IMPACT HISTORY OF LARGE BOLLIDES AT MARS: IMPLICATIONS FOR THE LATE-HEAVY BOMBARDMENT AND ISOCHRON UNCERTAINTIES.

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Introduction: A hotly debated topic in planetary science is the concept of the Late Heavy Bombardment – a hypothetical era of enhanced impacts some time around 3.8 Ga [*e.g.* 1]. In addition to the question about whether or not it actually occurred, issues about its origin and when it began and ended in the inner solar system are unconstrained. In theory, the largest preserved craters should trace the early impact flux on a planet and show any increase during the Late Heavy Bombardment period. We have attempted to constrain this for Mars by age-dating five large basins and all craters with diameters $D \geq 150$ km via smaller superposed craters. In doing so, we have also detailed issues with the Martian isochron systems [2, 3].

Crater Counts and Geologic Mapping: We have used the largest, most complete crater database of the planet Mars, containing 637,074 craters; 384,363 of these have diameters $D \geq 1$ km [4]. This database was created by identifying craters manually in THEMIS Day IR, Viking, and MOLA mosaics. Among other data, this database contains the center latitude, longitude, and diameter for each crater within it that were used. Geomorphic mapping was completed of the most pristine and intact regions of crater rims for all craters $D \geq 150$ km within the database. Besides the five basins that were mapped (Table 1), the database contains 101 craters $D \geq 150$ km (see Fig. **1** for locations). Of these, 73 could be mapped; the remaining 28 were too heavily modified.

Age Determinations: Craters from [4] within the mapping regions were extracted and mapped rim areas calculated. Cumulative size-frequency distributions (CSFDs) were created [5] for each large crater's superposed craters. From these, we determined ages in two main ways using two different chronologies each – Hartmann [2] and Neukum *et al*. [3, 6]. The first method used the cumulative crater density at $D = 10$, 25, and 50 km, also known as $N(10, 25, 50)$ ages. We selected a broad range that was bound on the small end to eliminate as much erosion and secondary crater effects as possible, and we bound the large end to be as inclusive of craters as possible while minimizing erosion issues. Including basins, only 38 craters had discernable $N(50)$ ages, and 64 had $N(25)$ ages. All had $N(10)$ ages.

The second age-dating method was to fit isochrons to the CSFDs. This was done "blindly" without trying to match an $N(\#)$ age nor one age determined by previous researchers [*e.g.* 7, 8, 9]. We chose locations on the CSFDs that best paralleled the isochron functions [2, 3] and fit within that range. We did this for all 78 mappable craters and basins, and these are the ages quoted in Table 1.

Results: All ages are illustrated in Fig. **2** as a smoothed probability distribution. This was created by taking the determined age and associated uncertainties and creating a normalized, piece-wise Gaussian (because the uncertainties were often asymmetric). These were then summed for every crater with an age calculation. This procedure has three desirable effects. First, it helps to smooth the data for better readability. Second, it gives lesser weight to an age with a large associated uncertainty and more weight to one that has a well defined age. Third, each normalized Gaussian can be scaled by the crater diameter-cubed – a rough approximation of the mass of the impactor – to derive a mass flux distribution (Fig. **3** – large basins have been left out of this calculation).

Implications for the Late Heavy Bombardment: To first order, the data show a clear spike in cratering approximately 3.9-4.1 billion years ago and a decline since that time. The youngest of these craters that was dated has an isochron age of 3.54 or 3.61 Ga and an $N(25)$ age of 3.51 or 3.46 Ga (first uses [2], second [3]). The oldest dates to 4.23 Ga and 4.28 Ga. For ages before ~4 Ga, we find a sharp decrease in craters, but we interpret this as obliteration by subsequent crater formation, the formation of the large basins after these, and the vast Tharsis region that has resurfaced ~25% of the planet. An additional possibility is that the crust of Mars was not solid enough to support a large crater cavity before this time [10]. Regardless, it is likely that the cratering rate continues to climb further back in time from our observed peak at ~4 Ga.

Erosional History: To explore possible implications for the resurfacing history of Mars, we examined each CSFD to determine where the isochron "turn-off diameter" was located. This was where the CSFD slope shallowed at smaller diameters relative to the isochron functions (done for both [2] and [3]); this shallowing is most easily attributable to crater erasure through resurfacing processes.

The results are shown in Fig. **4**; in general, due to the different isochron shapes, turn-off was at a greater diameter for the Hartmann versus the Neukum system. It is difficult to draw extended conclusions at this time, but we can state that prior to ~4.15 Ga, craters $D > 10$ km were easily removed from the surface, consistent with >1 km of material based on the complex crater depth/Diameter relationship [4]. After ~3.9 Ga, craters $D > 5$ km were and are preserved, consistent with <1 km of erosion based on the simple crater depth/ Diameter relationship [4].

Isochrons and Crater Chronologies: We have used the two major crater chronologies for Mars in this work, and both show reasonable agreement as a whole but different results individually. This was especially apparent in smaller craters where the isochron systems have greater divergence. It is important to note that *neither* of the isochron systems worked for *any* CSFD over a broad diameter range (more than ~half an order of magnitude).

An artifact that requires note is that ages between the three $N(\#)$ differ and, on average, result in progressively older ages as # increases. The isochron ages are generally between $N(25)$ and $N(10)$ ages because the majority of that region in the CSFDs best paralleled the isochron function. Due to the nature of the two different isochron systems, $N(10)$ and $N(50)$ ages under the Hartmann system were younger while $N(25)$ was older, and the $N(25)$ often agreed better with $N(50)$ ages under Hartmann than Neukum. These illustrate well the problem with using $N(\#)$ ages and inherent and systematic uncertainties associated with isochrons.

Conclusions: From this work, we can conclude: (1) Unless the Martian cratering chronology is significantly revised, we see no evidence for a Late Heavy Bombardment spike in the cratering rate around 3.8 Ga; there is either a continuous decay in the cratering rate past ~4.1 Ga, or the spike occurred during or prior to 4 Ga on Mars. (2) Resurfacing/obliteration decreased dramatically after ~4 Ga. (3) Age dating within the same chronology is fraught with uncertainty based upon the diameters chosen to age-date, and larger diameters result in progressively older ages; cross-chronologies will also yield different results though they generally agree *on average* to within each others' uncertainties.

References: [1] Gomes *et al.* 2005. [2] Hartmann 2005. [3] Neukum *et al.* 2001. [4] Robbins & Hynek, 2012–in rev. [5] Crater Analysis Techniques Working Group 1979. [6] Ivanov *et al.* 2001. [7] Nimmo & Tanaka 2005. [8] Werner 2008. [9] Fassett *et al*. 2011. [10] Hauck & Phillips, 2002. [11] Smith *et al.* 2001.

Table 1: Ages in Ga of five large basins dated in this work compared with previous results. Top ages are based upon fitting the Hartmann isochrons [2] and bottom ages are based upon fitting Neukum isochrons [3, 6].

	This Work	[7]	[8]	[9]
Hellas	4.11±0.01 4.15±0.02	4.08	3.99±0.01	4.04
Argyre	3.93±0.02 $3.94^{+0.02}_{-0.03}$	4.04	3.83±0.01	3.92
Isidis	4.00±0.02 $4.00^{+0.02}_{-0.03}$	3.93	3.96±0.01	3.96
Prometheus	$4.09^{+0.03}_{-0.04}$ $4.07^{+0.03}_{-0.04}$	*Not Dated Elsewhere*		
Ladon	4.13±0.02 4.11±0.03	*Not Dated Elsewhere*		

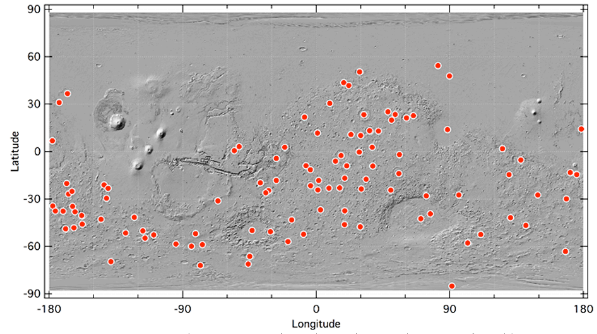

Figure 1: Red ● mark the location of all craters $D \geq 150$ km. Background is MOLA shaded relief [11].

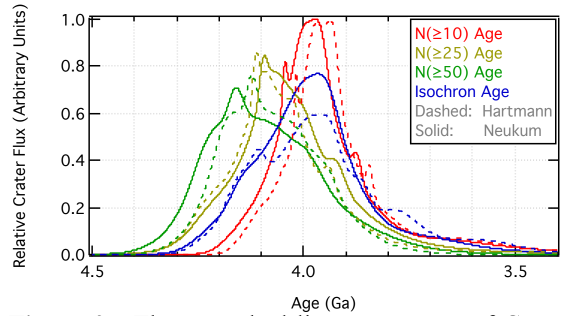

Figure 2: The smoothed lines are a sum of Gaussian distributions based upon the ages and uncertainties calculated for each crater from each method for each chronology.

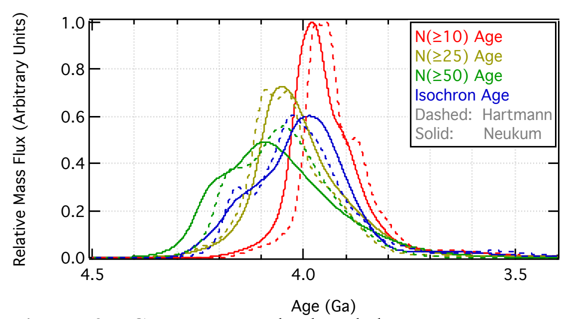

Figure 3: Curves are calculated the same way as ages from Fig. **2** except that each Gaussian for each crater has been scaled by D^3_{crater} to approximate the mass of the impactor. The large basins have been excluded.

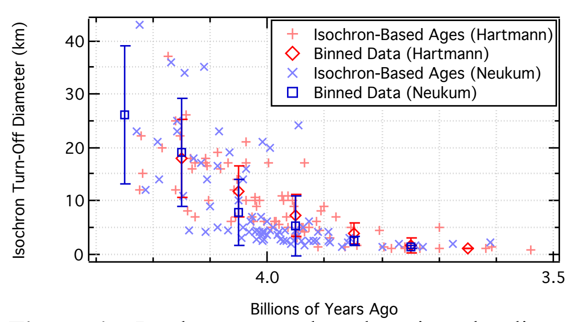

Figure 4: Isochron ages plotted against the diameter at which CSFDs deviate from the isochron function. Both isochron systems are shown with the binned data illustrating general agreement.