Fresh Impact Craters and Clusters on Mars: What do they tell us about Mars and Asteroids? William K. Hartmann1, Ingrid Daubar2, Olga Popova3, Sylvain Breton4, Cathy Quantin4  
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Introduction: Ongoing formation of fresh, single, decameter-scale impact craters and clusters of such craters, during modern spacecraft missions, was discovered during the Mars Global Surveyor mission [1]. The clusters indicate that some of the incoming meteoroids fragment in the Martian atmosphere. Great expansion of these observations has been provided by the Mars Reconnaissance Orbiter, especially by the HiRISE imagery team [2,3]. Their studies found that, averaging among various data sets, roughly 50%-60% of the new impacts are clusters. We have noted that ratios of fresh single to clustered craters can be used to clarify the numbers of small secondary craters in a region, thus improving crater-count chronometry at small-crater sizes [4]. In our present study, we attempt to integrate altitude/elevation information into the interpretation of such objects, to understand how meteoroids are fragmenting in the Martian atmosphere and what this tells us about the bulk physical properties of these objects. (We use “elevation” to refer to surface elevation relative to the MOLA mean surface, and “altitude” to refer to distance in the atmosphere above the mean surface.) Thus we have an interesting interdisciplinary interface between Mars surface features, Mars chronology, and the properties of asteroidal and cometary fragments that enter the Martian atmosphere.

An initial, perhaps naïve, view, which we considered at the outset, is that in the very thin Martian atmosphere, if a few meteoroids composed of fractured rocky material fragmented, numbers of hard-rock fragments would increase toward lower elevations, so that high elevations might have mostly single craters and lowest elevation might have the maximum density of clusters/km². In studying the statistics of clusters as a function of surface elevation we have not confirmed that expectation.

Examination of Fresh Single Crater and Cluster Populations: The fresh impacts are initially detected from low-resolution CTX context camera images of “splotches” of ejecta material, not present in earlier images. The “splotches” contrast in albedo with the background. They are then investigated with high-resolution HiRISE images (25-cm pixels). High-resolution images reveal either single craters or clusters as the cause of the “splotches.” The fresh impact craters are typically in the diameter range of ~2 m to ~40 m. The “splotches” are most strongly produced in dusty areas. In order to reduce bias we thus studied only areas with the highest dust cover index, namely “dust cover index” > 0.96 [5]. We have verified that there is no significant correlation between high dust content and elevation that might bias our technique. Figure 1 shows a map of Mars with these high-dust areas in color, superposed raw data on fresh impacts as compiled in [2] and [3].

![Figure 1. Map of Mars with regions of highest dust cover (5) shown in color. Fresh impact detections are shown by open and closed circles (2,3 respectively). Highest (MOLA) elevations (Tharsis, red-browns) appear to show highest densities of fresh impact densities, and lowest elevations, (Hellas blue-mauve), lowest densities, but see text for caveats.](image)

Figure 2 shows another example of our results. We divided the high-dust Mars surface into 1-km elevation zones and plotted numbers of detected fresh impact features/km² vs. elevation zone. The densities of fresh impact detections are highest in the high elevation zones but the error bars are also highest there, because the areas of the highest zones (typically Tharsis volcano upper slopes) are very small, leading to small total samples of craters in spite of high density. The fact that significant numbers of clusters have been found at elevations from +2 to +10 km above the mean surface of Mars indicates that fragmentations occur in the Martian atmosphere above these levels. This, in turn, implies significant numbers of meter-scale meteoroids with bulk strengths less than coherent rock. This finding is consistent with numerous terrestrial fireball that fragment at high altitudes indicating weak, highly-fractured or rubbly bulk properties [6].

Our histograms, such as Fig. 2, show a dramatic reduction in detected impact densities below elevations of ~2 to 4 km, which might imply complete loss of some weak meteoroids and their weak fragments during descent. However, the concept of detections is emphasized in the above paragraphs because the detections are dependent on the numbers of CTX images in
each zone, and, more significantly, the number of them that have been studied in a search for fresh impacts. At the time of this writing it is not clear to us that CTX search statistics, such as Figure 2, (or any other search statistics) are uniform enough to prove losses of meteoroids and meteoroid breakup fragments as they descend into the Martian atmosphere.

**Fig. 2.** Detections of fresh impact features/km² (abscissa) as a function of elevation (ordinate), for single craters (right), clusters (middle), and total numbers (left). All three detection categories decrease in spatial density toward lowest elevations --- but see text.

We have also studied size-frequency distribution ("SFD") of the fresh single craters and the “effective diameter” of the fresh clusters (crater size had the meteoroid not fragmented). At D ≥ 8m, the slope of the SFD is roughly consistent (within error bars) with the isochron slope derived from small craters observed in young regions [7]. At D ≤ 8 m, however, losses of fresh impact detections are evident, relative to the small-crater counts in [7]. Our calculations indicate that velocities of objects making craters in that size range are significantly reduced by drag, causing smaller craters and probably less pronounced “sploches” of debris. Loss of detections at D ≤ 8m may thus be due to these effects, which are much less at larger crater sizes.

**Continuing work:** We are continuing our attempts to understand better how the fresh-impact detection procedures may affect the statistics of fresh impact features, and especially whether there may be effects that influence detections as a function of surface elevation. We are also comparing Martian meteoroid behavior with both ground and satellite observations of terrestrial meteoroids terrestrial meteoroids. Popova et al. [6] showed that 13 out of 13 well-observed terrestrial fireballs fragmented at high altitudes, indicating bulk strengths much smaller than their rock fragments collected on the ground, so that meter-scale asteroidal and cometary objects in space may be laced with fractures, or granular, or volatile-rich. We also continue our analysis of cluster sizes and dispersion of the fragments, with modeling of the behavior and breakup of fragments following initial breakups of Martian meteoroids.

**Future Work:** As mentioned above, understanding the ratio of primary clusters to primary singles as a function of elevation will help in improving the field of crater chronometry. For example, suppose we know that half of primary impacts in these size ranges, in a given area, involve clusters. If 100 single craters and primary clusters are observed in a given size range and Martian area, and 20 of them are primary clusters (noting that primary clusters are identifiably smaller than secondary clusters because of velocities and flight times), then another 20 of that 100 must be primary single craters, so that the remaining 60 single craters would be secondaries [4]. Crater-count chronometry has been criticized for uncertainty about numbers of secondaries; this work should improve the system. The longer we continue observations of the fresh impacts, the larger the crater sizes we can incorporate into these discussions.

**Provisional Conclusions:**  (1) Many of the few-meter-sized asteroid and cometary objects striking Mars are weak enough to fragment in the Martian upper atmosphere at elevations > +10 km. (2) This result appears consistent with objects striking the Earth. (3) Some weak objects, and their fragments, may be breaking up during descent; and may be lost entirely during descent to lower elevations. However, we need a better understanding of how the process of detection of fresh impacts may affect these statistics as a function of elevation. (4) Accurate statistics of fresh primary cluster abundances vs. fresh primary single craters will help us understand the numbers of secondary craters among small craters. (5) Continued monitoring of newly formed single and clustered craters will extend our understanding to craters of diameter D > 40 m.