SUB-SURFACE EXCAVATION OF TRANSIENT CRATERS IN POROUS TARGETS: EXPLAINING THE ‘IMPACT DELAY’.

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Introduction: The Deep Impact spacecraft collided with the surface of comet 9P/Tempel 1 on 4 July 2005 [1]. The event was recorded by the flyby spacecraft’s 64x64 pixel Medium Resolution Imager (MRI) camera with a spatial resolution of 86 m/pixel and a temporal resolution of 59 ms [2]. In the first 2 MRI images little effect is seen except for a ‘faint light’ uprange of the impact point. In the third frame a bright plume of incandescent material appears, quickly saturating the MRI’s sensor in the fourth and fifth frames. Finally, sun illuminated ejecta appears and becomes the dominant photometric source throughout the rest of the observations.

The delay of ~118 ms before the emergence of the vapor plume poses a problem in that an expanding shell of SiO_2 vapor should have appeared in a matter of milliseconds [3]. The issue of this ‘impact delay’ can be resolved by an understanding of the early evolution of transient craters in highly porous target materials. In non-porous media, the transient crater expands hemispherically downwards and outwards from a depth similar to the diameter of the impactor. In the case of a small impactor, such as the Deep Impact spacecraft, there should be an unimpeded view from the flyby spacecraft into the interior of the transient crater at a very early point in crater evolution. For highly porous targets the impactor can penetrate deeply into the target material. The transient crater then expands quasi-spherically away from a point located at the (greater) depth of burial. The result is that the crater can open to considerable volume while remaining largely unexposed at the surface. Any incandescent material within this subsurface pocket is essentially ‘blocked’ from observation until the top of the crater opens.

The behavior of early transient craters in porous material has been noted and investigated experimentally [2,4]. Because laboratory impacts cannot reproduce the scale and velocity of the Deep Impact event, it is worthwhile to explore the issue numerically using validated equations of state. The development of an accurate and numerically fast porosity model [5] for shock hydrocodes allows us to simulate the earliest moments of the Deep Impact event across a broad range of initial conditions, on a large numerical mesh, and out to distant time steps.

Numerical Modeling: Crater formation is modeled using the iSALE shock physics code [5-7], which utilizes a strain-based porosity model [5]. Simulations were run in 2D with cylindrical symmetry which requires that the impact angle must be 90 degrees. The impactor was modeled as a 366 kg copper disc with a 1 meter diameter and a velocity of 10.2 km s^{-1}. A disc was chosen in order to mimic the mass of the Deep Impact spacecraft (which was 49% copper) while maintaining its surface area, which plays an important role in coupling the impactor to the target [1]. The target material was modeled as a half space of strengthless, porous water ice. Gravity does not play an important role in the earliest stages of transient crater evolution, and was not considered. Tillotson equations of state were used for both materials. Simulations were run with initial target porosities of 0, 50, and 75%

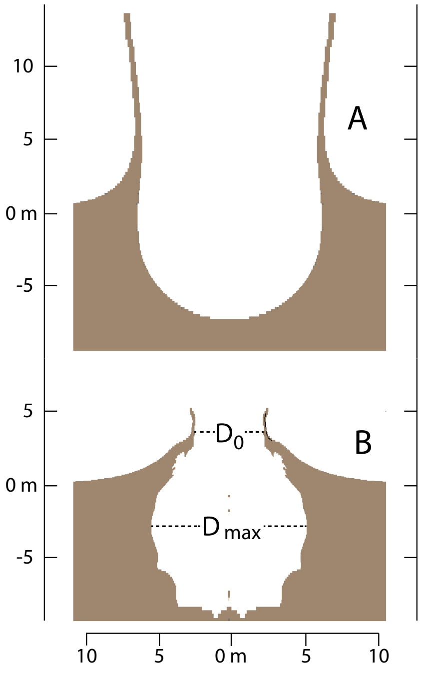

Fig. 1: shows crater profiles 50 ms after impact for (A) non-porous target material and (B) 75% porous target material. D_0 and D_{MAX} are illustrated in the porous case.

Results: We can quantify the degree to which a transient crater has opened by taking the ratio of the crater opening diameter (D_0) over the diameter of the crater at its widest point (D_{MAX}),

$$R = \frac{D_0}{D_{MAX}}$$

As time progresses R approaches unity, and the crater can be considered fully open. Figure 2 shows R as a function of time for different target porosities. In the case of a non-porous target, R trends quickly towards 1, and the crater can be considered open after ~20 ms. In the intermediate case (50% porosity) R increases considerably more slowly, but the transient crater can be considered sufficiently 'open' after 100 ms. In the very porous case (75% porosity) R increases slowly, only reaching .6 after 100 ms (approximately the length of the 'impact delay'). This corresponds to a transient crater opening of only 8.6 meters, or 0.7% of one pixel. Based on density estimates of comet Tempel 1 [8] 75% is not an unreasonable estimate of regolith porosity, and may be low. Increasing the porosity of the target past 75% would futher amplify the observed effect.

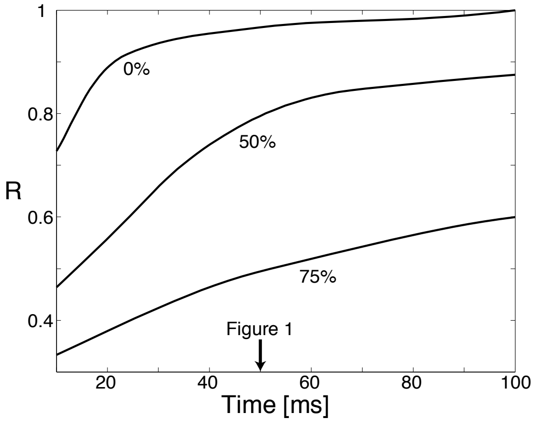

Fig. 2: shows how R varies with time after impact for different target porosities. For non-porous targets, R quickly reaches unity and the transient crater can be consider 'open'. For high porosities, the transient crater remains largely 'closed' to external observation on timescales relevant to the 'impact delay' seen during the Deep Impact experiment.

Conclusions: The 'impact delay' observed during the first 118 ms of the Deep Impact event can be explained by subsurface excavation of the transient crater during which observable surface expression is minimized. We have numerically investigzated this phenomenon for the first time. This effect is a function of porosity, and requires that Tempel 1's regolith have a porosity on the order of 75% or greater, which agrees well with independent estimates.

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