PREVIOUSLY UNRECOGNIZED LARGE IMPACT BASINS ON MARS AND THE MOON: IMPLICATIONS FOR THE LATE HEAVY BOMBARDMENT IN THE INNER SOLAR SYSTEM

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Summary: Crater retention ages of the Martian highlands and lowlands, and of the interior of South Pole-Aitken basin on the Moon, suggest the cumulative number of basins on Mars is about 12 times, and on the Moon about 2 times, greater than previously thought (at least). Crater retention ages for large impact basins on Mars suggest most formed in a relatively short time, perhaps in less than 200 million years. This supports a spike-like Late Heavy Bombardment which may have been common throughout the inner solar system.

Introduction: The discovery of previously unrecognized craters and large basins on Mars [1-3] and the Moon [4-6] has significantly changed ideas about the early history of Mars [3] and is likely to do the same for the Moon. At the very least it is clear that early cratering was far greater than previously thought, which has implications for using the Moon as a standard for estimating absolute surface ages from crater counts. Despite the large increase in the inferred number of impact craters now detectable on Mars using MOLA data [3] and more recently crustal thickness data [7,8], and on the Moon [6] using Clementine-derived gridded topographic data [9], it is likely crater retention ages will still be minimum estimates of the actual crater density on these surfaces. Despite this, important implications concerning both the Late Heavy Bombardment and the early crustal evolution of the planets of the inner solar system, including the Earth, derive from these new insights into the greater than previously thought cratering of Mars and the Moon.

Early Cratering at Mars and the Moon: Both the highlands and lowlands of Mars have extensive, previously unrecognized, populations of likely impact basins revealed by MOLA data and crustal thickness model data derived from MOLA topography and gravity data. As shown in table 1, the N(300) CRA for the highlands and lowlands have increased from earlier estimates based only on visible basins by factors ~12 and ~80 respectively, such that both regions now appear to have a similar N(300) CRA of about 3.18 [8]. The greater increase in crater density seen in the lowlands supports the idea that most of the previously unrecognized basins on Mars are probably buried.

Table 1. Change in N(300) Crater Retention Ages for the Highlands and Lowlands of Mars based on Basins found in MOLA Topography and Crustal Thickness (CT) Data (from Edgar and Frey [6])

	Vis	Vis+Topo	Vis+Topo+CT
Highlands	0.27	1.98	3.18
Lowlands	0.04	0.87	3.19

On the Moon, which has fewer ways to bury large basins, the increase in the cumulative number of basins > 300 km in diameter is at least a factor of 2: we found 92 [6] using ULCN topography compared with the 45 listed by Wilhelms [10] based on photogeologic mapping. This is similar to the increase found for basins > 100 km diameter superimposed on the large South Pole-Aitken basin, where the N(100) CRA for visible basins was found to be 12 and that for the total population (visible plus previously unrecognized) was 21, a factor 1.8 higher. These are likely minimum CRAs because there may be even more previously unrecognized basins (PUBs) which better topographic and crustal thickness data will reveal. At present, we can say with some confidence that the early cratering on the Moon was likely a (cumulative) factor of 2 greater than thought, and on Mars likely a (cumulative) factor of 12 higher than thought (based on the highlands CRAs.

Ages of Large Impact Basins on Mars: Crater retention ages for the 20 largest impact basins on Mars (D> 1000 km) based on superimposed large visible or buried basins [6] and even more deeply buried impacts revealed in crustal thickness data [8] suggest that most of the basins formed in a relatively short period of time [11]. As shown in Figure 1, N(300) CRAs for 65% of the large basins lie between 2.5 and 5.0 [3], and 50% of the population have CRAs between 2.5 and 4.0. Conversion to the Hartmann-Neukum model chronology [12] suggests an absolute age of 4.10 to 4.25 BYA for all but the three youngest (Hellas, Argyre and Isidis), with most falling within an even narrower interval of 4.12-4.14 BYA [11].

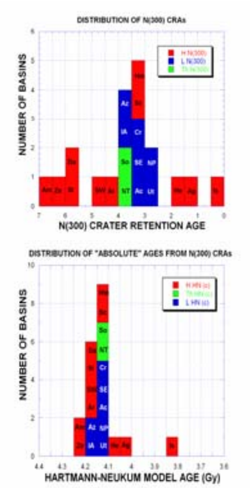

Figure 1. Distribution of N(300) Crater Retention Ages (CRAs) (upper left) and model absolute ages (lower left) for the 20 largest impact basins on Mars. Absolute age bin 50 MY. Highland basins (red) have a broader range of ages than lowland basins (blue). If CRAs are equivalent to formation ages, > 50% may have formed in a relatively short time between 4.1 and 4.2 BYA.

The sharp peak in likely formation ages for the largest impact basins on Mars has several important implications. It suggests the possibility of a cataclysmic Late Heavy Bombardment (LHB) on Mars. The short time is consistent the NICE model [13,14] and a "terminal lunar cataclysm" [15,16]. The absolute ages, however, are wrong: the lunar cataclysm occurred between 4.0 and 3.8 BYA. The Martian ages are model ages based a number of assumptions [12] and could be off by several hundred million years. If the peak shown in Figure 2 is part of an inner solar system event, it may be that the Martian chronology can be corrected by pinning this peak to the ~3.9 BYA cataclysm on the Moon.

The Martian global magnetic field apparently died during the peak in impact basin formation, and likely abruptly [17,18]. This would have left the Martian atmosphere (what remained or recovered from the effects of these very large impacts) unprotected from the solar wind. Combined with the likely environmental insult due to the formation of impacts up to 10 times larger than Chixulub, the time immediately during and after the Late Heavy Bombardment on Mars was not very hospitable.

The apparent lack of large basins earlier than those shown, if real, suggests the impacts may have been very tightly confined in time, permitting a ~400 MY period before 4 BYA during which planet-sterilizing impacts did not occur. This may support the idea of a "cool early Earth" [19] during which Earth (and Mars?) may have been more habitable than during the 4.0-3.8 BYA LHB interval.

Late Heavy Bombardment on the Moon and Mars: Open Questions. Topography reveals a significant number of large lunar basins > 300 km diameter that were not previously recognized [6]. Lack of previous recognition does NOT mean these newly-found basins are all older than those previously known: it may be poor lighting geometry contributed to lack of previous discovery. Large diameter crater retention ages for these are being determined, and absolute ages could be estimated through ties with basins of known age. It is important to know if the lunar basins are tightly confined in time as it appears the Martian basins may have been. This has bearing on the exact nature of the Late Heavy bombardment on the Moon and elsewhere.

The size distribution of lunar basins as currently known from photogeologic mapping and topography (see Figure 2) suggest a significant gap between the 2600 km wide SPA and the next largest basin, Imbrium, at ~ 1160 km. There are currently no known 1500, 1800 or 2200 km diameter basins. It is interesting to speculate whether this suggests SPA is of a different population than the other lunar basins, which tend to follow a -2 power law trend in a cumulative frequency diagram. Alternatively, it may be that better topography or crustal thickness data will reveal some subtle expression of basins in this size range that have not yet been recognized. We are currently looking at existing crustal thickness data [20,21] for such possibilities. We have not yet identified any obvious candidates in this size range but have found smaller features not previously identified. Improved topography from LOLA [22] and especially the better gravity field anticipated from GRAIL [24] should provide even better limits on the actual number and size of large lunar basins.

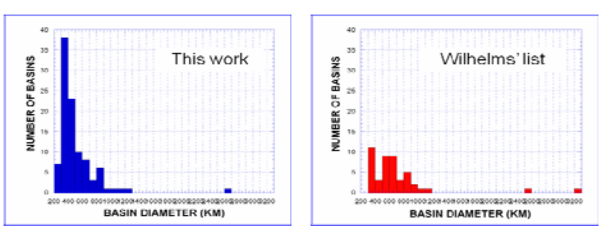

Figure 2. Size distribution of lunar basins > 300 km diameter from Wilhelms [10] (right) and from ULCN topography [6] (left). Note the very large gap between South Pole-Aitken and Imbrium (left).

Likewise it is important to determine, for the Martian basins, if there really are no basins older than those shown in Figures 1 and 2. New crustal thickness data with improved resolution and signal-to-noise quality [23] offers the possibility of finding features not previously recognized, and we are currently searching that data for subtle but unrecognized large basins. Because the present population of basins > 1000 km on Mars [11] has a total area of only 43% of the surface area (not allowing for overlap) and actually occupies less than 35% of the surface area of Mars, it is possible that some subtle signature of even older basins might survive. If so, it will be extremely interesting to determine if such a basin has an N(300) CRA substantially older than 7, and thus might not be part of the apparent spike in CRAs for the basins currently recognized. Note that in the conversion to Hartmann-Neukum model absolute ages, it would require an N(300) > ~15 to have an absolute age > 4.3 BYA (but recall that these model ages are uncertain enough that the peak at 4.10-4.15 could actually be at 3.9 BYA). Such older areas may not exist, however, if the effects of the 20 known very large impacts extend to great distances (e.g., twice the basin diameters), but it is important to search for such very old crust or older basins.

Absolute ages for most Martian and lunar basins will almost certainly require returned samples. In the interim, ages for these basins will come from crater counts. Recent experience indicates that those counts will be substantially higher than we currently have, and that topographic data should be used in conjunction with image data to get closer to the true total cratering on planetary surfaces.

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