Hydrodynamic Modeling of the Deep Impact Mission into Comet Tempel 1

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Abstract

Kinetic impact is one of the primary strategies to deflect hazardous objects from an Earth-impacting trajectory. The only test of a small-body impact is the 2005 Deep Impact mission into comet Tempel 1, where a 366-kg mass impactor collided at 10 km/s into the comet, liberating an enormous amount of vapor and ejecta. Code comparisons with observations of the event represent an important source of new information about the initial conditions of small bodies and an extraordinary opportunity to test simulation capabilities on a rare, full-scale experiment. Using the Adaptive Smoothed Particle Hydrodynamics (ASPH) code, Spheral, we use two-dimensional modeling to explore how variations in target material properties such as strength, composition, porosity, and layering affect impact results, in order to best match the observed crater size. Benchmarking against this unique small-body experiment provides an enhanced understanding of our ability to simulate asteroid or comet response to future deflection missions.
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1 Introduction

The impact of potentially hazardous objects with Earth has the potential to cause local to regional or even global destruction. The mission of the planetary defense community, including the Planetary Defense Group at the Lawrence Livermore National Laboratory, is to understand the threat posed by small bodies such as comets and asteroids, as well as the methods that may be used for their mitigation, deflection or disruption.

Comets are a particularly dangerous breed of these hazardous objects, despite their relative rarity. Due to this and the difficulties inherent in studying them, knowledge regarding comet interiors and changes in composition as a result of their travel around the sun is extremely limited [1]. Another factor contributing to the danger posed by comets is their very large size. Though many of the sizes of near-Earth comets are not known [13], the smallest short period comets tend to have diameters of 1-10 km, while the largest comets can be an order of magnitude larger [15]. This range of sizes could generate global destruction in the case of an impact [13]. Additional factors contributing to the risk posed by comets include their high velocities relative to Earth and the short warning times associated with long-period comets. In the worst case, certain long period comets may have a warning time on the scale of weeks to months [18][20].

Currently, there are two mature options for the mitigation of hazardous objects. The first is nuclear deflection or disruption. The second is kinetic deflection, where an impactor is launched into the object at high speeds with the hope of altering the objects orbit and timing. Under the conditions that a kinematic impact will prove effective, it is preferred to nuclear mitigation [20]. Due to short warning times and large sizes, whether kinematic impaction is a useful technique for comets specifically remains uncertain [10].

To the planetary defense community, the 2005 Deep Impact Mission (DI) has proved particularly important to the field and to knowledge of potentially hazardous objects. During its execution, the Deep Impact Mission collided a probe at hypervelocity speeds (defined by the European Space Agency as a relative velocity exceeding the speed of sound in a solid object[9]), into comet Tempel 1, producing a crater and ejecta plume[1]. As the first
full-scale space experiment of its kind, Deep Impact has enormous ramifications for the planetary defense field.

Surprisingly, the DI mission has never been modeled with a hydrodynamics code. Certain processes and features, such as shock melting, vaporization and low gravity cannot be modeled in Earth-based laboratories, making numerical modeling the best option for investigating Deep Impact [23]. This work uses Spheral, an Adaptive Smoothed Particle Hydrodynamics code [21], to model the Deep Impact Mission and investigate how composition, strength and porosity affect simulation results. As the first of its kind, this study will provide critical information about Comet Tempel 1s composition, crater excavation, ejecta shape and ejecta mass.

We begin with a discussion of the Deep Impact Mission parameters and known results, as well as a description of the hydrodynamics code, Spheral, used during modeling. Subsequent sections will relay the methods and results for this work at its current stage of development, and future work will be discussed.
2 Experimental Background

2.1 Comet Overview

Comets, including the Comet Tempel 1 that was impacted during the DI mission, are members of a photo-planetary class of objects that formed approximately 4.6 billion years ago at the same time as planetary formation within the solar system. Within astronomy and the planetary defense community, comets are further differentiated by their orbital period. Short period comets, such as the well-known Halleys Comet, come from a disc-like belt of icy objects outside of Neptunes orbit. As a result of gravity or the rare collision, they are pushed into orbits that bring them close the Sun. These short-period comets have relatively brief (less than 200 years long) orbits, and their orbital path and time of appearance can be predicted. Comet Tempel 1 is a member of the short period comet class [8].

In contrast, many comets fall into the far less predictable long period class. These comets come from the Oort cloud, a spherical cloud of objects surrounding the entire solar system. Effects from the gravitational control of the outer planets, as well as occasionally perturbations from passing stars or even the Milky Way disk can sufficiently alter the objects orbit to lead it to enter the planetary solar system. These objects are known as long period comets [8]. Due to the wide range of possible entry points, orbits and speeds that they can display, long period comets can be difficult to find and track, and even more challenging to defend against.

Methods to defend against comets are also made difficult by our limited knowledge of their composition and characteristics. The general consensus regarding comet composition is that they are made of varying types of ice, including but not limited to water, CO and CO$_2$ ice, mixed or coated with dust and dark organic material. As a result, it is common for astronomers to compare comets to dirty snowballs. Due to low gravity present during their formation, comets are believed to exhibit high porosity and low strength in their material makeup. Here, porosity can be defined as the measure of void spaces in a material, and strength as the ability to withstand stress or force without failure [16]. However, due to limited experimental knowledge and the variety seen in comet populations, exact numbers...
for these values as well as answers for comet questions, such as surface materials, remain unknown and would likely vary between comets.[8] [24] [14].

Though many parameters of comets are undecided, general comet structure is thought to be consistent across populations. In their frozen state, comets are composed of a relatively solid, frozen core, known as the nucleus. This nucleus contains frozen gases and ice along, dust and rock, and ranges from a few kilometers to tens of kilometers in scale. As a comet nears the Sun, solar heat causes materials near its surface to sublimate and a comet atmosphere, known as a coma, to develop. The coma dwarfs the nucleus, and can extend hundreds of thousands of meters.[8]

2.2 The Deep Impact Mission

Though comets could arguably pose one of the greatest and most unpredictable threats to Earth, knowledge of their properties and subsurface materials is limited. In an effort to address this knowledge gap, NASA and JPL launched the Deep Impact Mission over a decade ago. The goals for DI focused on the excavation and observation of comet interiors in an effort to gain knowledge about their composition, material properties and structural properties (AHearn et al.). As the only space-based impaction to date and as an experiment that far surpasses the capabilities of Earth-based laboratories, DI remains a particularly relevant experiment.

On July 4th, 2005, the Deep Impact spacecraft arrived at Comet Tempel 1, a short-period comet, after roughly seven months of space travel. The DI spacecraft included two components. The first was an impactor probe that would be launched into the comet. The second was a fly-by spacecraft equipped to observe and gather impact data. The impactor probe weighed either 364 kg (AHearn et al.) or 366 kg (Richardson, Melosh, Lisse, et al.) (there is some discrepancy in the literature) and was made of 49% copper to minimize reaction with water that may lead to misleading emission features (AHearn et al.). Twenty-four hours before impact, the two-part craft separated and the fly-by diverted to miss the comet by 500 km, depicted in Figure 1. The probe impacted Comet Tempel 1 at a hypervelocity
speed of 10.3 km/s, and an oblique angle of 34 degrees from the local horizontal (AHearn et al.). The resulting impact caused cratering at the surface of the comet and large ejecta plumes. Figure 2 presents images of Comet Tempel 1, the targeted impact site and the ejecta about 700 seconds after impact.

Figure 1: An artistic rendition distributed by NASA of the two components of the Deep Impact spacecraft. One piece, the impactor, split away from the flyby to continue towards the comet, while the fly-by craft followed an orbit that would allow it to bypass and observe the impact. Image Credit to NASA/JPL.

The DI mission is also notable for the sheer amount of observational data collected, both from the fly-by and from ground based telescopes. The fly-by craft captured observations of the impact and subsequent 800 seconds [1], giving highly detailed images of the comet surface and conical ejecta plume[26]. DI also represented an unprecedented Earth-based observational effort. Visible, infrared and x-ray regions were observed through a worldwide collaboration, resulting in a collection of data including ejecta volume, gas production and type, and dust properties [14]. From these measurements, rough estimates of Comet Tempel 1s properties were determined. The mean radius of the comet is 3.0±0.1 km and the overall
The shear strength of the excavated material was believed to be very weak at less than 65 Pa. The bulk density was estimated at 0.4 g/cm³ [25]. Analyzing ejecta during the 800 seconds following impact suggested that the mass of Comet Tempel 1 is roughly 4.5 * 10¹³ kg, the escape velocity is about 1.7 m/s², and the mean surface gravity is 3.47*10⁻⁷ that of Earth [25].

Unfortunately, most of the crater was obscured by the impact plume [26]. Accordingly, several studies have endeavored to estimate the size of the DI crater on Comet Tempel 1, with varying results. Prior to the impact, Richardson et al. (2004) predicted a crater range between extremes of 60.4 meters for loose sand to 250m for competent rock [24]. Using ballistics modeling based off of the Navier-Stokes equations and data from the impact, Richardson et al. (2007) finds that the initial transient crater possibly ranged from 85 to 140 meters across for virtually strengthless gravity dominated cratering (Y = 0 Pa) and strength dominated cratering (Y = 10 Pa), respectively [25]. However, Richardson is careful to note the potential limitations of a ballistics-centered approach, including our limited knowledge of highly porous small bodies and the role of volatiles in comet kinetic impacts [25]. Earth-based observations of Deep Impact and the resulting ejecta plume suggest a much larger formation: a circular crater with a between 130-220 meter diameter [26]. Observations from the Stardust-NExT mission, which revisited the comet 5.5 years after the original impact, seem to corroborate this, finding evidence that suggests the DI excavation crater was about 200 m ± 20 m, but it does not help resolve initial cratering, only what the final crater settled to [28]. As a result, final crater size and shape are not entirely agreed upon, but knowing the ejecta shape and mass from the impact can help constrain crater dimensions through numerical modeling.
Table 1: Table 1 highlights the experimental data collected from the Deep Impact mission. Using Spheral, this work aims to match the experimental crater depth, diameter, ejecta shape and mass through means of simulation scans incorporating different comet density and shear strength parameters (from the ranges listed in Table 1) as well as changing comet composition. Further discussion of simulation setup and model selections can be found in Section 3.

<table>
<thead>
<tr>
<th>Comet Density</th>
<th>Comet Strength</th>
<th>Crater Depth</th>
<th>Crater Diameter</th>
<th>Ejecta Shape</th>
<th>Ejecta Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>200-1000 kg/m³</td>
<td>0-10 kPa</td>
<td>20-80 m</td>
<td>60-250 m</td>
<td>Conical</td>
<td>1.5x10⁷ - 2.2x10⁷</td>
</tr>
</tbody>
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Figure 2: Figure 2: Depictions of Comet Tempel 1 before impact and after. (a) Abridged from Schultz et al. (2007), the first image shows composite ITS images of Comet 9P Tempel 1. The inset shows the general impact region. (b) Pseudo-stereo view of rays mapped onto the well-defined rays for MRI frames 901041 (left) and 901019 (right) about 700 seconds after impact. The rays map the conical shape of the ejecta curtain, with the darker spot in the middle showing the presence of less haze above the impact site. [26][27][25]
2.3 Numerical Modeling with Spheral

Deep Impact is a case of extreme conditions: hypervelocity speeds, large size scales, extensive
damage, widely varying temperatures and largely unknown comet parameters. Numerical,
hydrodynamic modeling of kinematic impaction events, such as Deep Impact, requires the
use of specialized codes. The calculation of total momentum transferred to small bodies,
including comets, through hypervelocity impacts requires the use of a shock-physics code
that can resolve ejected particles mass and velocity during the cratering process [5].

For impact problems, meshless modeling approaches such as Smoothed Particle Hydro-
dynamics (SPH) codes [17] are well suited. SPH methods do not need a grid to calculate
special derivatives. Instead, they discretize the modeled fluid into a set of separate elements,
or particles. Each of these particles have their properties smoothed by a kernel function
over a defined spatial distance, known as the smoothing length [17]. In mesh-based ap-
proaches, extreme deformation such as that found in kinematic impacts can lead to mesh
entanglements, where the mesh collides with itself when normal vectors between mesh el-
ements are not parallel. With meshless approaches, mesh entanglements are avoided and
tracking ejecta mass through large displacements across the problem domain is simpler than
for most grid-based methods [5]. In this paper, we utilize an extension of the SPH method
known as Adaptive Smooth Particle Hydrodynamics (ASPH). ASPH generalizes the scalar,
or isotropic, smoothing length for each SPH particle to a tensor form of smoothing length
[22]. This generalization allows the smoothing length of each particle to vary with direction,
thus enabling ASPH to better define and resolve problems involving anisotropic distortions.
As noted by Bruck Syal et al. (2016), the tensor generalization provided by ASPH is es-
pecially important for small body hypervelocity impacts, as it more adequately captures
geological failure when materials experience large shear stresses [5].
Figure 3: A side by side comparison of the capabilities of a typical SPH code and of Spheral using ASPH for tensile rod breaking. (a) Shows the SPH modeling, which results in highly segmented breakage patterns. (b) Shows Spheral modeling the same rod, resulting in a more natural breakage pattern. Damage along the fractures can also be seen in this image, represented by green.

The hydrodynamics code used in this paper is the open-source, ASPH code known as Spheral, developed at the Lawrence Livermore National Laboratory by Dr. James Michael Owen. Several qualities make Spheral particularly well suited to modeling Deep Impact. As an ASPH code, it is meshless and Lagrangian. The tensor generalization used in Spheral is that of the Benz-Asphaug Damage model [2][3]. Unlike many SPH codes, it is also perfectly energy conserving, which assists with demonstrating self-convergence in the simulation of kinetic deflection [21]. In addition, Spheral allows the combination of various strength models, equations of state and strain models.
3 Methods and Results

The extremely large scale of Comet Tempel 1 and the impact event caused by Deep Impact limits how much of the mission can be modeled using Spheral due to computational expense. Full three-dimension models can require between 10^7 and 10^8 particles and weeks of computational time. This limitation has been addressed in several ways. First, in lieu of modeling the entire comet, comet sections large enough to accommodate all cratering estimates without damage saturation during early excavation are modeled. Additionally, various parameter scans are conducted using two-dimensional models to constrain possible parameter ranges for Comet Tempel 1. In this section, we discuss achieving resolution convergence and the two-dimensional scans of different equations-of-state, material layering, porosity and strength parameters to match the experimental data listed in Table 1.

3.1 Resolution Convergence Study

Accuracy and efficiency are paramount for our simulations. Three-dimensional modeling is extremely expensive so it is desirable to limit the number of 3D simulations, as well as the size and resolution of the comet section that must be modeled to correctly portray the impact. Thus, we began this work by completing a resolution convergence study. The goal of such a study is to estimate the smallest dimensions of the comet section that can be modeled and the lowest node resolution that can be reached without sacrificing accuracy. The determination of the optimal size and resolution of the comet section requires consideration of two things: estimates of crater diameter from earlier Deep Impact modeling attempts (Table 1) and the scale of damage propagation into the comet.

Since it is possible that hydrodynamic modeling will demonstrate damage propagation farther from the impact site than the experimental estimates, the second component of the convergence study required that we determine the smallest diameter above 225 m where damage propagation does not exceed model boundaries at time scales of about 1 second. To test this, we used a two-dimensional modeling mode, known as 2DRZ, which uses cylindrical
coordinates to distribute particles around a central length-wise axis, and effectively models a slice of the three-dimensional model. For simplicity, we only simulated two-dimensional pumice targets (single material composition) for the convergence study.

It is expected for the crater to be much wider than it is deep [26]. Accordingly, the original comet section dimensions we modeled were 250 meters wide and 60 meters deep. Figure 4a shows that at 33,800 microseconds the damage propagation reaches 60 meters into the comet, rebounding off the model boundaries and quickly saturating the pseudo-comet with damage by 90,000 microseconds, Figure 4b. Pseudo-comet dimensions of 250 meters wide and 60 meters deep proved to be too shallow.
Figure 4: An impact into a pumice target with dimensions 250m x 60m. Both images plot the effective tensor damage trace, which tracks the damage in the material at a given time. The key is shown in the two left corners of both images (a) and (b). Dark blue indicates undamaged materials. (a) shows the simulation at 33,800 microseconds, just as damage propagation reaches the depth boundary. (b) shows the same simulation run to 90,000 microseconds, at which point the damage has rebounded off of the boundaries and saturated the entire model comet block.

We gradually increased the depth and width of the model until damage propagation ceased to exceed the pseudo-comet (target) boundaries at 1 second (100,000 microseconds). The dimensions of this model were 400 meters wide and 300 meters deep, shown in Figure 5, and it evident that the resulting damage ceases to propagate past 200 meters wide and 150 meters deep, constraining our pseudo-comet dimensions.
Figure 5: For dimensions 400 meters wide and 300 meters deep of pure pumice, at approximately one second, the impact does not reach model boundaries. The variable plotted is tensor damage trace. All dark blue material is undamaged, and damage increases from green to red coloring.

In upcoming work, this result will be extrapolated to three-dimensional models. In the three-dimensional models, model parameters for the comet will begin with a radius of 150 meters and a depth of 200 meters. To decrease computational intensity, three-dimensional models will incorporate a technique known as ratio resolution, described in greater detail in Section 3.3.

### 3.2 Parameter Scans Using Two-Dimensional Models

#### 3.2.1 Equations of State

The extreme nature of kinematic impacts requires careful selection of equations-of-state. Due to the fact that Spheral was originally developed as a n-body code and thus is designed for simulating fluids, models were created to describe solids, known as an equations-of-state (EOS). These equations-of-state allow for the characterization of the state of matter of a
material under a given set of physical conditions, and inform the code about how the solid responds to different temperatures, pressures, and energies. There are many different types of EOS, including analytic, tabular, or a combination of both, and every material has its own EOS. To model DI, we compared two different equations-of-state, Tillotson and ANEOS, each well known in the planetary defense community, to determine which performed better for our hypervelocity comet impact simulations. The Tillotson EOS model is a relatively simple, but well-respected, analytic equation-of-state ideal for high strain rates [31], the same regime in which DI falls. ANEOS is a semi-analytic equation-of-state that fills the gaps in tabular data using its analytic capabilities [30]. When compared to Tillotson, ANEOS is considered to include more accurate treatment of melt and vapor transitions as well as the partition of energy into the melting and vaporization of target material [5]. Due to this increased accuracy, ANEOS is typically regarded as the preferred equation-of-state of the planetary science community when dealing with ice [5].

The performance of Tillotson and ANEOS were compared in a series of models, including solid pumice, solid ice and a mixture of both. A side by side comparison of both EOS models is given in Figure 6. It should be noted that both images are reflected across the horizontal axis (comet depth). In Figure 6a, the Tillotson equation-of-state performs well for early modeling, and is thus useful for estimation purposes. However, it is not as detailed or realistic as ANEOS, shown in Figure 6b. Thus, as expected, ANEOS more closely matches Deep Impact and is superior to Tillotson in performance. For the remainder of this paper, unless otherwise indicated, simulations were running using ANEOS.
3.2.2 Material

The DI Mission offered an unparalleled opportunity to explore the material composition of comets, and especially comet interiors. Knowledge of comet material composition, and especially how those materials change as the comet passes through perihelion is very limited [1]. The status of Comet Tempel 1 as a short period comet that had traversed through multiple near-sun passages made it an ideal candidate for a mission.

Comets are generally considered to made up of very weak material, including porous weak dust and a collection of volatiles including but not limited to water ice, CO, CO$_2$ and H$_2$CO. For a discussion of the chemical composition of Comet Tempel 1 from DI observations, please see [19].

To mimic the presence of ice and dust on Tempel 1, our models use water ice and weak, porous pumice. Material properties for both were drawn from the Spheral materials library. To gain insight into DI and Comet Tempel 1, we ran models with alternate layering of ice and pumice, varying of layer thicknesses and material combinations. A sample small-scale
setup for a pumice-ice-pumice model with varying thicknesses is shown in Figure 7. These results were then compared to DI observational data (see Table 1).

![Figure 7](image)

Figure 7: A sample model before impact with a 5m deep pumice crust, a 2m thick layer of ice, and a final 8m thick pumice layer. The impactor is represented as the small blue square near the left side of the image.

At the current state of our study, two primary findings have emerged. The first is that ice-topped models create irregular, vapor-rich ejecta plumes that do not match Deep Impact morphology. Figure 8a compares a model with a surface ice layer to images taken by the DI fly-by. Vaporization of the ice during impact creates a highly irregular plume that does not represent the conical ejecta plume seen during DI initial stages.

Additional findings show that pumice topped models create smoother conical plumes that more closely match mission findings. This can be seen in Figure 8b. It should be noted that two-dimensional modeling, though useful for constraining parameters, is not considered to be completely accurate. This result will be checked later, although initial findings for three-dimensional modeling do seem to confirm that rock-topped crusts appear closer to DI morphology.
Figure 8: (a) an ice topped model with an irregular, vapor rich plume, a scattered ejecta cloud and irregularities in the crater (b) a rock topped model, which has a much smoother, conical plume that is much closer to the original morphology of Deep Impact (see Figure 2).

3.2.3 Porosity

Comets are known to be highly porous objects. Just how porous is the subject of study and debate. Porosity can be generally defined as the fraction of voids over the total volume of a material, typically expressed as a percentage[16]. Estimates of the bulk density of the comet taken from observations at the time of impact suggest a nucleus bulk density of
approximately 0.4 g/cm$^3$ [25], although this number does have somewhat substantial error bars as measurements on Comet Tempel 1's mass, size and gravity are not exact.

To analyze the effect of porosity, we began with performing a parameter scan of low to high porosity, from bulk densities of 0.2 g/cm$^3$ to 0.91 g/cm$^3$. However, initial findings suggest that very high porosity, between 74 and 91 percent porous, leads to too much energy being absorbed and dampens the impact shock. This leads to a wide, shallow crater with minimal damage propagation into the comet. This is consistent with impact mechanics that suggest cratering efficiency tends to decrease for highly porous targets, as compression requires more energy [27].

We performed a constrained parameter scan ranging from 0.2 g/cm$^3$ (high porosity) to 0.6 g/cm$^3$ (lower porosity) shown in Figure 9. For 0.6 g/cm$^3$, the impact yields a very wide, shallow crater with almost no excavation and extensive compression. For 0.2 g/cm$^3$, the higher material porosity leads to a large amount of damage propagation and a narrow, deep crater.

From analysis of parameter scans, and from comparisons with DI observations, ballistic models and numerical estimates [1][25][29], we selected a bulk density value of 0.4 g/cm$^3$, or 82.8% porous pumice and 56.4% porous ice. This bulk density represents a reasonable value between the extremes of 0.2 g/cm$^3$ and 0.6 g/cm$^3$ and will be used as the initial value in upcoming 3D modeling.
Figure 9: A comparison of 2D models using bulk densities of 0.2, 0.4 and 0.6 g/cm$^3$. (a) 0.2 g/cm$^3$ results in too much damage propagation into the crater, indicating too little porosity. In contrast, (c) 0.6 g/cm$^3$ leads to too little damage propagation into the depth of the comet, and instead causes a wide, shallow damage signature. (b) 0.4 g/cm$^3$ is the closest to known DI morphology.

### 3.2.4 Strength

Our limited knowledge of comet material and comet formation suggests that they tend to be very low strength. Observations of ejecta and gravitational estimates from DI suggested 65 Pa for the shear strength of moderately shocked material around the rim of the final crater [1]. This would imply an extremely weak, powder-like substance. For the sake of comparison, the shear strength of sand is usually in the tens of kPa [32].

For the case of DI, the low-gravity of Comet Tempel 1 suggests that strength will play a more important role in crater formation than it would in a gravity dominated regime [24]. To constrain strength values for the comet surface, we modeled various strength regimes ranging from 10 Pa, or virtually strengthless, to 10 kPa, considered the upper limit for comet material strength [4], and much larger than the 65 Pa estimate [25]. For these models, we used the pressure-dependent Collins strength model [6] in Spheral.

Figure 10 below shows a side-by-side comparison of a solid ice model, using ANEOS, with strength values of 10 Pa, 100 Pa, and 1 kPa. Unfortunately, due to computational
constraints, we were unable to run 1 kPa to the same time as 10 and 100 Pa and we were unable to include 10 kPa. However, for an image of the minimal impact of strength over the 10 Pa to 1 kPa range, please see Figure 11 in the Additional Images section, which includes the results of preliminary three-dimensional modeling for all-pumice models over the range of 10 Pa to 1 kPa. Surprisingly, model results are strikingly similar, indicating that strength appears to have negligible effect on the DI early-time excavation. This by itself is a rather interesting result, although perhaps not altogether unprecedented, as will be discussed in the following section.

Figure 10: A comparison of performance for varying strengths on pure ice with medium porosity of 49%. (a) Model using very low strength (10 Pa) run to a time of 32,481 microseconds. (b) Model using medium strength of 100 Pa run to a time of 35,055 microseconds. (c) Model using high strength of 1 kPa run to a time of 10,910. Note: Unfortunately due to computational constraints, we were unable to run 1 kPa to 30,000 microseconds, and the 10 kPa model was in too early a stage of excavation to be shown in comparison.
4 Discussion

As the only kinetic impact of a small object, Deep Impact has been the subject of much scrutiny, study and numerical analysis. Yet hydrodynamic modeling offers additional valuable information about kinetic impacts and the comet class. In this section, we consider our findings so far in the context of the DI observables and previous research.

The first result, that of ANEOS’s superior performance when compared to Tillotson, is not surprising. Though Tillotson is a well-adapted code for impacts, and it does provide a good rough estimate, it lacks the incorporation of tabular data that makes ANEOS ideal for impact simulations where ice and volatiles are present. Through our research so far, and in upcoming three-dimensional modeling, ANEOS will be used.

Our results suggest that rock-topped models create a conical ejecta plume that is more consistent with DI morphology than ice-topped models, which result in irregular, vapor-rich plumes. This makes sense given the case of Comet Tempel 1. As a short period comet, Tempel 1 has undergone multiple perihelion passages near the sun, each of which causes approximately 109 kg of material to sublimate off [12]. Ice and other volatiles sublimating off should leave behind a rocky, dusty crust that generates a smoother ejecta plume. This matches what we found in our simulations. This result is consistent with both DI observables and numerical modeling performed since the mission. According to surface temperatures, colors, albedos and spectra of Comet Tempel 1, it is unlikely that there is ice on the surface, although observations do suggest that there may be some very close to the surface [1]. Additionally, according to Sultanov et al, (2008), numerical modeling results suggest that the comet surface is not made of ice, as an ice crust does not agree with the forming and spreading of ejecta [29].

Preliminary two-dimensional modeling suggests that Comet Tempel 1 is quite porous, as expected for a comet. By modeling various porosity regimes, we found a bulk density of 0.4 g/cm$^3$ to yield simulations most closely matching DI morphology. It should be noted that this value was chosen as it represented the most reasonable results from 2D simulations, and it is very possible that it will change during upcoming 3D modeling. This 0.4 g/cm$^3$
matches well with the value given in Richardson et al. (2007), but it is slightly lower than that some other numbers reported, which include 0.6 g/cm$^3$ [1]. However, several reasons might explain this. First, Comet Tempel 1’s many perihelion passages have likely caused much of the porous ice near the surface to sublimate off, leaving a denser crust. Alternatively, knowledge of comet porosity is rather unconstrained. Studies on other well-known comets, including 67P/Churyumov-Gerasimenko have estimated bulk density to be between 0.1-0.37 g/cm$^3$, with 0.5-0.6 g/cm$^3$ as an upper limit [7]. Even for Comet Tempel 1, the numbers vary substantially [1][25].

Perhaps the most intriguing result thus far is the apparent lack of effect of strength in DI modeling. A parameter scan of strength ranging from virtually strengthless to 10 kPa, a very large strength for comets, yielded little observable differentiation in results during early-time crater excavation. This contrasts directly with some estimates made by later attempts to model the mission. Earth-based ballistics modeling suggests that low strength material should correspond to a larger crater than medium strength material, although concessions are made for the presence of gravity [25]. However, the negligibility of strength is not unprecedented, and may even be supported by the literature. Biele et al. (2009) claims that a large range of strength values, including less than 1-10 kPa and even 10kPa yield results consistent with Deep Impact [4]. Housen and Holsapple (2006) corroborate this view, concluding that with errors any strength, tensile or shear, between 0 and 12 Pa is consistent with DI observations. Due to this, whether the crater is strength or gravity dominated cannot be distinguished. Analysis of ejecta particulate matter implies that strength would have negligible effect until time had reached the scale of ten’s of minutes [11], far later than the micro-second scale we are modeling. Thus, although this result will be tested in later 3D modeling, there is support for the minimal effect of strength in early-time DI cratering.
The parameters used in the two-dimensional simulation results that best match the experimental data from the Deep Impact mission are shown in Table 2. Implementing a pumice-ice-pumice layering, comet density of 400 kg/m$^3$ (equivalent to 82.8% porous pumice and 56.4% porous ice), and a strength in both pumice and ice of 10 kPa, the two-dimensional simulations were able to render a crater diameter of 100 meters and crater depth of 125 meters. It is typical in two-dimensional modeling to have unrealistically excessive damage, so it is predicted that the crater depth will be less when modeling in three-dimensions. However, the crater diameter from the preliminary two-dimensional results is well within the experimental range.

At the present point, we have primarily modeled DI using two-dimensional geometries. Though two-dimensional modeling provides a useful and largely accurate DI simulation, it is primarily used as a means to estimate the parameters that should be used in three-dimensional modeling and to roughly anticipate what three-dimensional models will return. These three-dimensional models will serve to both test two-dimensional findings and inform actual parameter selections. They will utilize a technique called "ratio" resolution, which has high resolution at the impact site and feathers out with increased distance. This will allow for large sizes and high resolution to be modeled with the much more computationally expensive three-dimensional models.

**Table 2:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Comet Density</th>
<th>Comet Strength</th>
<th>Crater Depth</th>
<th>Crater Diameter</th>
<th>Ejecta Shape</th>
<th>Ejecta Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep Impact</td>
<td>200-1000 kg/m$^3$</td>
<td>0-10 kPa</td>
<td>20-80 m</td>
<td>60-250 m</td>
<td>Conical</td>
<td>1.5x10$^5$ - 2.2x10$^7$</td>
</tr>
<tr>
<td>Simulation</td>
<td>400 kg/m$^3$</td>
<td>0-10 kPa</td>
<td>200m (150 Observed)</td>
<td>300m (200 Observed)</td>
<td>conical</td>
<td>—</td>
</tr>
</tbody>
</table>
5 Conclusion

The Deep Impact Mission was the first and remains the only one of its kind: a space-based, hypervelocity kinematic impact into comet Tempel 1, with a global observational effort and a goal to increase our knowledge of comet interiors and evolution. As an experiment, DI is important to the multiple scholarly communities, but especially so to the Planetary Defense community for its ability to increase our knowledge of kinetic impacts. Additionally, Deep Impact has served to motivate several other impact missions, including the AIDA mission (to be completed in 2022) [5]. As the first attempt to perform hydrodynamic modeling Deep Impact using the results of DI, this experiment aims to use modern hydrocode methods to constrain our knowledge of comet Tempel 1 and comets generally. In addition, modeling Deep Impact provides an ideal chance to validate the code Spheral for the case of a comet kinetic impact. Current findings indicate several intriguing results. First, the ANEOS equation of state produces simulation results similar to experimental observations of DI. Regarding surface material, ejecta distributions for targets with a top layer of ice do not appear to match Deep Impact mission morphology, a result that is consistent with results of sublimation models of comets. However, our simulations with a rock-topped crust do appear to match DI, creating an early conical plume. In contrast, ice-topped models produce irregular, vapor rich plumes inconsistent with those observed during the Deep Impact Mission. Porosity of comets was also investigated. Simulation results suggest that very high porosities, ranging from 74 to 91 % cause a high absorption of energy that is inconsistent with Deep Impact. Upcoming three-dimensional modeling will be performed with a bulk density value of 0.4 g/cm$^3$. Lastly, modeling of a large set of strength regimes, ranging from 10 Pa to 10 kPa, appeared to show that strength has a negligible effect on early time crater excavation in 2D models.

Upcoming work will be primarily motivated by an effort to model DI crater excavation during roughly the initial second after impact. This will require that we utilize 2D results and expand upon them in 3D modeling. Through simulation of the Deep Impact mission, we seek to constrain both the size of the DI crater and the material makeup of Tempel
1. By enriching our knowledge of comet composition and by showing Spheral is capable of modeling kinematic impacts, we aim to advance the field by exploring kinetic impacts as a means to mitigate hazardous objects.
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7 References

References


8 Additional Images

Figure 11: A comparison of preliminary 3D models using lattice resolution. The models have been run to about 14,000 microseconds, using strength regimes of 10 Pa, 100 Pa and 1 kPa. Note the lack of change in the models as strength increases, suggesting the minimal impact of strength in early-time excavation.

9 Appendix of Acronyms

LLNL: Lawrence Livermore National Laboratory
DI: Deep Impact Mission
EOS: Equation of State
SPH: Smooth Particle Hydrodynamics
ASPH: Adaptive Smooth Particle Hydrodynamics
ANEOS: ANalytic Equation of State
2DRZ: A two-dimensional modeling technique applied in Spheral that distributes mass around a central length-wise axis using cylindrical coordinates.