IMPACT DELIVERY OF ORGANICS TO MARS: OBLIQUE IMPACTS.

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Introduction and Motivation: Apart from Earth, Mars and Europa are the most likely worlds in our solar system on which evidence of present or past life may be found. In the case of Earth, we concluded that impact delivery of organics, in particular amino acids, could have played an important role in the organic inventory of the early Earth [1]. This was a result more optimistic with respect to organic impact survival that was found in much, though not all, previous work. In the case of Europa, we have found that intact organic delivery is unlikely to be important, although cometary delivery of biogenic elements appears significant [2].

A preliminary study for impact delivery on Mars indicated results for Mars similar to those for Earth, that is a substantial survival for some amino acids in comet impacts on Mars with little or no survival in asteroidal impacts, even though the mean impact velocity (9.3 km/s) is lower than that on the Earth [3]. However, in the case of Mars the lower gravitational field results in a much lower escape velocity, increasing the probability of projectile escaping after the impact. The earlier study using 2D impact simulations [3] indeed showed that in vertical impacts significant escape of cometary material occurs even at the lowest impact velocity modeled, 12.5 km/s. As found by Pierazzo and Melosh [4] this effect becomes more important for oblique impacts, when a larger fraction of the initial impact energy is partitioned to the projectile.

Impact Modeling: We investigate the effect of impact angle on the survival and delivery of organics to Mars by carrying out impact simulations spanning different angles of impact, while keeping all other input parameters constant. The simulations were carried out using the 3D hydrocode SOVA, developed at the Institute for Dynamics of Geospheres [5], coupled to tabular equations of state built from the ANEOS package [6]. The code has been benchmarked in 3D simulations against the well-known hydrocode CTH [7]. The results show similar shock melting and vaporization patterns in CTH and SOVA simulations [8], with a better run efficiency (faster runs for the same spatial resolution) for SOVA.

We model spherical comets 2 km in diameter impacting Mars' surface at 15.5 km/s. This corresponds to the median impact velocity for short-period comets (average impact velocity is 18.6 km/s) according to the data from [9].

Simulations have been carried out for 90° (vertical), 60°, 45°, and 30° impact angles. A spatial resolution of 20 cells-per-projectile-radius (cppr) is maintained over a central region (only the $y>0$ half space is modeled, where the $y<0$ half space is its mirror image) about 8 km in size, followed by regions of progressively lower resolution, extending over 20 km downrange (and 10 km uprange), and over 20 km above (10 km below) surface. Tabular versions of ANEOS equations of state for granite (no basalt ANEOS is available at this time), water ice, and CO_2, were employed to model the target, projectile, and atmosphere respectively. A very thin CO_2 atmosphere was included in the simulations to model the present-day Martian atmosphere, although it has been suggested that a thick atmosphere could have been present early in Martian history.

A total of 542 Lagrangian tracers were regularly distributed inside the (model half-) projectile to follow its thermodynamic history (using time steps of 0.005 seconds) during the impact. These tracers record temperatures and pressures as well as positions and velocities during the impact, thus providing the important information on which portion of the projectile (if any) would reach Mars' escape velocity (5 km/s).

Survival of amino acids: To assess organics survival in the impact event, temperature histories from the projectile tracers are combined with experimentally derived kinetic parameters for amino acids in the solid phase [10] via the Arrhenius equation, as described in [1]. The experimental parameters differ substantially from previously available kinetic parameters for thermal degradation of amino acids in solution [11]. Although neither case is a good analog for impact events (shock tube or hypersonic velocity gun experiments are the best analog), we feel that the experiments of the thermal degradation of amino acids in the solid phase are closer to the impact case. The application of Arrhenius equation to all tracers' temperature histories provides a map of amino acid survival [1]. The fraction of amino acids successfully delivered to Mars in the impact event is then determined by integrating over the volume of the projectile that does not reach escape velocity.

Results: The angle of impact affects significantly the post-impact dynamical evolution of the projectile.

Table 1 and Figure 1 summarize the results from this study compared to the earlier 2D simulation for the same cometary impact (D_{pr}=2 km; v_{imp}=15.5 km/s) and normal incidence angle. The survival of some amino acids (all of which have been found in Murchison, and may be present in comets) delivered to Mars are reported as fractions relative to the original amount in the projectile. In Table 1 the fraction of surviving amino acids contained in the fraction of the projectile that reaches escape velocity (and is considered lost) is shown in parenthesis. Contrarily to the earlier 2D numerical simulations, which showed a loss of 1/3 of the projectile, we find a much lower escape of projectile material in the 3D vertical impact simulation with SOVA. This discrepancy is a consequence of the switch from 2D to 3D numerical simulations. It has been shown [4,12] that 2D simulations tend to overestimate shock temperatures (and underestimate shock pressures) by at least a factor of two, with possible excursions of up to an order of magnitude. This translates into a higher internal energy of the impact plume, and results in a larger fraction of the projectile material reaching escape velocity in 2D simulations. The lower impact temperature in the 3D simulation of a vertical impact (90°) also results in a larger survival rate for amino acids relative to the earlier 2D (CSQ) counterpart [3].

Overall, the delivery fraction of surviving amino acid is significant for impact angles as low as 30° where the majority of the projectile exceeds Mars' escape velocity. This is because the increased loss of projectile material with decreasing impact angle is counterbalanced by a weakening of the overall shock effects, as shown in [4], which, in turn, increases the overall amino acid survival (e.g., see [1]).

Table 1. Fraction of projectile escaped (V_{esc}) and fraction (relative to the initial amount in the projectile) of amino acids surviving impact in SOVA (90º down to 30º) and equivalent 2D simulations. In parentheses are surviving amino acids in the fraction of projectile that reached escape velocity.

Angle	V_{esc} (%)	Glycine (%)	Aspartic Acid (%)	Glutamic Acid (%)
2D (CSQ)	*33.6*	*0.11 (0.1)*	*0.5 (0.77)*	*0.65 (0.63)*
90°	5.4	0.33 (0.09)	1.13 (0.19)	1.74 (0.35)
60°	15.8	0.5 (0.39)	1.01 (0.99)	2.01 (1.22)
45°	44.43	0.49 (1.68)	0.76 (3.71)	1.57 (4.39)
30°	74.4	0.25 (8.9)	0.61 (6.6)	0.75 (16.7)

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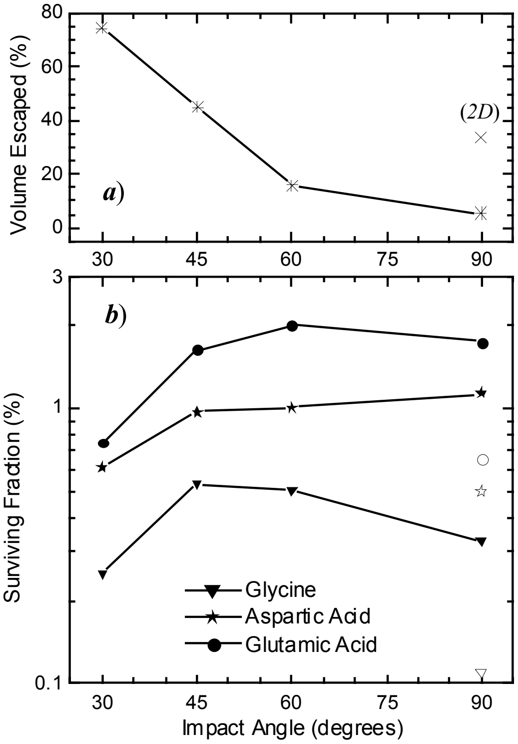

Figure 1: ***a)*** Volume of projectile reaching escape velocity after impact, for various impact angles; ***b)*** Fraction of surviving amino acids (relative to initial concentration in the projectile) delivered to Mars' surface (solid symbols). Open symbols: results of earlier 2D simulations.