# THE RECENT ATMOSPHERIC HISTORY OF MARS FROM SMALL CRATERS OBSERVED BY MSL.

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**Introduction:** The obliquity of Mars has undergone semi-periodic, chaotic fluctuations that have been theorized to alter the atmospheric density [1], [2]. The density fluctuations are a result of $CO_2$ being released from reservoirs of polar ice. At greater obliquities, the Martian poles are exposed to the sun for longer periods of time, causing the solid $CO_2$ ice at the poles to sublimate, resulting in a denser atmosphere. At smaller angles of obliquity, the opposite occurs. The $CO_2$ freezes out of the atmosphere and results in a less dense atmosphere. These obliquity fluctuations and corresponding atmospheric density fluctuations should be reflected by geological processes such as the threshold for the smallest meteorites to survive the journey through the atmosphere and form a small crater. By analyzing these “threshold craters,” or the smallest craters of a population from the surface of Mars, the recent history of the atmospheric pressure can be determined and compared to modern measurements.

**Cratering Mechanics:** Every meteorite that travels through an atmosphere experiences a degree of deceleration, ablation, and possibly fragmentation. Deceleration occurs as the result of aerodynamic drag and gravity, which causes a reduction of an objects velocity from loss of kinetic energy to the atmosphere [3], [4]. The magnitude of a projectile’s deceleration is dependent on the local density of the atmosphere, cross-sectional area, velocity, and mass of the projectile, the local gravitational acceleration, the angle of incidence, and the drag coefficient, which is a dimensionless parameter that pertains to skin friction, flow speed, flow direction, fluid density, and viscosity [5]. Ablation is the result of heating and vaporization of the projectile’s surface from friction with the atmosphere. It is dependent on the local density of the atmosphere, the projectile’s cross-sectional area and velocity, the heat transfer coefficient, and the heat of ablation [6]. Fragmentation occurs when the dynamic pressure experienced by the projectile during entry exceeds its bulk strength [3]. Aerodynamic breakup results from structural weaknesses and heterogeneity of the impactor. Since smaller objects generally have a homogeneous matrix and less fracturing, they experience less fragmentation than larger objects which are inherently weaker [3]. There is a size dependence on fragmentation because smaller objects begin to ablate and decelerate higher in the atmosphere, experiencing smaller peak dynamic pressure while larger, faster objects experience larger peak dynamic pressure [3], [7]. Therefore, small ($D < 5$ m) craters are expected to be heavily influenced by deceleration and ablation but not fragmentation.

Ablation is more sensitive to velocity and is the most significant atmospheric factor for cm-sized projectiles entering the atmosphere [3]. If smaller projectiles ablate completely, it will be impossible to form a small impact crater. If smaller projectiles ablate significantly, the resulting projectile may be too small to form a hypervelocity impact crater.

There is also an ongoing debate in the literature about the concentration of primary vs. secondary craters amongst small craters [8], [9]. Secondary craters are the result of ejecta from larger impacts traveling and impacting elsewhere. Secondary craters are generally more oblique, shallower, and a part of a cluster or rays connected to a larger primary impact crater [8]. Distant secondaries travel greater distances and create more circular craters because they impact at higher angles, making them harder to distinguish from small primaries. The small craters investigated are unlikely due to recent large primaries, but must be young enough to retain a crater shape and not subsequently eroded given known erosion rates. It may be possible for a small fragment to come from a larger piece of ejecta traveling from the primary impact, but this scenario requires multiple processes to occur and is less probable. Since there are no obvious rays, clusters, or indications of a larger primary impactors for the small craters in this catalog, it is assumed that most are the result of small primary impacts.

**Threshold Craters:** The smallest craters found on a planetary surface translate the atmospheric constraints. Previously, it was predicted that the minimum projectile size of an iron meteorite as it impacts the surface is 3.6 cm and 4.4 cm for a chondrite under current conditions of the Martian atmosphere [10]. Various types of compositions of meteorite were modeled to determine the minimum crater diameters that can be formed to be 0.3 m from iron meteorites and 0.5 – 6 m from stony meteorites, and derived that small Martian craters ($D < 1$ m) could be formed by iron impactors as small as 1 - 4 cm in diameter, which refines earlier predictions [11]. Projectiles entering the Martian atmosphere under current conditions have a predicted cutoff for crater diameters of 0.24 m [3], [12].

Past missions have also identified as small craters similar to this catalog. Pathfinder found possible 0.25 cm impact craters on a boulder [10]. The MER rovers found small, sub-meter diameter craters. A 1 m diameter crater along the Opportunity traverse was identified while cataloging 5 – 30 m diameter craters [12]. A preliminary investigation of small craters discovered near Curiosity's traverse found no examples of craters smaller than 33 cm in diameter, although smaller craters should be present based on predictions with the present atmospheric density.

**Methods:** All craters are from the Mars Science Lab (MSL) traverse and were measured with the ruler tool in OnSight, a 3D Mars terrain visualization tool. Craters were found primarily with OnSight and were confirmed with Midnight Mars and MSLICE, which are also resources for viewing images from the mission. Craters are verified using the z-axis, or depth measurements in OnSight to determine if the center of a circular feature is a depression. If the change in the z-axis indicated a dip in the center of a circular feature, it is considered a strong candidate for a crater. Crater diameters were measured rim-to-rim in OnSight to determine length, width, average diameter, and eccentricity of each crater.

**Crater Catalog:** For the first 1962 sols of MSL, 237 craters were found, 55 were smaller than or equal to 1.5 m in diameter. The smallest crater identified has D = 0.33 m. Of the 237 craters found, 27 are D < 1 m and 4 are D < 0.5 m. The abundance of sub-meter craters is smaller than expected for a 6 mbar atmosphere, or the current conditions on Mars [13]. As the frequency of craters nears the atmospheric cutoff, the cumulative abundance of craters of the smaller diameters flattens. The craters were found over an area of 334,029 $m^2$.

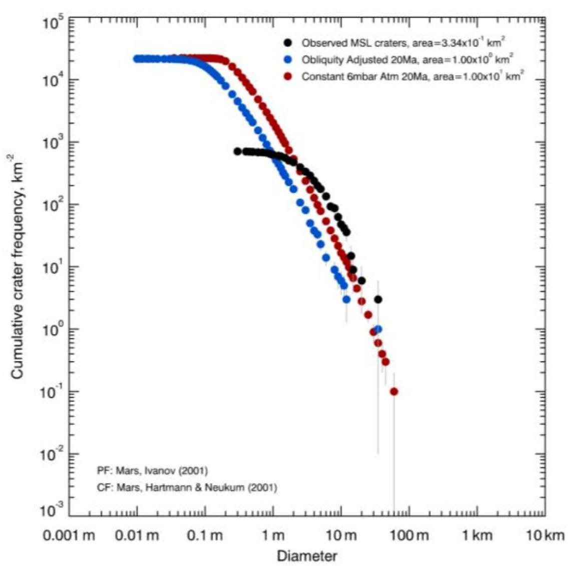


Figure 1. The cumulative crater frequency of the craters identified along the traverse (black) compared with simulations of the current 6 mbar average Martian atmosphere propagated for 20 Ma (red) and of a Martian atmosphere varying in pressure with obliquity over 20 Ma (blue) from Williams et al., (2018).

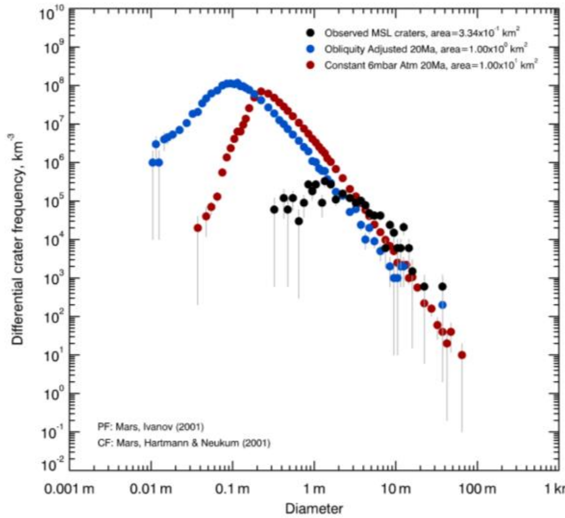


Figure 2. The differential crater frequency of the craters identified along the traverse compared with the same simulation as figure 1. Plots from craterstats 2 [14].

**Atmospheric Implications:** The cutoff of observed craters at D = 0.33 m indicates that the atmosphere was denser within the lifespan of a small crater, which is expected to be at least 20 million years [12], [13]. Further work is needed to investigate the timescales of aeolian erosion of small craters. If the density of the atmosphere responds to greater Martian obliquities as predicted, then the atmospheric pressure could have been 20 times greater than present conditions [13]. The crater catalog from Curiosity's traverse indicates that Mars recently had a denser atmosphere, possibly greater than theoretical models that correlate singularly with obliquity. A denser Martian atmosphere could have repercussions on peak erosion rates, saltation levels, or even survivability of liquid water at the surface for which previous predictions have not accounted.

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