ATMOSPHERIC ENTRY STUDIES AND THE SMALLEST IMPACT CRATERS ON MARS. F. Hörz[1], M. J. Cintala[1], W. C. Rochelle[2], C. M. Mitchell[2], R. N. Smith[2], J. Dobarco-Otero[2], B. K. Finch[2], and T. H. See[2]; [1]Astromaterials Research Office, NASA Johnson Space Center, Houston, Texas 77058, [2]Lockheed-Martin Space Operations, 2400 NASA Parkway, Houston, Texas 77058.

Introduction: High-resolution images from the Mars Orbiter Camera reveal impact craters as small as 10 m [1], and still smaller craters (< 0.5 m) have been inferred from surface boulders at the Pathfinder landing site [2]. Any small-scale impact environment at scales of meters or smaller would obviously be a potent contributor to erosive processes on Mars, to the small-scale evolution of its surface, and to mineralogic/compositional alterations of its surface materials. It is not very clear from the analysis of Viking and Pathfinder images, however, what the smallest craters are on Mars. As a consequence, it might be informative to consult atmospheric-entry calculations that specify the smallest meteoroid able to survive passage through the present martian atmosphere. We conducted such calculations and perceive them as providing useful constraints for understanding small-scale surface processes on Mars and as possible guides for the interpretation of surface images from past and future lander missions.

Methods: The algorithms used represent state-of-the-art, finite-difference calculations developed by spacecraft trajectory and orbital-debris interests, empirically tested and verified when possible with actual entry events on Earth. The basic trajectory code SORT (Simulation and Optimization of Rocket Trajectories, Version 8.3) [3] was used in combination with the Mars GRAM (Global Reference Atmospheric Model, Version 2001) [4] for the martian atmosphere, which we assumed to be 100% CO_2; entry into this atmosphere was defined to occur at 130 km altitude. Drag coefficients for a pure CO_2 atmosphere were calculated following [5] and the aero-heating calculations for pure CO_2 were modeled after [6], adopting the case for spherical objects [7]. The thermal histories and ablation of the entering objects were calculated by the ORSAT (Object Re-Entry Survival Analysis Tool) code [8] and imported into SORT. Typical atmospheric transit times are on the order of minutes and the calculations proceeded in time steps of 0.1 s. The objects were allowed to spin following [9], who calculates the heating rate for spinning spheres to be some 0.26 times the heating rate of the stationary stagnation point case. [7] The spherical objects consisted of a series of *n* concentric shells, with *n* typically between 10 and 20. The outermost shell was deemed ablated and destroyed when the absorbed heat exceeded the heat of ablation. As a result, the entering objects were affected in discrete steps according to specific thermodynamic criteria and consequences; the present model does not allow for mechanical material properties and possible fragmentation histories due to dynamic stresses.

The major variables, treated in parametric fashion, included initial velocity (V_i = 7, 9, 12, and 15 km/s) and entry angle (γ = 15, 20, 30, 45, 60, 70, and 90°), and the radius of the entering spherical object (r_i = 0.5 to 50 cm). Two generic meteorite materials were simulated, chondritic (30% olivine, 65% pyroxene, 5% Fe) and iron-objects (90% Fe, 10% Ni). Specific heat and thermal conductivity were varied as a function of temperature (*e.g.*, [10]). The thermodynamic assumptions and model parameters used for these materials are summarized in Table 1. Typical outputs for any given run included object-size, temperature, velocity, and trajectory angle as a function of time and altitude.

Results: The salient results are summarized in Table 2, which illlustrates two objects of size r_i and r_u, respectively, both representing useful boundary cases for small-scale cratering processes on Mars. The object of initial size (r_i) is the *smallest object* capable of yielding a surviving remnant at the martian surface; all objects initially smaller than r_i are destroyed in the atmosphere. The actual size of the surviving remnant of object r_i that reaches the martian surface is r_s and the corresponding impact velocity is V_s; obviously, both the size and speed of these smallest survivors will be much smaller by the time of impact. In contrast, the relatively large object of initial radius r_u reaches the surface without significant ablation; by definition, it would have lost at best the outermost shell only, impacting the martian surface at some size $> 0.95\, r_u$; r_u thus defines the smallest impactor size that is minimally ablated after complete passage through the atmosphere. It follows that all objects $> r_u$ will reach the martian surface without significant mass loss. Note, however, that the impact velocity (V_u) of these relatively large objects may be significantly affected, especially at $\gamma < 30°$. Nevertheless, many chondrites some 10 cm across will reach Mars at some 80 to 90% of their initial impact speed and all meter-sized objects will be minimally decelerated. Although not listed, the effective impact angle at the martian surface is generally steeper than the initial entry angle, yet rare exceptions exist.

Table 1. Model Properties for Mars Meteorite Materials.

Material	Density (kg m^{-3})	Specific Heat (J kg^{-1} K^{-1})	Melt Temperature (K)	Emit-tance	Thermal Conductivity (W m^{-1} K^{-1})	Heat of Fusion (J kg^{-1})
Chondrite	3400	226 < Cp < 1216	1650	0.90	2.4 < k < 3.2	450,000
Iron	7970	450	1800	0.85	83.0	252,200

Table 2. Atmospheric entry calculations for small chondritic and iron meteoroids for a variety of initial trajectories.

	V_i = 7 km/s					V_i =9 km/s					V_i = 12 km/s					V_i = 15 km/s				
	r_i	r_s	V_s	r_u	V_u	r_i	r_s	V_s	r_u	V_u	r_i	r_s	V_s	r_u	V_u	r_i	r_s	V_s	r_u	V_u
γ	**Chondrite**																			
15	1.0	0.4	0.1	10.0	1.4	2.0	0.2	0.2	20.0	2.6	5.0	2.8	0.3	50.0	1.6	5.0	0.9	0.2	20.0	1.1
30	1.0	0.6	0.2	10.0	4.4	1.0	0.1	0.1	20.0	5.6	2.0	0.7	0.1	50.0	11.0	5.0	2.8	3.3	20.0	11.7
45	1.0	0.7	0.2	5.0	3.8	1.0	0.4	0.1	10.0	6.6	2.0	0.9	0.5	20.0	10.3	2.0	0.1	0.1	20.0	12.9
60	0.5	0.2	0.1	5.0	4.4	1.0	0.5	0.2	10.0	7.0	2.0	1.0	1.2	20.0	10.7	2.0	0.3	0.2	20.0	13.4
90	0.5	0.2	0.1	5.0	4.6	1.0	0.5	0.3	10.0	7.4	2.0	1.1	2.2	10.0	9.9	2.0	0.5	0.4	20.0	13.5
	Iron																			
15	2.0	1.0	0.3	5.0	1.8	5.0	3.8	1.1	10.0	3.2	10.0	7.0	1.6	20.0	1.6	10.0	2.0	0.8	20.0	1.6
30	1.0	0.2	0.1	2.0	2.6	2.0	0.4	0.4	5.0	6.2	5.0	3.5	7.5	20.0	10.8	5.0	2.2	7.2	20.0	13.6
45	1.0	0.4	0.4	2.0	3.7	2.0	1.0	3.5	5.0	7.0	5.0	4.2	9.1	10.0	10.6	5.0	3.0	10.6	20.0	14.1
60	1.0	0.5	1.2	2.0	4.3	2.0	1.4	4.8	5.0	7.3	5.0	4.4	9.7	10.0	10.8	5.0	3.6	11.8	20.0	14.3
90	1.0	0.6	2.0	2.0	4.6	2.0	1.6	5.5	5.0	7.6	5.0	4.5	10.1	10.0	11.1	5.0	3.8	12.3	10.0	13.8

γ Entry angle (degrees) into atmosphere, measured upward from local horizontal
r_i Initial radius (cm) of the smallest object that will reach the surface of Mars at the given conditions
r_s Radius (cm) of the surviving object (of initial size r_i) upon encounter with the martian surface
V_s Impact velocity (km/s) at the martian surface of the smallest survivor (of radius r_s)
r_u Initial radius (cm) of an object sufficiently large that it will reach the surface without substantial mass loss
V_u Impact velocity (km/s) at martian surface of an object with radius r_u

Our parametric calculations were limited to objects with values for r_i of 0.5, 1.0, 2.0, 5, 10, 20, and 50 cm; Table 2 is substantially affected by these size increments, especially at small sizes. For example, the parameter r_i actually refers to the size that yielded a physical survivor, while the next smallest size totally ablated at some altitude. The limiting case is obviously in between and can thus be somewhat smaller than the listed r_i. Similarly, the real value for r_u could be modestly smaller than listed. The values for r_s were rounded to millimeter scales in Table 2, and the encounter velocity is given in increments of 0.1 km/s.

Referring to Table 2, shallow trajectories are more destructive as evidenced by decreasing object sizes with increasing γ (vertical columns in Table 2). Small entry angles cause longer transit times and relatively long periods of aero-heating compared to steep entry angles. Also, low velocities are more benign than high entry speeds as manifested by systematically increasing object sizes with increasing velocity (horizontal rows at constant γ). Chondritic objects as small as 1 cm in radius survive at relatively modest entry velocities (*e.g.,* V_i = 7 km/s) and at almost any entry angle; indeed, objects as small as 0.5 cm survive at $\gamma > 60^0$. Trajectories between 45° and 90° yield generally similar results; shallow angles are thus more critical, as they result in prolonged transit times and associated ablation of the objects. Atmospheric heating becomes progressively more severe with increasing V_i, mandating increasingly larger initial objects if they are to survive (*e.g.*, r_i equal to 1.0 and 5.0 cm at 7 and 15 km/s, respectively, for a constant γ = 15°). In general, many millimeter- to centimeter-sized, chondritic objects will reach the martian surface at velocities between 0.1 and 1.0 km/s. Most chondritic objects of r_u >5 cm have impact speeds >4 km/s, many even within 80% of V_i. The increased thermal conductivity of metals necessitates somewhat larger iron-objects for survival compared to stony objects at all conditions, yet especially for those that either have shallow trajectories or high velocities, if not both.

Conclusions: These results are qualitatively similar to earlier atmospheric-entry calculations [11-13]. They substantiate the survival of cm-sized objects at impact speeds > 1 km/s and thus the presence of a significant, small-scale cratering regime on Mars. The formation of impact craters <1 m in diameter should be common. The production rate of craters >10 m on Mars must be qualitatively similar to that of the Moon, considering the higher meteoroid fluxes [1] and accounting for lower impact velocities and higher gravity on Mars via suitable crater-scaling relationships (*e.g.*, [14]). Comminution of bedrock into coarse rubble seems unavoidable, yet the lack of micrometeorites <1 mm will keep this rubble from being pulverized into fine-grained soils, at least by primary impacts. Non-impact processes will be responsible for the production of most fines and will further interact with the impact-produced rubble and shock-products, leading to mineralogic and compositional alterations of the martian surface soils that are common on neither the Earth nor the Moon.

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