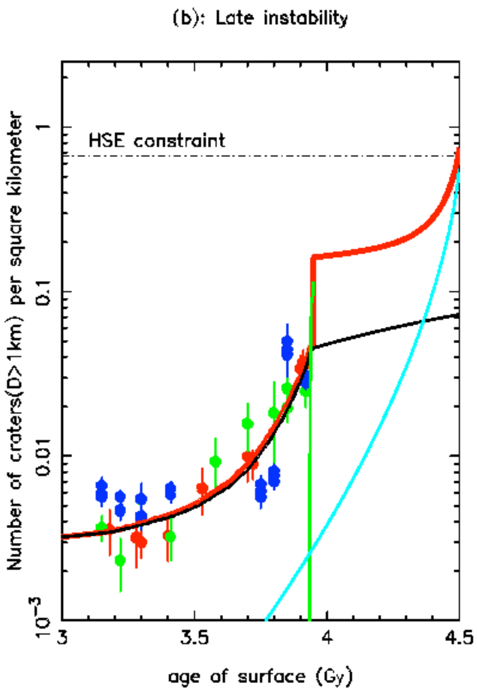

Figure 2: The points and the lines are the same as in Figure 1. The difference between the two figures is the timing of the giant planet instability. In Figure 2, this instability occurs at ~3.9 Gy causing a massive influx into the inner solar system.

ester HSEs into the core with such high efficiency that any subsequent accretion of chondritic material overprints the old geochemical record, and so the mantle HSE abundance measures the accreted mass after the last core forming event. If metal segregation during primary lunar accretion from the proto-lunar disk is the last core forming event, then far too much chondritic mass is delivered to the Moon if the source of the LHB is the tail-end of planetary accretion, see Figure 1.

The terminal cataclism hypothesis can thread the needle matching both the lunar cratering record and the HSE constraint, see Figure 2. However, the terrestrial mantle HSE record indicates that the Earth accreted significantly more mass after the Moon-forming impact relative to the Moon (~1200 times more). This cannot be explained by the ratio of accretional cross-section, which would imply an accreted mass ratio of ~20. Thus, a special appeal must be made that the projectiles delivering the Earth's HSEs should have a very top heavy size distribution such that 99% of the mass is carried by only a few bodies [5].

But this prior way of thinking has been overturned by new results. Namely, the last core forming event, which sequesters HSEs to the core, is not metal segregation immiediately after the Moon-forming impact but Fe-S segregation occuring later during the crystallization of the subsequent mantle magma ocean [14]. Sulfur saturates in the solidifying mantle and so excess sulfur is exsolved as an Fe-S which, due to its high density, sinks as a diapir to the core dragging HSEs with it. Thus, the HSE content of the lunar mantle does not record accretion after lunar formation, but instead accretion after mantle crystallization.

Unlike Earth, where crystallization occurs in a few My after the Moon-forming collision, the crystallization of the lunar magma ocean is expected to take potentially 100s My, because of tidal heating and the establishment of a flotation crust, which acts as a conductive lid [15]. Indeed, this means that any signature of chondritic bombardment during this period is eventually erased by the Fe-S segregation core forming event. Therefore, the second hypothesis is revived—the tail-end of planetary accretion can explain both the lunar cratering record and the HSEs in the lunar mantle, provided that the lunar mantle crystallized ~4.35 Gy ago. Furthermore, unlike the terminal cataclysm model, it is not necessary to assume a projectile size distribution vastly dissimilar to the current asteroid size distribution. The increased abundance of HSEs in the Earth relative to the Moon is merely indicative of the crystallization timescales of their respective magma oceans, not of the size distribution of the projectile population.

Conclusions: Both hypotheses can be made consistent with the evidence at hand. However, the terminal cataclysm hypothesis must make two significant assumptions: (1) a projectile size distribution unlike that seen in the solar system today and (2) an outer disk with the correct properties to trigger a late giant planet instability. For this reason, we find the tail-end of accretion hypothesis to be more likely.

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