**WHERE ARE THE EMPIRICAL DATA TO SUPPORT THE ORBIT EVOLUTION MODELS?**

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Pre-Apollo evidence as early as 1966 showed that the lunar cratering rate prior to ~3.5 Ga ago *averaged* at least ~150x the post-mare rate [1]. Consistent with this, it was suggested in 1973 from Apllo lunar samples that "in the interval 3.88 to 4.05 aeons… at least three and probably six of the major lunar basins formed by impact in this period" [2], and the term "terminal cataclysm" was introduced at least by 1974 [3]. Since 1990, the "classic terminal cataclysm model," based on impact melt ages, asserted that the intense cratering happened primarily between 4.0 and 3.85 Ga ago in a bombardment spike, with few impacts before that [4, 5]. An early success of the Nice model [6] was an explanation of the spike, invoking dynamical instabilities in the outer solar system (OSS), which scattered OSS bodies into the inner solar system (ISS) (although the timing was a free parameter in the model). The terminal cataclysm paradigm thus seemed secure. However, the current totality of empirical observations, such as lack of the 3.9 Ga-age spike in *lunar, "Vestoidal," and other asteroidal meteorite* impact melts [5,7,8], and evidence of lunar basin-forming impacts before 4.0 Ga ago [9], suggests that the terminal cataclysm paradigm has been wrong for four decades.

This opens a question of when the proposed dynamical instabilities happened in the OSS, and the magnitude of consequent scattering of bodies into the ISS, and in broader terms, how the theoretical dynamical models are being related to empirical evidence.

To take another example, the dynamical models of scattering from the OSS led to a major re-evaluation of the giant impact hypothesis of lunar origin. An "isotope crisis" was proposed in 2009 [10]. Based on the theoretical dynamical models of scattering from the OSS [see papers in 11],it was assumed that the Earth-impactor was not a near-Earth ISS body, which in turn meant that it must have very different isotope ratios than Earth (based on asteroidal and meteoritic data). Giant-impact modeling had already indicated that the moon would end up with a different percentage of impactor material than Earth, hence, under these assumptions, the moon would have clearly different isotope ratios than Earth --- which is not observed. An alternate approach is to start not with the dynamical modesls, but with the empirical observation that the moon is very similar to Earth in isotopic chemistry, meaning the moon did not form as a result of giant impact with an OSS body. Indeed, it has been noted that the enstatite class of meteorites, believed to have formed in the ISS near 1 A.U., has isotope chemistry nearly identical to Earth and moon (relative to other bodies) [11, 12]. Thus we know that a class of parent bodies was plausibly available to collide with primordial Earth and form the moon with virtually no isotope crisis. Signficantly, it has been suggested that the lunar isotopic data are skewed somewhat toward the enstatite chondrite isotopic ratios [13].

Where, then, is the evidence of a massive OSS scattering and cratering episode in the asteroid belt and ISS at 3.9 Ga. agof not 3.9 Ga, when *did* the putative episode occur? The cratering rate was clearly, on average, much higher before 3.5 Ga ago, and C, P, D taxonomic classifications of outer (captured?) satellites of Saturn and Jupiter (and Mars?) suggest that some OSS scattering did occur [14, 15], but dynamical models of a cataclysmic OSS bombardment episode among main belt asteroids and ISS worlds, after planet surface formation, appear to lack empirical evidence in meteorites and Apollo samples. There is no doubt that the dynamical studies of resonance effects, planet migration, and scattering of small interplanetary bodies is an important step in understanding solar and extra-solar planetary systems, but we need to cautious the relationship of th emodels to empirical isotopic, telescopic, and cratering data.

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