

IF THE LATE HEAVY BOMBARDMENT ON THE MOON WAS A TERMINAL CATACLYSM, WHAT ARE SOME IMPLICATIONS FOR MARS? Sean C. Solomon¹ and James W. Head III².

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Introduction. The late heavy bombardment on the Moon has variously been attributed to the tail of a more or less monotonically declining population of impactors in the inner solar system or to the so-called terminal cataclysm [1], a pronounced interval of greater impact flux at ~3.8-3.9 Ga than either subsequently or between that time and the final stages of planetary accretion ending around ~4.5 Ga [e.g., 2]. Although this question has not been settled definitively, recent dynamical modeling has added to the arguments in favor of some form of terminal cataclysm. It is therefore worth considering seriously the consequences of that hypothesis for the geological evolution of other bodies in the inner solar system. Here we present such an evaluation for Mars.

Arguments Favoring a Cataclysm. The earliest arguments for a terminal lunar cataclysm were based on the clustering of ages of impact-brecciated highland samples between 3.8 and 3.9 Ga [1-3]. The difficulty attributing this clustering to resetting of ages by a few relatively young basin-forming impacts [2] and the lack of impact melts older than ~3.9 Ga in lunar meteorites, a more random sampling of lunar material than the Apollo or Luna collections [4], strengthen the case for a cataclysm but do not prove it.

Radiometric dates are available for only a few of the frontside lunar basins, but a strong case can be made on the basis of those data and stratigraphic arguments that the youngest ~15 lunar impact basins at least 300 km in diameter [5] formed within the 100-My period 3.80-3.90 Ga [3] and perhaps within a shorter interval bracketed by those ages. Although earlier orbital dynamical simulations were regarded as consistent with a monotonically decaying population of impactors in the inner solar system [6], more recent simulations — which include the effects of collisions, extend for longer integration times, and are constrained by lunar basin ages — suggest instead that the declining bombardment model is inconsistent with the lunar cratering record [7].

Dynamical Models for a Cataclysm. Two dynamical hypotheses have recently been put forward to account for a terminal lunar cataclysm. One is based on the suggestion that the era of accretion of the inner planets (following the Moon-

forming impact and the impact postulated to have stripped much of Mercury's mantle) yielded five planetary bodies [8]. For suitable choices of initial orbital semi-major axis and eccentricity the fifth planet may have been long-lived but unstable on a timescale of ~700 My and thereafter lost. Perturbation of such a planet into an eccentric orbit could have scattered main belt asteroids into resonances or Mars-crossing orbits [8].

An alternative hypothesis is that the gas-giant planets originally formed between 5 and 15 AU from the Sun, but interactions with planetesimals scattered inward from an outer disk of primordial material caused Saturn to pass through the 1:2 mean motion resonance with Jupiter [9-11]. This event increased the eccentricities and inclinations of Jupiter and Saturn, pushed Uranus and Neptune outward, and destabilized the planetesimal disk, contributing to the late heavy bombardment. The new orbital configurations of the major planets also caused secular resonances to sweep across the main asteroid belt, adding another population of impactors at the same time period [11]. Observational support for the idea that the main asteroid belt was a significant contributor to the late heavy bombardment comes from the demonstration that the size distribution of craters on the highlands of the Moon, Mars, and Mercury matches the size distribution of objects in the asteroid belt, whereas craters on younger solar system surfaces have a distinct size distribution similar to that of near-Earth asteroids [12].

A Cratering Cataclysm on Mars? Both of the above dynamical hypotheses for the late heavy bombardment of the Moon would have also produced an intense pulse of basin formation and smaller crater formation on each of the inner planets, including Mars.

The most obvious implication for Mars is that most, and perhaps all, of the large preserved basins would date from the limited time interval ~3.8-3.9 Ga. This statement would extend to basins substantially to fully buried by younger sedimentary and volcanic materials and now discernible only from their signatures in surface topography [13,14] or radar sounding [15,16]. A corollary is that the density of basins and craters on surfaces older than 3.8-3.9 Ga could not be

converted to equivalent surface age [cf. 14,16]. The deduction that global differentiation on Mars and the formation of much of the Martian crust occurred within several tens of millions of years of planet formation [e.g., 17] would, of course, be unaffected by these arguments, because it is based on evidence from the decay products of short-lived radionuclides in the source regions of Martian meteorites [18-20].

Another implication of a terminal cataclysm is that the history of the Martian dynamo would require re-examination. The absence of detectable magnetic anomalies in the youngest major impact basins on Mars had been taken as evidence that the core dynamo ceased prior to the end of heavy bombardment [21], and the suggestion that older, more degraded basins that could be recognized from topography include magnetized crust implied that the dynamo shut-down might be bracketed by estimating the ages of these respective basins [14]. If the recognizable basins on Mars are dominantly products of a terminal cataclysm, however, then the time interval between the formation of more degraded and better preserved basins might have been 100 My or less and would point to a dynamo that persisted until a time during the cataclysm period, and perhaps even longer if mechanisms for removing the coherence of magnetization at scales of several hundred kilometers and greater were areally important [17]. The discovery that two volcanic centers with Hesperian surface ages display magnetic anomalies [22, 23] lends credence to this inference.

The specific dynamical models accounting for the terminal cataclysm involve the delivery of bodies from the outer asteroid belt [8-11] and possibly from beyond the original orbits of the giant planets [9-11]. Much of that material would have been rich in ices and other volatiles. There would therefore have been a substantial delivery of water to Mars within a comparatively short interval near the end of the Noachian, a process that would have contributed to the observed narrow age range of most valley networks [24, 25], extensive development of drainage systems [26], denudation of broad highland areas [27], and substantial sedimentary infilling of the northern lowlands. On the basis of estimates for the cumulative mass of impactor material that formed the youngest 15 lunar basins [28], scaling impact flux from the Moon to Mars [29], and a range of water contents for the impactors, the mass of water delivered to Mars during the late heavy bombardment would be comparable to or in excess of es-

timates for the water released by Tharsis magmatism [30], but at a later time and likely over a shorter time interval.

In addition to delivering volatiles the terminal cataclysm would have delivered kinetic energy, a fraction of which would have gone into heating of the Martian upper mantle [31]. Because the entire time interval for delivering that impact heating to the mantle would have been comparable to the lithospheric cooling time, there would have been a sustained increase in the average temperature of the uppermost mantle and an increased likelihood for pervasive melt production. We speculate that such heating may have contributed to the widespread occurrence of volcanic plains in the Early Hesperian [32] and that the cooling that followed the upper-mantle heating event may have contributed to the contractional deformation of those plains [33].

References. [1] F. Tera et al., *EPSL*, 22, 1, 1974. [2] W. K. Hartmann et al., *Origin of the Earth and Moon*, Univ. Ariz. Press, p. 493, 2000. [3] G. Ryder et al., *Origin of the Earth and Moon*, Univ. Ariz. Press, p. 475, 2000. [4] B. A. Cohen et al., *Science*, 290, 1754, 2000. [5] D. E. Wilhelms, *USGS Prof. Pap. 1348*, 1987. [6] A. Morbidelli et al., *MAPS*, 36, 371, 2001. [7] W. F. Bottke et al., *Icarus*, in press, 2007. [8] J. E. Chambers and J. J. Lissauer, *LPS*, 33, 1093, 2002. [9] K. Tsiganis et al., *Nature*, 435, 459, 2005. [10] A. Morbidelli et al., *Nature*, 435, 462, 2005. [11] R. Gomes, *Nature*, 435, 466, 2005. [12] R. G. Strom et al., *Science*, 309, 1847, 2005. [13] H. V. Frey et al., *GRL*, 29, 1384, 10.1029/2001GL013832, 2002. [14] H. V. Frey, *JGR*, 111, E08S91, 10.1029/2005JE02449, 2006. [15] G. Picardi et al., *Science*, 310, 1925, 2005. [16] T. R. Watters et al., *Nature*, 444, 905, 2006. [17] S. C. Solomon, *Science*, 307, 1214, 2005. [18] T. Kleine et al., *Nature*, 418, 952, 2002. [19] L. E. Borg et al., *GCA*, 67, 3519, 2003. [20] C. N. Foley, *GCA*, 69, 4557, 2005. [21] M. H. Acuña et al., *Science*, 284, 790, 1999. [22] R. J. Lillis et al., *GRL*, 33, L03202, 10.1029/2005GL024905, 2006. [23] B. Langlais and M. Purucker, *PSS*, in press, 2007. [24] M. H. Carr, *Water on Mars*, Oxford, 229 pp., 1996. [25] C. I. Fassett and J. W. Head III, *LPS*, 38, 2007. [26] B. M. Hynek and R. J. Phillips, *Geology*, 31, 757, 2003. [27] B. M. Hynek and R. J. Phillips, *Geology*, 29, 407, 2001. [28] G. Ryder, *JGR*, 107, 5022, 10.1029/2001JE001583, 2002. [29] B. A. Ivanov, *Space Sci. Rev.*, 96, 87, 2001. [30] R. J. Phillips et al., *Science*, 291, 2587-2592, 2001. [31] C. C. Reese et al., *JGR*, 107, 5082, 10.1029/2000JE001474, 2002. [32] J. W. Head III et al., *JGR*, 107, 5003, 10.1029/2000JE001445. [33] S. A. Hauck II et al., *LPS*, 34, 1667, 2003.