MODELING COMET-EARTH COLLISIONS TO ASSESS SURVIVABILITY OF ORGANIC MATERIALS DURING IMPACTS

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Introduction: Comets, estimated to contain up to 25 wt.% organic material as both ices and more complex, refractory compounds [1], have been proposed as a vehicle for the delivery of organic compounds to the early Earth. Successful delivery requires that some of the organic materials survive the extreme temperatures associated with impact, but the response of organic compounds to impact (shock) processing under these conditions is unknown. Previous authors have explored organic-delivery scenarios computationally and experimentally (e.g., [2,3]), and our approach is complementary to their earlier work. Here, we track on phase-state of water during a modeled comet-earth collision over a range of impact angles and use the results to infer survivability of organic compounds using a three-dimensional shock physics code.

Modeling Details: Calculations were performed using GEODYN, a Godunov-based Eulerian code with adaptive mesh refinement capabilities [4]. GEODYN utilizes high-pressure tabular equations of state to model the extreme conditions associated with shock loading. For simplicitiy, our comet was modeled as a 1-km diameter sphere of ice at 200K impacting a basalt half-space under atmospheric pressure. Both materials were described using tabular (LEOS) equations of state to accurately capture their high pressure behavior [5]. Here, we show results generated using a velocity of 11.2 km/s (Earth's escape velocity), to illustrate results under the most-favorable conditions possible. Simulations were conducted for impact angles of 90° (normal), 60°, 45°, 30°, and 15°, starting at the moment of impact. The domain was a half-space (due to the bilateral symmetry) centered on the impact point. The domain extended 12.8 km along the horizontal axes and 4.8 km and 3.2 km above and below the impact point, respectively. Calculations were performed with a resolution of 12.5m on the finest refinement level, and the entire mesh consisted of ~10^7 cells.

Survival Metrics: Survivability of organic compounds is tied to the condensed phases of water. This is likely a conservative estimate, as will be discussed in more detail. We considered survivability using three metrics: (*1) Peak temperature experienced by each material point.* This metric does not account for kinetic or pressure effects and therefore probably underestimates the survival of organic materials. The threshold value of 870K from gas gun experiments [3] is used to indirectly account for pressure effects. (*2) Thermodynamic state of the cometary material.* This criterion assumes that any material remaining in a condensed phase survives the impact. The comet is modeled as pure water, so this criterion is only effective up to the critical point of water (~650K); the phase of particular organic materials may be more relevant but involves too much uncertainty for this work. (*3) Estimated final temperature on unloading.* The state at the end of the simulation (~1s) is unloaded isentropically to ambient pressure. The resulting state is mapped to existing thermal decomposition data and provides an approximate upper boundary for survival at a given temperature. A conservative threshold temperature of 373K is used for this work.

Results & Discussion: Simulations were run until cometary material reached the edge of the computational domain (and in the 15° case, this domain was extended). Peak temperatures of each material point, mass averaged over the entire comet, are shown for the impact angles studied (Fig. 1).

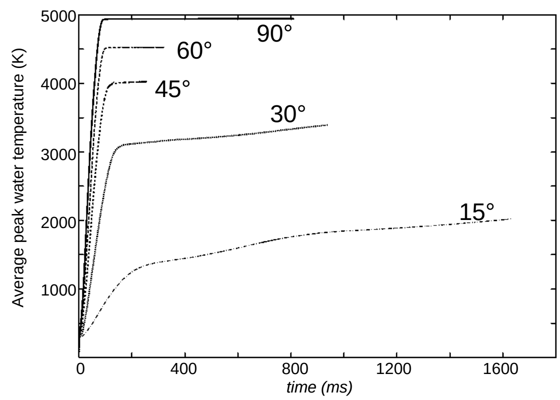

Figure 1. *Peak temperatures for various impact angles.*

As expected, peak temperatures decrease as the impact becomes more oblique. The initial sharp rise can be attributed primarily to the heating due to shock compression of the comet. Peak temperatures for the more normal impacts (≥45°) level off after the initial spike, indicating that the temperature of the initial shock is equal to or greater than any subsequent temperature. For the more oblique angles (15° and 30°), however, the temperature continues to rise after the initial shock has passed (~200ms). This late time heating can be attributed to the conversion of kinetic energy to internal energy as the comet decelerates after the initial impact. For the case of the 15° angle impact, almost no crater is formed and very little of the material remains in the crater; most of the material appears to "skid" along the ground, in keeping with frictional heating due to deceleration.

The fractional survival estimated using the criteria described above is summarized in Table 1. By 200 ms, roughly the time that the initial shock has passed through the comet, only the 15° impact simulations shows any surviving material using the first two criteria. For the less oblique impacts, the initial impact vaporizes the entire comet, heating the entire mass

TABLE 1. *Fractional survival of organic compounds estimated using various criteria.*

	IMPACT ANGLE				
	15°	**30°**	**45°**	**60°**	**90°**
Fractional Survival at 200 ms					
CRITERION 1: Peak temperature < 870K	82%	0%	0%	0%	0%
CRITERION 2: Condensed phase	75%	0%	0%	0%	0%
Fractional Survival at end of simulation, time =	*1100 ms*	*900 ms*	*250 ms*	*300 ms*	*800 ms*
CRITERION 1: Peak temperature < 870K	55%	0%	0%	0%	0%
CRITERION 2: Condensed phase	25%	0%	0%	0%	0%
CRITERION 3: Isentropic release to 1 atm, T < 373K	44%	< 1%	-	-	< 1%

above the 870K survival threshold. The third criterion was only applied to the impact angles of 15°, 30°, and 90°, but again only showed survival for the most oblique case.

Figure 2 shows the fraction of material with a peak temperature below various thresholds as a function of time for the 15° impact. The initial shock heats all of the comet material above the normal boiling point of water at ambient pressure (373K) but the material is not vaporized initially due to the high shock pressures. Figure 3 shows the condensed mass fraction as a function of time. The fraction of the material intact to t~1s in the 15° impact scenario would decrease with time due to deceleration heating, which would continue until the material came to rest. However, this deceleration heating is heavily dependent on droplet formation and breakup, as well as gas phase mixing, which become important beyond one second. The relevant physics for these phenomena are not modeled here but should be included in a more rigorous estimate of final survivability.

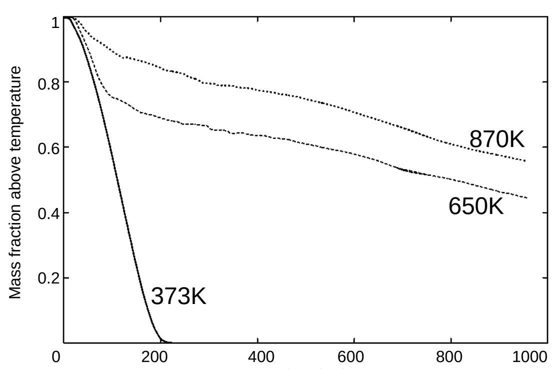

Figure 2. *Fraction of material below various peak temperature thresholds for 15° impact.*

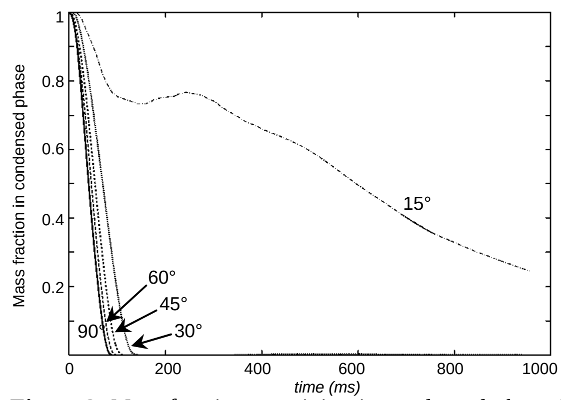

Figure 3. *Mass fraction remaining in condensed phase for various impact angles.*

Conclusions: In our example, organic materials are only expected to survive for impact angles lower than 30°. For oblique angles, deceleration heating was found to be important, indicating that scaling of the shock temperatures may be insufficient for low impact angles. At 1s, a significant fraction of the material is estimated to survive a 15° impact, but estimating the effect of deceleration heating at later times requires further modeling of droplet formation/breakup and gas phase mixing.

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