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The event that produced heat shield rock and its implications for the Martian atmosphere

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[1] Methods developed in previous work were used to estimate the mass, trajectory, and atmospheric conditions that produced Heat Shield Rock, the iron meteorite discovered on Mars by the Opportunity rover in January, 2005. We find that Heat Shield Rock encountered Mars at high speed and shallow entry angle, probably at a time when the planet possessed a thicker atmosphere. It entered the atmosphere with a mass of more than 60 kg, underwent significant ablation during atmospheric passage, and ricocheted across the surface upon impact. We conclude that Heat Shield Rock probably represents physical evidence that Mars once had a denser atmosphere.

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[2] The January, 2005, discovery of the iron meteorite "Heat Shield Rock" (hereafter: HSR) [*Arvidson and Squyres*, 2005; *Bell*, 2005; *Christensen*, 2005; *Rodionov et al.*, 2005] in Terra Meridiani, Mars, led to speculation that the presence of such a large, dense object implies that Mars must have had a denser atmosphere when it arrived (e.g., http://www.space.com/missionlaunches/mars_meteor_050119.html). If so, HSR amounts to physical evidence of a past, denser Martian atmosphere. It has also been suggested that HSR's unweathered appearance and its well-exposed position indicate that it may have arrived quite recently on Mars (e.g., http://www.space.com/missionlaunches/mars_meteor_050120.html), but also that the absence of a nearby impact feature contradicts this theory (e.g., http://www.space.com/missionlaunches/mars_meteorites_050126.html). If recent, HSR may represent hard evidence that Mars has indeed experienced the large, recent, obliquity-coupled atmospheric density variations posited by several researchers [e.g., *Ward*, 1992; *Bills*, 1990; *Nakamura and Tajika*, 2003]. In this work we investigate these issues quantitatively.

[3] Imagery of Heat Shield Rock implies that it has an average radius of ~0.12 m [*Arvidson and Squyres*, 2005; *Rodionov et al.*, 2005] and a mass of ~50 kg. Its exterior is covered with features consistent with surface ablation during high speed passage through an atmosphere (i.e. regmaglypts), and none suggestive that it is a fragment of a larger object that broke up in the atmosphere or upon impact (e.g., planar and/or angular features; see Figure 1). While the possibility remains that HSR came from some parent body which broke apart very high in Mars's atmosphere (thus allowing time for ablation to re-work its surface), previous work [*Chappelow and Sharpton*, 2005] indicates that fragmentation of iron meteoroids, even in the lower Martian atmosphere, is exceedingly rare. Thus, for our purposes, HSR is assumed to be the result of a single incident iron meteoroid, at least 40 kg in mass, which was aerobraked (decelerated) by the Martian atmosphere into a soft-landing on the surface, without fragmentation or deformation either in the atmosphere or upon impact.

[4] To investigate the atmospheric and entry conditions that produced HSR, methods previously used to study impact cratering and meteorite production on Mars [*Chappelow and Sharpton*, 2005, 2006] were applied to the mass-range of iron objects (density = 7500 kg m^{-3}, heat of ablation = 5000 kJ kg^{-1}) considered capable of producing HSRs ($m_o \geq 40$ kg). A computer program employing a 4th order Runge-Kutta method was used to simulate the motions of a "test projectile" passing through the Martian atmosphere, and to determine its ultimate fate. The test object is characterized by initial (entry) values of mass m_o, velocity v_o, and trajectory angle θ_o, where θ_o is referred to the horizontal. The atmosphere was modelled as a simple exponential in pressure, characterized by a surface value which we varied, and by a fixed scale-height of 10.9 km. Entry was considered to occur at an altitude of 100 km, or about nine atmospheric scale heights.

[5] The integration continues until the object 'skips out' of or burns up in the Martian atmosphere, or impacts the surface. Objects which impact the surface at less than 2 km s^{-1} are deemed to have survived impact whole and undeformed as meteorites [*Chappelow and Sharpton*, 2006]. Of these, ones with masses between 40 kg and 60 kg are considered to be HSR-like.

[6] The entire simulation procedure is "scanned" over the ranges of interest in m_o, v_o, and θ_o as follows. The ranges of interest are viewed as a "volume of interest" in (m_o,v_o,θ_o)-space. Breaking m_o, v_o, and θ_o down into discrete bins breaks this volume into 3-d bins, each representable by a central value ($m_{o,i}$, $v_{o,j}$, $\theta_{o,k}$). Each 3-d bin is also associated with a "weight factor", $W_{ijk} = P_m(m_{o,i}) \bullet P_v(v_{o,j}) \bullet P_\theta(\theta_{o,k})$, where the Ps are incremental probability distributions given by [*Chappelow and Sharpton*, 2006]

$$P_m\left(m_{o,i}\right) \propto \left(m_{o,i-}^{-1.27} - m_{o,i+}^{-1.27}\right) \quad m_o \geq 40\,\mathrm{kg}$$

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Figure 1. "Heat Shield Rock." Features on its surface indicate considerable ablation of the object during atmospheric passage. No evidence is seen of aerial or impact fragmentation or of impact deformation.

$$P_v(v_{o,j}) \propto \exp\left(-\left(\frac{v_{o,j}-7}{8}\right)^2\right) \qquad 6\,\mathrm{km\,s^{-1}} \leq v_o \leq 32\,\mathrm{km\,s^{-1}}$$

and

$$P_\theta(\theta_{o,k}) \propto \left(\cos^2\theta_{o,k-} - \cos^2\theta_{o,k+}\right) \qquad 0° \leq \theta_o \leq 90°.$$

where the subscripts + and - refer to the upper and lower boundary values of bin *i,j,k*. The weight factor represents the probability that any given meteoroid that falls within the volume of interest, also falls within bin i, j, k. The fraction of a real incident population of iron meteoroids incident on Mars that eventually result in HSR-like meteorites is then

$$F_{HSR} = \frac{\sum W_{HSR}}{\sum W}.$$

where the numerator is the sum of the weight factors associated with HSR-like outcomes and the denominator, the sum of all of the weight factors, normalizes F_{HSR}.

[7] Our results for four potential Martian atmospheres (2, 6, 20 and 60 mbar) are summarized on Table 1 (It should be understood that these surface pressure values represent long-term, global averages, and so do not reflect short-term (diurnal, seasonal) or topographic variations in surface pressure; inclusion of such effects is beyond the

Table 1. Statistics for Production of HSR-Like (40 kg to 60 kg) Meteorites by 40 kg to 10^9 kg Iron Meteoroids Incident on Mars[a]

Atmospheric Surface Pressure, mbar	Entry Velocity Range, km $\mathrm{s^{-1}}$	Minimum Entry Mass, kg	Entry Angle Range, deg	Maximum Impact Angle, deg	Percent HSRs	Fraction HSRs
2	–	–	–	–	zero	–
6	16–24	70	12.7°–13.5°	11.2°	5.5×10^{-3}	1/18000
20	16–31	60	11.7°–13.9°	21.4°	3.2×10^{-2}	1/3100
60	16–31	60	11.0°–23.0°	43.3°	2.3×10^{-1}	1/450

[a] The second through fourth columns display entry conditions which may have produced HSR. The final column estimates the fraction of 40 kg+, Mars-incident meteoroids that eventually become 40 kg to 60 kg meteorites.

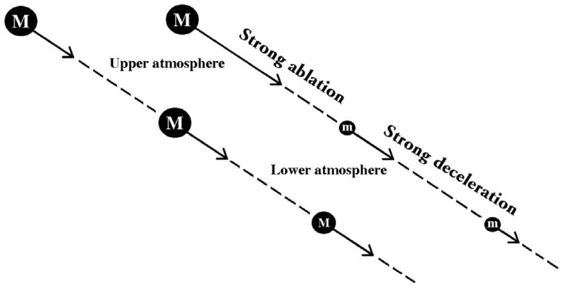

Figure 2. The "speed effect." The fast-entering projectile (upper right) experiences stronger ablation, and subsequent stronger deceleration than the slower one (lower left). As a result the faster object impacts the surface both smaller and slower than its counterpart.

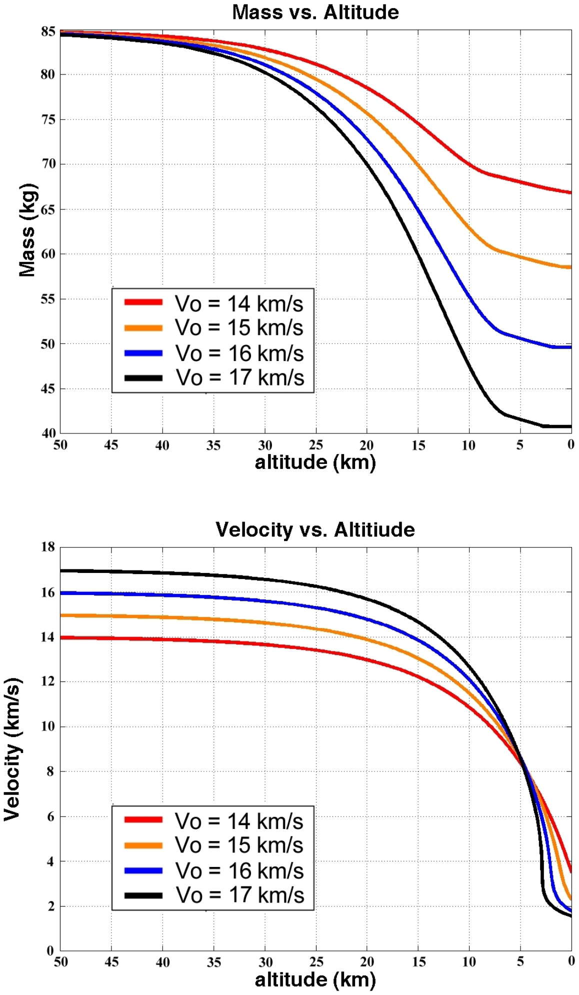

Figure 3. Mass (top) and velocity (bottom) vs. altitude for an 85 kg meteoroid entering a 6 mb Martian atmosphere at 13.1°. Faster objects (black, blue) shed mass much more rapidly than their slower counterparts (red, orange), and therefore lose considerably more velocity passing through the atmosphere. As a result, the initially faster objects actually impact the surface at lower speeds than initially slower ones. The blue and black traces end with velocities assumed herein to be survivable by iron projectiles and with masses consistent with HSR.

scope of this study). The rather counter-intuitively high lower limit on the entry velocity of HSR (16 km/s in all cases) is a result of the higher ablation rates ($dm/dt \propto v^3$) experienced by faster-entering projectiles, and the subsequent higher drag-deceleration rates ($dv/dt \propto m^{-1/3}$) they encounter (Figure 2). Figure 3 illustrates this "speed effect" via an example. The effect leads to an interesting situation wherein a fast-entering meteoroid may eventually land as a much-ablated meteorite, while a slower equivalent object impacts the surface destructively (Figure 3).

[8] In order for atmospheric drag to decelerate potential HSRs from over 16 km s^{-1} to less than 2 km s^{-1}, a considerable amount of ablation must also occur. This sets a lower limit to the mass HSR must have had at entry of at least 60–70 kg (Table 1, column 3). For such ablation to have time to occur, HSR must have traversed a long flight path through the Martian atmosphere. This, in turn, accounts for the fact that possible HSRs are limited to narrow ranges of very shallow entry angles for all of the atmospheres we considered (Table 1, fourth column). In fact, after first descending, many of our simulated HSRs regained altitude due to Mars's curvature, before finally falling back to the planet's surface.

[9] Assuming they land with HSR-like masses (40–60 kg), larger objects must lose more mass to ablation than smaller ones, so upon entry they must also have higher velocities. Thus, the probability of any given entry event producing an HSR decreases sharply as the mass of the impactor involved increases above the 60–70 kg lower limit (refer to the equations for P_m and P_v above). As a result, the overwhelming majority (>99.9%) of eventual HSRs enter the atmosphere with masses less than 1000 kg, for 6, 20 and 60 mbar atmospheres, and most (61%–81%, depending on atmosphere) mass less than 100 kg. A value of ~1000 kg therefore represents a useful estimate for an upper limit to HSR's mass before it encountered Mars.

[10] Under the current Martian atmosphere, about one in every 18,000 iron impactors more massive than 40 kg soft-lands as an HSR-like meteorite (Table 1, seventh column). The fraction of 40+ kg iron impactors that may yield HSRs increases to about 1-in-3100 and 1-in-450, for the denser atmospheres (20, 60 mbar surface pressure, respectively), assuming there are no associated, significant changes to the atmospheric scale-height. This is due to these atmospheres' higher ablation and aerobraking efficiencies. Thus the production rate of HSRs increases by roughly a factor of 6 for each 3-fold increase in atmospheric surface pressure, up to at least 60 mbar.

[11] Using the same mass, velocity and entry angle resolution as for the 6 mbar atmosphere, the 2 mbar version appears incapable of producing any HSRs. Indeed, it appears that this atmosphere produces no iron meteorites larger than 10 kg at all. It thus appears highly unlikely that Heat Shield Rock could have landed under a Martian atmosphere significantly less dense than today's, but quite likely that it was brought in by one considerably denser.

[12] Finally, almost all of the prospective HSRs hit the surface at very shallow impact angles (Table 1), so it is quite probable that Heat Shield Rock ricocheted upon impact and does not currently rest where it struck the surface. Therefore, even if Heat Shield Rock landed very recently, the absence of a small impact pit or structure near or under it (see Figure 1) should not be surprising.

[13] In conclusion, although we cannot rule out the possibility that HSR was produced by a Martian atmosphere similar to today's, it appears much more likely that HSR landed under one significantly denser; it seems highly improbable that HSR landed under a Martian atmosphere thinner than today's. From this we conclude that Heat Shield Rock constitutes physical evidence that Mars has at some time had a significantly denser atmosphere than it does today. Discovery on Mars of any iron meteorites larger than HSR, or of other HSR-sized irons at higher altitudes, would further substantiate this conclusion.

[14] We also find that HSR encountered Mars at a relatively high speed and very shallow entry angle, probably with an original mass of 60–100 kg. It experienced strong ablation on its long flight path through the atmosphere, struck the surface at a shallow angle, and almost certainly ricocheted upon impact. For this reason the lack of a nearby impact feature on the surface should not be taken as evidence that HSR has, or has not, been on Mars for a very long time; the question remains open.

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