DOES THE LITTLETON METEORITE REQUIRE A PAST, DENSER MARTIAN ATMOSPHERE?

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Introduction: To date at least ten known or suspected iron meteorites have been discovered by the Mars Exploration Rovers (MERs) Spirit and Opportunity and the Mars Science Laboratory (MSL) rover Curiosity. Most recently (May 2014) Curiosity found three closely clustered iron meteorites, that include the largest yet found, called "Littleton" (Fig. 1), as well as "Lebanon" (slightly smaller) and "Lebanon B". The previously-largest martian iron meteorite Block Island (BI; ~240-250 kg) was found to be explainable, even under Mars' current thin (6 mbar) atmosphere, but only given certain highly restricted entry velocity (v_o) and angle (θ_o) conditions (flight paths 2 and 3, Fig. 2) [1,2]. BI required very special, and improbable, entry conditions (Fig. 3) to land at less than 2 km/s; it would have had to follow a "fallback" type of trajectory (Fig. 2, flight path 3) [2]. Its presence on Mars thus *suggests*, but does not require, that Mars had a denser atmosphere when it arrived.

Like other martian iron meteorites, Littleton is covered with regmaglypts caused by atmospheric passage, and appears virtually undamaged by impact with the surface, thus requiring it be slowed well below hypervelocity impact (~2 km/s). It sits essentially fully exposed on the surface and stereo Navcam images taken from MSL yield a volume of ~0.8 m^3 and a mass estimate of ~6370 kg for an assumed density of 7900 kg/m^3. Thus Littleton is the most massive of all martian iron meteorites that have been identified (27 times more massive than BI); Lebanon is about 21 times more massive than BI. These iron meteorites again raise the question: Can the current 6 mbar martian atmosphere aerodynamically slow such a massive object enough to land it intact on the Mars' surface?

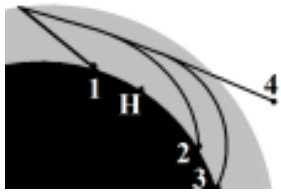

Fig. 1 (Left): Martian iron meteorite "Littleton". Fig. 2 (Right): Flight path types discussed herein, defined: (1) "direct", (2) "over the horizon", (3) "fallback", (4) "escape". H denotes the horizon viewed from meteoroid entry point.

Methods: A 4th order Runge-Kutta numerical integration method was used to simulate atmospheric passage of large numbers of Littleton-like meteoroids (see [1,2] for details). The simulation was "scanned" over ranges of interest in entry velocity and angle, and the results tabulated according to impact speed and flight path type (Fig. 2). Test objects were started from an altitude of 100 km, with entry velocities of 5.5 km/s (close to the minimum physically possible) to 10.5 km/s (near the mean, for Mars) and entry angles $9° \leq \theta_o \leq 14.5°$, measured downward from the local horizontal. This range was limited to those entry angles which may produce meteorites - steeper enterers impact destructively (Fig. 2, path 1), and shallower ones simply pass through and escape the atmosphere (Fig. 2, path 4). A condition that impact velocity, v_f, be less than 2 km/s was then applied as a limit for identifying any possibly survivable impacts; meteroids impacting at higher velocities will form craters and be largly destroyed in the process. In fact, given its large size and intact state, Littleton probably impacted significantly slower than this to survive, so 2 km/s constitutes a very conservative estimate.

Results: Not a single simulated Littleton-type test object struck the surface at less than 2.3 km/s under the 6 mbar martian atmosphere (Fig. 3) - well above even our generous upper limit of 2 km/s for an intact meteorite. Few even impacted at less than 4.5 km/s, and all of these followed long, 'over the horizon' or 'fallback' type flight paths, and not direct ones.

Doubling the atmospheric pressure produced a very few 'fallback meteorites' (Fig. 4), but these are rare events and all still impact at very nearly 2 km/s. Thus it is quite unlikely that even a 12 mbar atmosphere could have landed Littleton. By incrementally increasing the atmospheric density, we find that only when the surface pressure reaches ~44 mbar do any Littletons land via the much more common 'direct' type of flight path.

Conclusions: We find that Mars' current atmosphere cannot land Littleton sized irons, and this conclusion is quite robust. We used a value for the survivable impact speed intended to *favor* survival of meteorites, and yet found no such results. The 12 mbar atmosphere could, in theory, land Littleton, however a more realistic estimate for the minimum atmospheric surface pressure when Littleton arrived is probably at least 50 mbar. Thus, while previous results suggested (but did not require) that BI encountered Mars at times of higher atmospheric density, Littleton represents positive meteoritic evidence of a past, denser atmosphere. It appears impossible to explain its presence on Mars otherwise.

References: [1] J. E. Chappelow & V. L. Sharpton (2006), *GRL,* **33**, L19201. [2] J. E. Chappelow & M. P. Golombek (2010), *JGR*, **115**, E00F07.

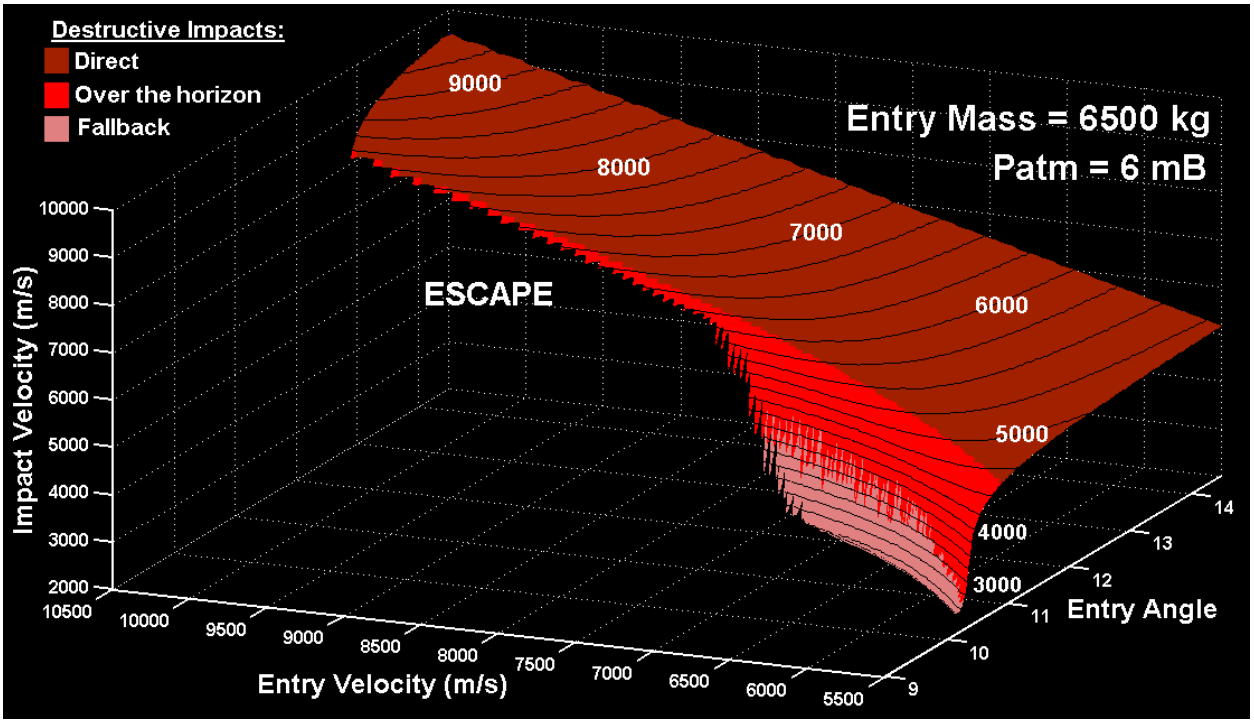

Fig. 3: Test meteoroid outcomes for a 6 mbar martian atmosphere. No Littleton-like meteoroids were found to impact at speeds less than 2.3 km/s. Artifacts due to the rendering process and gridded nature of the output appear where the surface is extremely steep, but are of no consequence to the conclusions. Impact velocity contours are provided for assistance in interpretation.

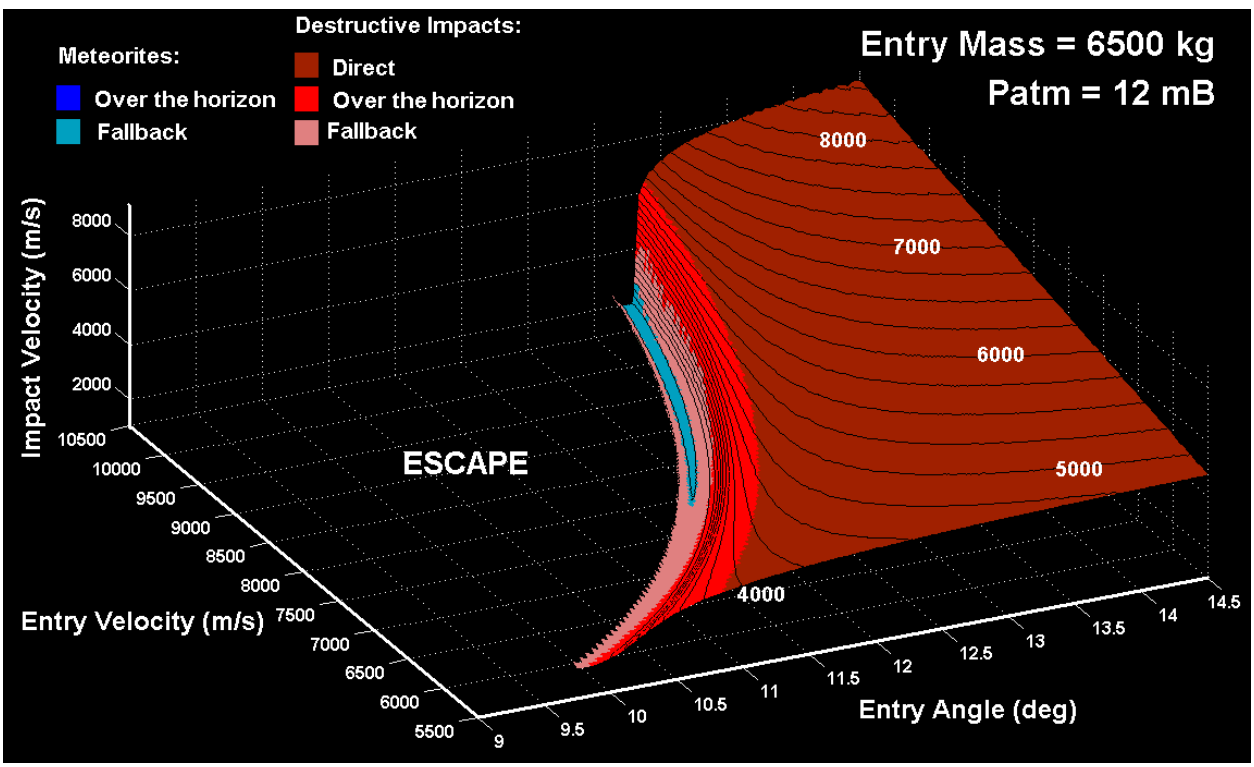

Fig. 4: Test meteoroid outcomes for a 12 mbar martian atmosphere. The small blue area represents a very few 6000+ kg meteorites, all of which followed "fallback" type trajectories. These events would require very improbable entry conditions, so they would be exceedingly rare. The blue shadings outside of the 2 km/s isoline are artifacts.