THE EVENT THAT PRODUCED HEAT SHIELD ROCK AND ITS IMPLICATIONS.
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Introduction: The January, 2005 discovery of the iron meteorite "Heat Shield Rock" (HSR) in Terra Meridiani, Mars, led to some speculation that its presence implies that Mars must have had a denser atmosphere when it landed. However, to date no quantitative work either supporting or countering this theory has been presented. Here we address this issue.

Figure 1: Martian meteorite "Heat Shield Rock".

The description of HSR as "basketball-sized" (http://marsrovers.jpl.nasa.gov/newsroom/pressreleases/20050119a.html) implies that it has an average radius of about 0.12 m and mass of about 50 kg. Its exterior is covered with features consistent with surface ablation during high speed passage through an atmosphere (e.g., ablation concavities), 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) (Fig.1). Also, results of previous work [1] strongly suggest that fragmentation of iron meteorites in Mars's atmosphere is highly unlikely. Thus HSR is assumed to have been a single incident meteoroid which was slowed by the martian atmosphere into a soft-landing on the surface, and which did not fragment in the atmosphere or upon impact.

Methods: To investigate the atmospheric and entry conditions that produced HSR, we used a numerical simulation that detemines the fate of a "test object" (characterized by initial (entry) values of mass (m_o), velocity (v_o), and trajectory angle (θ_o)) entering a martian atmosphere (specified by a surface pressure value, P_{atm}). Iron objects that impact the surface at less than 2 km $^{-1}$ are considered to survive impact as meteorites. This simulation was "scanned" over values of m_o, v_o and θ_o appropriate for asteroidal objects encountering Mars, and which could potentially result in HSR-sized meteorites (40 kg $\leq m_{final} \leq$ 60 kg) and four different martian atmospheres (P_{atm} = 2, 6, 20 and 60 mb).

A weight-factor, $W(m_o,v_o,\theta_o)=P_m(m_o)P_v(v_o)P_\theta(\theta_o)$, was calculated for each test object, using entry-mass, -velocity and -angle frequency distributions, P_m, P_v, and P_θ [1,2]. These take the forms

$$P_m(m_o) \propto m_o^{-1.27} \qquad [3]$$

$$P_v(v_o) \propto \exp\left(-\left(\frac{v_o-7}{8}\right)^2\right) \qquad [1]$$

and

$$P_\theta(\theta_o) \propto \sin^2\theta_o$$

respectively.

All of the HSR-like meteorites were then sorted out of the results and the ranges of entry parameters (m_o,v_o,θ_o) that an impactor must have to be a potential HSR determined for each P_{atm} of interest. The associated weight-factors were added up, forming fractions of the original the meteoroid population under consideration (40 kg $\leq m_o \leq 10^9$ kg), that yielded HSR-like meteorites.

Results: Our results are summarized on Table 1. In order for atmospheric drag to decelerate a potential HSR iron from more than 6 km s^{-1} to less than 2 km s^{-1}, a certain amount of ablation must also occur. This sets a lower limit to the mass HSR may have had at entry of at least 60-70 kg, for atmospheres of 6 mbar or more (Table 1). Thus HSR must have been strongly ablated by passing through a lot of martian atmosphere at high speed. This accounts for the fact that potential HSRs are confined to narrow ranges of shallow entry angles.

The rather counter-intuitive lower limit on the entry velocity of HSR (16 km/s in all cases) is the result of the lower ablation rates (dm/dt $\propto$ -v^3), and consequent lower drag-deceleration rates (dv/dt $\propto$ -m$^{-1/3}$), encountered by slower projectiles. This leads to an interesting situation wherein a fast-entering meteoroid may eventually land as a much-ablated meteorite, while a slower counterpart impacts the surface destructively. Figs. 2 illustrate this "speed effect" via an example.

To become HSR-like, larger objects must lose more mass to ablation than smaller ones, and must therefore have higher entry velocities, as well as higher masses. Therefore, the probability of any given entry event producing an HSR diminishes sharply as the mass of the impactor involved increases above the lower limit of 60-70 kg (see the equations for P_m and P_v above). As a result, the overwhelming majority (>99.9%) of possible HSRs are less than 1000 kg in mass, for 6, 20 and 60 mbar atmospheres, and most (60%-80%, depending on atmosphere) are less than 100 kg.

Under the current martian atmosphere, about one in every 20,000 iron impactors more massive than 40 kg, but less than 10^9 kg, becomes an HSR-like meteorite (Table 1). For denser atmospheres (20, 60 mbar surface pressure), the fraction of 40+ kg iron impactors that may yield HSRs increases to about 1-in-3500 and 1-in-500, respectively, 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.

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, 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 is quite likely to have been brought in by an atmosphere denser than today's.

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 (D < 1 m) impact pit or structure near it (Fig.1) should not be surprising.

Conclusions: We conclude that HSR encountered Mars at a relatively high speed and shallow entry angle, probably massing between 60 kg and 100 kg. It experienced strong ablation in atmospheric passage, struck the surface at a shallow angle and most likely ricocheted on impact. Although it appears much more likely that HSR landed under a higher density martian atmosphere, we cannot rule out the possibility that it was produced by one similar to today's. It seems very improbable that HSR landed under an atmosphere thinner than this, however

References: [1] Chappelow J. E. and Sharpton V. L. (2005) *Icarus, 178,* 40-55. [2] Chappelow J. E. and Sharpton V. L., *Icarus.*, submitted. [3] Ivanov B. A. (2001) *Space Sci. Rev. 96*, 87-104.

Atmosphere (mbar)	Minimum entry mass (kg)	Entry velocity range (km s^{-1})	Entry angle range	Maximum impact angle	Fraction HSRs
2	--	--	--	--	zero
6	70	16 - 24	12.7° -13.5°	11.2°	5.03×10^{-5}
20	60	16 - 31	11.7° -13.9°	21.4°	2.97×10^{-4}
60	60	16 - 31	11.0° - 23.0°	43.3°	2.06×10^{-3}

Table 1: Statistics for production of HSR-like (40 kg - 60 kg) meteorites by 40 kg - 10^9 kg iron meteoroids incident on Mars. Columns 2-4 display entry conditions which may have produced HSR. The final column estimates the fraction of all such meteoroids that eventually become 40 kg - 60 kg meteorites.

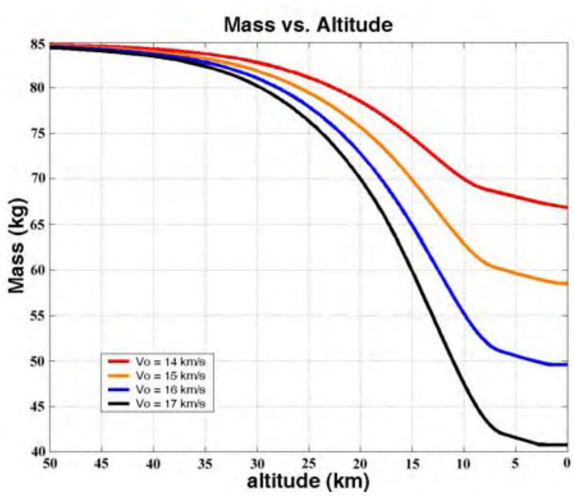

Fig. 2a: Mass vs. altitude for an 85 kg meteoroid entering a 6 mb martian atmosphere at 13.1°. Orange, blue, and black traces end with masses consistent with HSR.

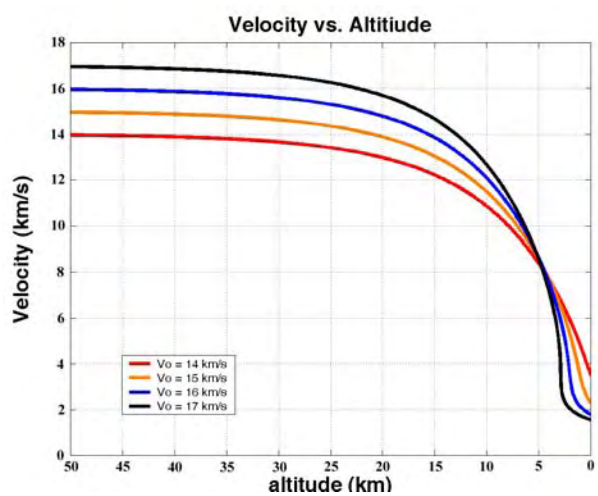

Fig. 2b: Velocity vs. altitude for an 85 kg meteoroid entering a 6 mb martian atmosphere at 13.1°. Blue and black traces end with velocities assumed herein to be survivable by iron projectiles.