CAN MARS' CURRENT ATMOSPHERE LAND BLOCK ISLAND SIZED METEORITES?

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Introduction: In 2005-6 Chappelow and Sharpton showed that iron meteorites up to a few kg in mass should be expected on Mars [1,2] and that even irons the mass of Heat Shield Rock (hereafter HSR, also named Meridiani Planum) (50 – 60 kg) could be landed, even under as low-density a martian atmosphere as the one that exists today, though only rarely. They would have to encounter the planet within narrow limits of initial mass, entry velocity, and entry angle [3] to have their velocity reduced sufficiently below hypervelocity impact speeds (< 2 km/s) to land a meteorite as opposed to forming a primary crater and being destroyed or severely deformed. The recent discovery of three more irons, two of them larger and more massive than HSR ("Block Island", BI, [~425 kg], "Shelter Island", SI, [~125 kg], and "Mackinac Island", MI, [25-55 kg]) has raised the question of how to account for these much larger meteorites. Our motivation is driven by the observations of the meteorites made by Opportunity [4, 5, 6] that show all have portions of their surfaces that are smooth with hollows that appear similar to regmaglypts [5], which form by ablation during passage through the atmosphere. These observations argue that the meteorites are not spall fragments that fractured off the impactor during impact because such fragments would have surfaces dominated by fracture planes and broken edges.

These observations raise the questions: Can meteorites as large as these land on Mars at low enough speeds to survive impact, even under today's low-density martian atmospheric conditions? And if so, how does this occur? The purpose of this work is to address these questions.

Methods: As the largest of the three new meteorites, this work focused on Block Island. It is assumed that if BI can be sufficiently slowed, that SI can as well. A 4th order Runge-Kutta numerical integration method was used to construct a simulation of atmospheric passage of meteoroids encountering Mars. This simulation was 'scanned' over ranges of interest of the entry parameters: entry mass (m_o), velocity (v_o) and angle (θ_o), and the Block Island –like outcomes sorted out of the results ('entry' is here defined to occur at 100 km altitude, or ~9 scale heights of Mars' atmosphere). This process was repeated as necessary to zero-in on the ranges of these parameters that land Block Island –like iron meteorites. Criteria of 400 kg $< m_f <$ 600 kg and $v_f <$ 2 km/s, where m_f is the final mass and v_f is the final velocity, were used to sort the BI meteorite outcomes out of the results.

Results: We found that Mars' current atmosphere can decelerate iron meteoroids as large as Block Island below 2 km/s, but only if they start with very specific masses, speeds, and (especially) entry angles. All of the positive results for BI that were found followed the type 3 flight path shown on Fig. 1 (termed "fall-back" trajectories in the caption). On this type of trajectory, the meteoroid enters the atmosphere, initially descends, but then ascends briefly as the planet curves away beneath it, before finally slowing and redescending to land on the surface. This sort of flight path can be many times the length of more common, direct ones (Fig. 2).

Limits on the necessary entry conditions to produce a BI meteorite were found to be m_o = ~410–780 kg, v_o = ~6.5–16.5 km/s, and θ_o = ~10.8°–13.3°. All of the positive results were found to impact the surface at speeds of 1.6-2.0 km/s and at angles less than 20° from horizontal. These shallow impact angles may mitigate the effects of impact, increase survivability of the meteorites, and possibly cause them to ricochet across the surface [7]. Final (impact) masses of the test meteorites were typically a few 10s-of-kg less than initial masses, due to ablation during atmospheric passage. The maximum dynamic pressure encountered by any of the positive results was 0.41 MPa. This is some 2-3 orders of magnitude smaller than the strength of meteoritic iron [8].

All of the simulated objects outside of these bounds either struck the surface faster than the assumed maximum survivable speed (1 and 2, on Fig. 1) or exited the atmosphere (4, on Fig. 1). However these are far from exclusive limits; the vast majority of sets of starting conditions, even that fall within these limits, do NOT produce Block Island meteorite –like results.

Observations: While it does seem possible for the current martian atmosphere to land Block Island -like meteorites, these events must be considered quite rare. The original object must pass through Mars' atmosphere on a very specific type of trajectory, and within a very small range of very shallow entry angles. Only about one object in eighty even has an entry angle between the bounds given above (based on the usual $\sin^2\theta_o$ entry angle distribution). Thus, in order to decelerate enough to soft-land, (as apparently happened to BI) it must have followed a very long flight path through Mars' atmosphere, and this strongly constrains its initial conditions, especially the entry angle.

The maximum observed dynamic pressure (0.41 MPa) is far below the strength of meteoritic iron. However, the strengths of actual meteorites is dependent on size, the presence of inhomogeneities and fractures and upon the constitutions of individual meteorites.

Recent developments: Recent results from MER Opportunity's scientific instruments indicate that HSR, BI and SI are all type IAB iron meteorites [4]. (Compositional information was not obtained for MI.) This suggests that at least these three may be pieces of a single original object that fragmented in the atmosphere. This fragmentation would have had to occur at or quite soon after atmospheric entry, given that all three meteorites have ablation features (regmaglypts) acquired during flight [5], and these would take time to form. Also, none of the meteorites have extensive sharp or jagged edges or surfaces that would be expected if fragmentation occurred upon, or just before, impact. In particular, there are no signs that any of the irons is a spall fragment.

This aerial fragmentation scenario would explain the three meteorites as belonging to the first strewn field discovered on Mars. However it presents at least two new questions: (1) Is Mars' atmosphere dense enough to disperse HSR ~10 km from BI and SI via differential deceleration? (2) How can the original meteoroid be so weak as to fragment high in the martian atmosphere, and yet its fragments are strong enough to survive impact at 1.6-2.0 km/s? In continuing work we will attempt to address both of these questions. If possible we will present results of this further work at the meeting.

Conclusions: We found that Block Island and Shelter Island meteorites could be landed on Mars, even under the low-density modern atmosphere of Mars. However they must have very specific, rare, entry conditions and follow a very special sort of flight path to decelerate sufficiently to impact at potentially survivable speeds. All of the positive results were found to impact the surface at speeds of 1.6-2.0 km/s and at angles less than 20° from horizontal. The very shallow impact angles of these objects may mitigate the shock of impact and reduce the chances of the meteorites fracturing.

References: [1] Chappelow J.E. and Sharpton V.L. (2005) *Icarus, 178*, 40-55. [2] Chappelow J.E. and Sharpton V.L. (2006a) *Icarus, 184*, 424-435. [3] Chappelow J.E. and Sharpton V.L. (2006b) *GRL, 33*, L19201. [4] Fleischer I. et al., this conference. [5] Ashley J. et al., this conference. [6] Johnson J. et al. this conference. [7] Gault, D.E. and Wedekind, J.A. (1978) *LPSC IX*, 3843-3875. [8] Petrovich, J.J. (2001). *J. Mat. Sci.*, *36*, 1579–1583.

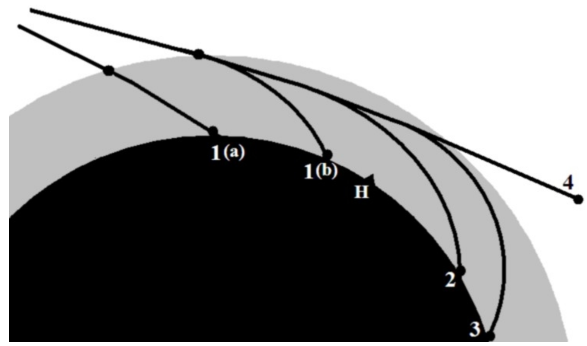

Figure 1: Possible trajectories for a large (kg to 1000s-of-kg) meteoroid incident on Mars' atmosphere. Flight paths 1a,b are termed 'direct', and impact the surface short of the horizon point (H). Flight paths like 2 and 3 are termed 'over-the-horizon' and 'fallback' trajectories, respectively, and may be many times longer in both length and time-of-flight than direct ones. Objects which enter at greater than the horizon angle, and whose mass and velocity are too high for the atmosphere to sufficiently decelerate them, follow 'grazing' paths like 4, which exit the atmosphere and return to space.

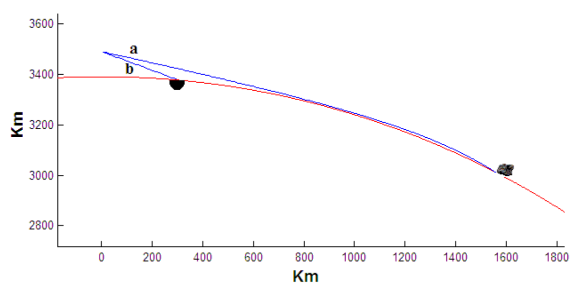

Figure 2: To-scale comparison of a 'direct' trajectory and a 'fallback' trajectory (blue lines), from typical results for the 6 mBar Mars atmosphere. Both represent 460 kg meteoroids entering atmosphere at 9 km/s, but at (a) 12.2° and (b) 20° entry angles. The flight path length and time of flight of (a) are several times greater than (b). Object (a) results in a Block Island – like meteorite (impact velocity = 1.86 km/s, angle = 6.2°, meteorite mass = 451 kg) while (b) results in a hypervelocity impact (impact velocity = 7.93 km/s, angle = 15.6°, impact mass = 457 kg). Note that the meteorite initially descends to within a few kilometers of the surface, then ascends as the planet curves away below it, before finally re-descending and impacting the surface at relatively low speed and very shallow impact angle.