REVISING THE EARLIEST RECORDED IMPACT HISTORY OF MARS AND IMPLICATIONS FOR THE LATE HEAVY BOMBARDMENT. S.J. Robbins[1] and B.M. Hynek[1,2], [1]LASP, UCB 392, University of Colorado, Boulder, CO 80309, [2]Geological Sciences Department, UCB 399, University of Colorado, Boulder, CO 80309.

Introduction: A topic debated in the solar system's impact history is the concept of the Late Heavy Bombardment – a hypothetical era of enhanced impacts some time around 3.8 Ga. In addition to questions about whether or not it actually occurred, issues about its origin, the length of time it spanned, and when it began and ended in the inner solar system are unknown. In theory, the largest 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 four large basins and all craters with diameters $D \geq 150$ km via smaller superposed craters.

Crater Database: 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 [1]. 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 in this work.

Geologic Mapping of Crater Rim Areas: Geomorphologic 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 four 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 for this purpose.

Age Determinations: The craters from Robbins & Hynek [1] that were within the mapping regions of each large crater/basin rim were extracted and the rim areas calculated in local projected coordinates. Cumulative size-frequency distributions (CSFDs) after Arvidson *et al*. [2] were created for each large crater's overlapping rim craters.

From these, we determined ages in two main ways, though all relied upon the chronology of Neukum *et al*. [3, 4]. 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. Including basins, only 37 craters had discernable $N(50)$ ages, and 63 had $N(25)$ ages. All had $N(10)$ ages.

The second method used was to fit isochrons to the CSFDs. This was done "blindly" without looking at crater diameters, trying to match an $N(\#)$ age, nor trying to match an age determined by previous researchers [*e.g.* 5, 6, 7]. We chose locations on the CSFDs that best paralleled the isochron functions [3] and fit it in that range. We did this for all 77 mapable craters and basins. These are the ages quoted in Table 1.

Results: All four ages from Table 1 are illustrated in Fig. **2** in two ways. The first is a histogram binned in 0.1-Ga intervals with the different ages slightly offset within each bin for readability. The second method is 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 visibility. Second, it will give lesser weight to an age with a large associated uncertainty and more weight to one that has a well defined age. Third, we can scale each normalized Gaussian 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).

To first order, the data show a clear spike in cratering approximately 4.0 Ga and a decline since that time. The youngest of these craters that was dated has an isochron age of 3.61 Ga and an $N(25)$ age of 3.46 Ga. The oldest dates to 4.23 Ga and 4.28 Ga via those methods. For ages before ~4 Ga, we find a sharp decrease in craters. However, we interpret this as obliteration of these large craters 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 [8]. It is likely that the cratering rate continues to climb further back in time from our observed peak at ~4 Ga.

An artifact that requires note is that ages between the three $N(\#)$ differ and, on average, give progressively older ages as the # 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. This illustrates well the problem with using $N(\#)$ ages as well as uncertainties associated with isochrons. However, regardless of any chronology used, the results clearly show there was no significant spike at ~3.8 Ga at Mars in the cratering rate, inconsistent with a Late Heavy Bombardment.

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 function; this shallowing is most easily attributable to crater erasure through resurfacing processes. The results are shown in Fig. **4**. 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 [1]. After ~3.95 Ga, barring one outlier (Argyre), craters D > 5 km were and are preserved, consistent with <1 km of erosion based on the simple crater depth/Diameter relationship [1].

Implications for the Late Heavy Bombardment and Erosion: From this work, we can conclude several things: (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 4.1 Ga on Mars. (2) 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. (3) Erosion decreased dramatically after ~4.0 Ga.

References: [1] Robbins & Hynek, 2011. [2] Arvidson et al. 1979. [3] Neukum et al. 2001. [4] Ivanov et al. 2001. [5] Nimmo & Tanaka 2005. [6] Werner 2008. [7] Fassett *et al*. 2011. [8] Hauck & Phillips, 2002. [9] Smith *et al.* 2001.

Table 1: Ages in Ga of four large basins dated in this work compared with previous results. Ages here are based upon fitting Neukum isochrons [3, 4].

	This Work	[5]	[6]	[7]
Hellas	4.15±0.02	4.08	3.99±0.01	4.04
Argyre	$3.94^{+0.02}_{-0.03}$	4.04	3.83±0.01	3.92
Isidis	$4.00^{+0.02}_{-0.03}$	3.93	3.96±0.01	3.96
Prometheus	$4.07^{+0.03}_{-0.04}$	*Not Dated Elsewhere*		

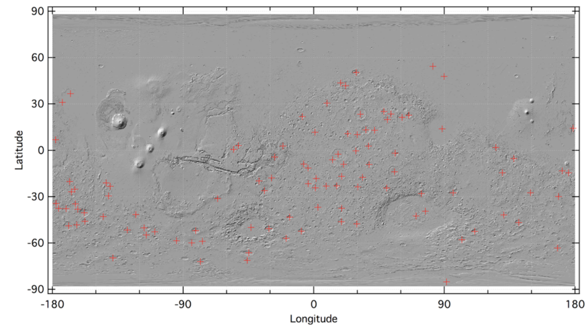

Figure 1: Red + mark the location of all craters $D \geq 150$ km. Background is MOLA shaded relief [9].

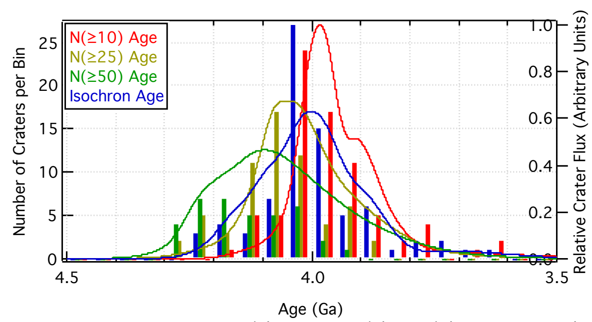

Figure 2: Bars are a histogram binned in 0.05 Ga intervals with the four different dating methods slightly offset for readability. The smoothed lines are a sum of Gaussian distributions based upon the ages and uncertainties calculated for each crater from method.

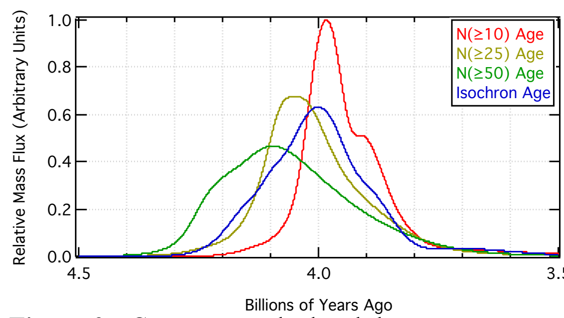

Figure 3: Curves are calculated the same way as ages from Fig. **2** except that each Gaussian for each crater has been scaled by D^3_{crater} to approximate the mass of the impactor. The large basins have been excluded.

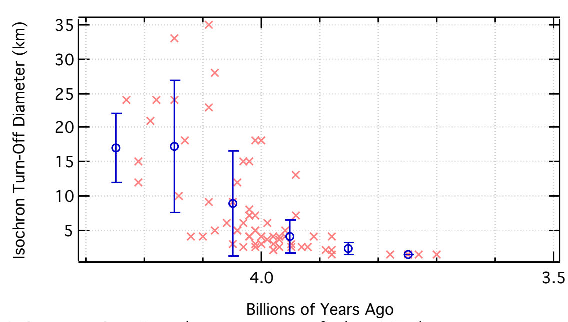

Figure 4: Isochron ages of the 77 large craters and basins plotted against the diameter at which CSFDs deviated from the isochron function. Blue points indicate mean and standard deviation of 0.1-Ga-wide bins.