The Deep Impact crater on 9P/Tempel-1 from Stardust-NExT

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ABSTRACT

The Stardust-NExT (SdN) mission returned to Comet 9P/Tempel-1 and viewed the site of the Deep Impact (DI) collision just over one comet year later. Comparisons between pre-impact images from the ITS camera on the DI probe and SdN images reveal a 50 m-diameter crater surrounded by a low rim about 180 m in diameter. The removal of a small mound uprange (but offset from the trajectory) from the impact site can be related to changes in the evolution of ejecta. A narrow gap in the ejecta curtain downrange indicates that a ridge extending from the impact-facing scarp downrange interrupted the final stages of cratering in one small region. Together, these observations indicate that the DI excavation crater diameter was about 200 m (±20 m), a value consistent with the ejected mass derived from Earth- and space-based observations with the assumption that this mass represents only 10–20% of the total ejected mass. As a result, the DI crater visible today is consistent with either a larger transient crater, which collapsed, or a central crater of a nested crater resembling an inverted sombrero. The latter alternative would be expected from a layered target: a loose particulate surface about 1–2 m deep over a slightly more competent substrate.

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1. Introduction

The Deep Impact (DI) mission guided a ~370 kg probe into the nucleus of Comet 9P/Tempel-1. The cratering experiment exposed material from depth, allowing spectral observations of pristine, subsurface ices and dust from the nucleus of a comet for the first time (A'Hearn et al., 2005). Measurements of the distinctive evolution of the ejecta from the cratering process itself (Schultz et al., 2007) and the gravity-controlled advance of the ejecta curtain (A'Hearn et al., 2005; Richardson et al., 2007) provided the first constraints on the bulk density of the nucleus.

One of the secondary goals of the DI mission was to assess surface properties from the size of the final crater. Fine ballistic dust rising from the impact site, however, obscured the crater from view throughout the entire approach. While disappointing, this result was not entirely unexpected. The formation of a high-angle plume matched a pre-encounter scenario: a nucleus covered by fine-grained, under-dense, and highly compressible particulates (Schultz et al., 2005). This scenario also predicted an initially faint impact flash followed by a delayed brightening, as was observed (Ernst and Schultz, 2007). The return to 9P/Tempel-1 by the Stardust-NExT (SdN) mission (Veverka et al., 2013) was an unprecedented opportunity to assess both the changes to the nucleus and the appearance of the crater 5.5 years after the Deep Impact encounter. Because of uncertainties in the rotation rate of the nucleus, observations of the crater were not raised to the level of a primary objective.

In this contribution, we first review the location of the impact point on the surface. Second, we compare features before (DI) and after (SdN) the collision. Third, we consider the possible size and evolution of the DI impact crater from SdN images. For reference, Fig. 1 provides two sets of stereo images covering the side of 9P Tempel-1 observed during the Deep Impact encounter in 2005. Several questions are to be addressed.

1. What is the nature of the DI crater and its surroundings and how has it changed? Here we directly compare pre-impact DI images from the High-Resolution Instrument (HRI) with images from the Impactor Targeting Sensor (ITS) and assess the maximum size of the crater.
2. Where was the impact point? This discussion is necessary in order to understand the initial conditions and to place the evolving cratering process and the observed ejecta in context. A separate contribution (Wellnitz et al., 2012) sets quantitative limits on this determination.
3. Is there evidence for remaining ejecta from the DI crater?
4. Did the transient crater change immediately after formation? Or did the final crater change over one comet-year (just over one orbit around the Sun)?

Since the DI imaging data set is essential for interpretation of some of the features imaged by SdN, we include discussion...
regarding the cratering process; for a full description of the DI cratering experiment see Schultz et al. (2007).

2. The DI impact point and crater feature

Trajectory reconstructions reveal that the DI-Probe struck the surface at an oblique angle, about 30° from the local horizontal. Although the DI-Flyby spacecraft cameras did not capture the final crater in spacecraft images, they did capture successive stages of cratering expressed by a downrange-moving (and expanding) vapor plume and ballistic ejecta (Schultz et al., 2007). Oblique impacts generate separate components in the sequence of ejection, each corresponding to different stages of cratering. These stages are clearly resolved in both laboratory (Schultz, 1996; Schultz et al., 2005, 2007) and hydrocode experiments (Pierazzo and Melosh, 1999). Understanding this evolution is important for interpreting the location of the impact point.

Cratering has several observable stages of formation in addition to the three mechanical stages (compression, excavation, and modification) introduced by Gault et al. (1968). First, the moment of contact for a hypervelocity impact generates a plasma traveling downrange at speeds over three times the initial impact speed (jetting stage), as described by Gault and Heitowit (1963), Vickery (1993), Sugita and Schultz (1999). As the projectile (or what’s left) penetrates below the surface drives target material below or downrange for oblique impacts (compression stage). This becomes a second vapor plume derived from upper surface layers that moves rapidly downrange at speeds ranging from 1 to 2 times the initial impact speed as observed experimentally (Schultz, 1996; Schultz et al., 2006) or in numerical models (Pierazzo and Melosh, 1999). For highly porous targets, a third observable stage also occurs: a reverse-angle plume that is initially directed uprange but quickly evolves into a high-angle plume above the growing crater (Schultz et al., 2005, 2007). The excavation stage comprises the fourth stage and represents the growth of the crater (expressed by ballistic ejecta) in response to the rarefaction behind the shock off the free surface.

Each stage of excavation results in ejecta radiating from different portions within the final crater corresponding to different stages of an evolving flow field (Anderson and Schultz, 2006a; Hermalyn et al., 2010). Oblique impacts produce a characteristic zone of avoidance uprange (Gault and Wedekind, 1978), typically with a curved uprange boundary (Schultz et al., 2005, 2009; Anderson and Schultz, 2006b). The zone of avoidance depends on impact speed, angle, and the porosity/compressibility of the target (e.g., Anderson and Schultz, 2006a; Wünnemann et al., 2006; Schultz et al., 2007; Elbehausen et al., 2009). Because this zone reflects the asymmetric flow field created during coupling (the transfer of momentum and energy), it becomes more apparent when the coupling zone, which is proportional to the projectile diameter ($a$), comprises a greater fraction of crater excavation as defined by the final transient crater diameter ($D_c$). Cratering efficiency is related to $D_c/a$ and increases with decreasing scale, or decreasing gravity (or increasing speed) in loose particulate targets as the result of gravity-limited crater growth (e.g., Schmidt and Holsapple, 1980; Schultz, 1992). Cratering efficiency also decreases for highly porous targets where compression consumes a greater fraction of the excavation stage (Housen et al., 1999; Schultz et al., 2005). For high-angle impacts into loose particulates, the coupling stage is expressed by evolving ejection angles (Hermalyn and Schultz, 2011) but is overprinted by each successive stage of crater growth, therefore hidden in the resulting pattern of ejecta. For oblique impacts, however, the coupling stage maps across the surface as a zone of avoidance with a curved uprange boundary observed at all scales (Anderson and Schultz, 2006b; Schultz et al., 2007, 2009).

Fig. 1. Stereo pairs (for stereo viewer) from Stardust-NExT showing the side of 9P Tempel-1 viewed by the Deep Impact flyby spacecraft. (a) n30034te01 (L) and n30033te01 (R); (b) n30036te01 (L) and n30035te01 (R).

Fig. 2. Stereo pairs (for stereo viewer) of the region where the Deep Impact probe impacted the surface. The larger crater-like feature near the center is 310 m in diameter. The DI impact occurred about halfway between the two large circular features. (a) n30034te01 (L) and n30033te01 (R); (b) n30036te01 (L) and n30035te01 (R); (c) n30036te01 (L) and n30034te01 (R).
2.1. Impact point

Multiple image sets, coupled with an understanding the sequence of cratering, allow pinpointing the impact site within 20 m, which then can be compared with the imaging from SDN encounter. Six strategies are used: (1) bore sighting of the camera on the impact probe (see Wellnitz et al., 2012); (2) impact flash; (3) evolution of the self-luminous vapor plume; (4) shadow of the initial ejecta plume onto the surface; (5) the shadow of an emerging high-angle plume onto the interior of the ejecta curtain; and (6) projections of ejecta rays back to the surface. Although some of these strategies had been previously presented (Schultz et al., 2007; Ernst and Schultz, 2007), they are re-examined here in order to demonstrate consistency in the identification of the impact point. Common features observed in both the Medium Resolution Imager (MRI) and High-Resolution Imager (HRI) then provide constraints on crater size through their effects on crater excavation (considered later).

The ITS camera onboard the DI probe provides one of the first key observations. This camera was bore-sited along the spacecraft trajectory, except during the final stages of approach when collisions on the spacecraft by dust in the inner coma induced slight torques and misalignments (see Wellnitz et al., 2012). In between, nested ITS images allow pinpointing the impact site relative to other surface features: on a textured (but flat) surface, just to one side of a small, low relief dark plateau (Fig. 3). Based on the dispersion of center points, this strategy is accurate to within about 10 m (cross trajectory), as discussed by Wellnitz et al. (2012). The low angle of approach results in considerable foreshortening and uncertainties along the trajectory line from the viewpoint of the ITS camera, which contributes to greater uncertainty (20 m) along the trajectory.

A second strategy uses the position of “first light” (first appearance of the flash) created around the moment of impact (Ernst and Schultz, 2007). Wellnitz et al. (2012) provide additional error bars using this approach. The identification of the impact point is based on overlapping a pre-impact HRI image with the edge of the nucleus in MRI images. Features can be identified in both the MRI and HRI (Fig. 4). Multiple fiducial points across the nucleus (limb, features) collectively contribute to the location of the first light. The initial brightening is spread over 3 pixels (width and height) with the centroid from all 9 pixels slightly offset (by 50 m) uprange from the location based on ITS approach images.

A third strategy assesses the evolution of the expanding self-luminous vapor plume. A centroid fit to the plume brightness, however, will not be centered on the impact point due to the rapid downrange motion of the plume as it expands outwards. Nevertheless, the source region for the freely expanding vapor plume can be used to identify the first point of contact through comparison with experiments (e.g., Schultz, 1996; Schultz et al., 2007) and modeling (e.g., Pierazzo and Melosh, 1999). As the vapor plume expands and travels downrange, its outer boundary appears pinned to near the impact point. Because the translational speed will be greater than the gas expansion speed, however, the plume becomes more elongate with time. This process describes the plume from the DI impact (Fig. 5a). Differenced images (one image subtracted from the previous image) reveal this more clearly: the brightest part of the self-luminous component appears to cover the 320 m circular structure uprange of the ITS-located impact point (middle, Fig. 5b). This offset can be understood if the initial plume does not correspond to the moment of contact at the surface; rather, it indicates a plume directed back along the trajectory. In laboratory experiments, reverse plumes are most pronounced for impacts.
into under-dense and compressible targets and result from impact vapor redirected out of a deep penetration funnel during the initial stages of compression (discussed later). Subsequent differences (right, Fig. 5b) reveal a brightened extension uprange, along with the expanding plume moving downrange, corresponding to the momentum-controlled vapor plume from the cavity. The vapor plume appears to move downward relative to the trajectory. Because the plume travels along the local surface (while expanding above), this displacement indicates that the impact occurred on a relatively flat surface. If the impact had first struck a facing slope, the plume would have been deflected from the trajectory line. Consequently, comparison between the first light and the evolution of the self-luminous component cannot determine the impact point to better than about 50 m on the surface (between the two circular features) but is consistent with determinations from bore sighting in the ITS camera.

Fourth, a shadow of the emerging high-angle plume on the surface can be traced back to the trajectory line within the first few seconds of impact (Fig. 5a). The shadow cast across the surface confirms the presence of optically thick, high-angle ejecta (not the vapor plume). Conversely, the absence of a shadow during first 5 frames after impact is consistent with optically thin vapor (or expansion above/beyond the surface). The shadow has a dense uprange edge corresponding to a high-angle ejecta plume (HAEP) extending from the crater. Its extension back to the impact site also indicates an impact point consistent with the ITS approach imaging. Later (~135 s after impact), a high-angle plume emerges (or becomes clearer during approach) and casts a long, straight shadow on the interior of the ejecta curtain (Fig. 6b), which represents a fifth strategy. This shadow intersects the trajectory and centers within ±30 m of the ITS impact point (Fig. 6c and d).

A sixth strategy extends rays back to the initial trajectory at the surface. Intersections of multiple rays from an HRI deconvolved image yield multiple points of convergence (Fig. 7). The cratering flow field, however, evolves downrange for oblique impacts (Anderson et al., 2003); consequently, convergence on a single point should not be expected. Tracing rays from the uprange component requires using only the ray segment closest to the surface (closest to the trajectory), where it is radial to the crater. Farther from the impact, the evolving flow field results in a curved ray pattern. The uprange ray segment represents the best locator for the impact point because the center of the ejecta curtain progresses downrange throughout crater growth (Schultz et al., 2007). Well after crater formation (>150 s after impact), rays will not converge on the crater but on the base of the ejecta curtain. For a vertical impact, the base of the advancing curtain maps as a widening concentric circle through time. For an oblique impact into particulate targets, however, this circle centers migrates downrange from the crater but remains close to the uprange rim. An oblique impact into an under-dense particulate target results in an impact point located near the uprange wall of the final crater, whereas the widening circle (corresponding to the base of the ejecta curtain) is pinned to the uprange wall (Schultz et al., 2007). Consequently, determining the impact point from the convergence of crater rays is not be useful, except at early times of crater formation or from uprange-ray segments near the crater. Even then, the inferred impact point will be offset downrange.

In summary, these six different strategies yield very similar results for the impact point within about 25 m with the best determination from ITS imaging data and telemetry (Wellnitz et al., 2012). Simple geometric methods (e.g., centroid of brightness or averaged ray convergence) will not yield an accurate location, even
though statistical uncertainties can be determined. Rather, pinpointing the location of first contact requires a self-consistent model of crater excavation from an oblique impact.

2.2. DI crater and Its surroundings

At closest approach to the nucleus of 9P Tempel-1, the SdN imaging system achieved a resolution of ~11 m/pxl, while a working resolution 2.2 pixels is needed in order to resolve features. Fig. 8 allows direct comparison between the pre-impact ITS and SdN images. The ITS approach images have much higher spatial resolution just before impact; nevertheless, small features close to the resolution limit can be readily identified in SdN images with appropriate image processing (logarithmic stretches and filtering). Certain regions appear to have changed, such as the disappearance of two patches slightly offset and uprange from the impact point (A–C, Fig. 8a). A third bright patch now missing was on a facing scarp (D, Fig. 8b). While other bright patches of similar size can be identified in both SdN and DI images, these three patches near the impact site have disappeared. The disappearance of the feature D along the scarp in the SdN images may be due to a shift in the local phase angle. This scarp was in sunlight and viewed face on during the DI encounter. During the SdN flyby, it was in shadow and viewed from above.

Based on the convergence of methods (discussed above), the impact point was just to the right of a small, dark mound (cross in Fig. 8). Interestingly, this small mound now appears very muted, at best. This loss of expression is not attributed to differences in resolution since comparable-scale features can be identified elsewhere in the two images. In addition, a feature extending from the scarp downrange appears less pronounced. The SdN mission provided multiple viewing angles of the DI site. As a result, successive images with changing phase angles and emission angles provide much greater confidence in the identification of a subtle (but obvious) 50 m-diameter dimple at the location of impact (Fig. 9, also revealed by stereoscopic viewing in Fig. 2). Although the best resolution for NExT images is only 11 m/pxl, the working resolution is typically cited as 2.25 times imaging resolution (or ~25 m/pxl) when applied to the identification of features. In practice, however, the identification of craters depends on local slope variations and reduces to 5–8 times the imaging resolution (Schultz, 1977). Even though the identified crater is close to the limiting resolution, it is visible both in successive views of the region and in stereo. Stereo images and different viewing angles also reveal a subtle arc consistent with a low-relief outer rim (about 180 m in diameter) that overlaps the region with the missing mound labeled in Fig. 10. This feature was absent in the pre-impact ITS imaging (Fig. 3). As pointed out by Minnaert (1954), linear features can be resolved well below the resolution limit (e.g., telephone wires); consequently, it is reasonable to assume that this is a real feature. Further interpretations of these two features are included in the following section.

3. Discussion

Although SdN images did not reveal a large, deep crater, there are four explanations. First, the crater was small due to unique...
properties of the surface of the nucleus (e.g., Housen et al., 1999). Second, the crater collapsed soon after formation due to the deep penetration by the DI probe. Third, localized mass wasting (e.g., localized venting and wall collapse) destroyed the final crater after 5.5 years. Fourth, the crater is a nested crater, i.e., a small central crater surrounded by a broad but shallow-rimmed excavated zone. These alternatives are considered in more detail below.

The most straightforward explanation is that the DI collision produced only a small crater, but this interpretation is inconsistent with Earth-based and space-based telescopic observations following the impact, as well as observations from the DI spacecraft throughout approach. Earth- and space-based telescopes estimated that $8 \times 10^6$ kg of dust and ice was ejected from the impact (Keller et al., 2005; Lisse et al., 2006). Such observations refer only to materials that left the gravity field completely, not the fraction that returned to the surface as represented by the ejecta curtain observed by the DI flyby. Inclusion of the unobserved near-rim increase the total amount of material excavated by the impact.

Fig. 7. Curved rays (a) extended back to the surface in (b) (HRI image hv-9000936) and mapped onto a pre-impact HRI image (c). At this stage, uprange and lateral rays provide better locators of the growing crater. Downrange rays appear to intercept the surface well downrange of the impact site. The center of brightness is significantly downrange due to scattered light off the diffuse ballistic ejecta above the crater.

Fig. 8. Comparison of common features identified in Stardust-NExT image at left (frame n30035) and the composite ITS image at right. In order to enable comparisons, the vertical scale is preserved in deference to the horizontal scale. This is necessary due to extreme foreshortening created during approach by the DI probe (right). Small cross (black) indicates the best-determined location for the DI impact. The small mound adjacent to the impact site in the pre-impact image (right) appears highly degraded in the Stardust-NExT image (left). Small bright patches (likely ice) occur prior to the impact (noted by A–D at right) have disappeared in the Stardust-NExT image (left).
factor 3–10 greater than estimates from telescopic observations. Consequently, a crater 50 m in diameter would have ejected only a fraction of the observed mass ejected by the DI collision, after correction for material returning to the surface. Secondary activity (chemical release) did not likely contribute to the observed ejecta since the evolution of the ejecta (asymmetry, high-angle plume, uprange plume, etc.) can be easily matched with the evolution of an oblique impact (Schultz et al., 2007). Moreover, the total mid-IR flux monotonically decreased after the first imaging observation (Sugita et al., 2005), which is inconsistent with a significant eruption unrelated to the impact.

Hence, the observed amount of dust and ice is consistent with a crater nearly 150–200 m in diameter (Schultz et al., 2007). Second, the disappearance (or muting) of the mound adjacent to the impact point indicates that the crater has to be larger than just the identified pit. Third, the observed evolution of the ejecta resembled a classic oblique impact into loosely bound particulates, including an uprange zone of avoidance, curved uprange rays, and expanding cone-shaped ejecta. Oblique impacts into strength-dominated targets generate a very different evolution characterized by a fan-shaped ejecta pattern downrange with the apex on the crater. Fourth, the evolution of the event resembled the unique effects of an oblique impact into an under-dense (and compressible) target (Schultz et al., 2007).

With these considerations, the question becomes: what happened? In the following discussion we first consider the possibility that the 50 m-diameter pit is unrelated to the initial excavation crater. We then consider additional observations that might reveal the size of the crater by reconsidering the event from SdN and DI images. We finally consider the possibility that the observed pit and outer rim represents a nested crater, typical of craters formed in a target with a weak surface layer over a stronger substrate.
3.1. Crater collapse

In very weakly bonded particulate targets, the crater profile may be unstable and collapse immediately after formation (e.g., Schultz et al., 2005, 2007). For oblique impacts, this instability results from deep initial penetration by the projectile and a highly steepened uprange wall, both resulting in wall collapse. Laboratory experiments using a target of fine microspheres, for example, completely removed the evidence for the excavation crater, leaving behind a small central dimple. In these experiments, crater collapse engulfed near-rim ejecta and re-filled the initial cavity. Similarly, impacts into fine-grained, under-dense (sieved) perlite targets also result in collapse immediately after formation (Schultz et al., 2005).

The observed high-angle ejecta plume (Fig. 5) indicates continued upward flow, which would reduce wall support and trigger subsequent wall collapse. The high-angle plume could have resulted from either cavitation of gas within the initial penetration funnel or a sustained response by chemical and thermal reactions associated with heated relicts of the deeply embedded DI probe. In either case, wall collapse would have occurred, even if the transient crater exhibited a typical crater profile with a 3:1–5:1 diameter-to-depth ratio. With this interpretation, the final crater found in SdN images places few constraints on the excavation crater, while the missing mound implicates a large transient cavity.

3.2. Constraints on initial crater size

The closest approach to the nucleus by the DI flyby provided clear evidence of a large crater because ballistic ejecta continued to fill half of the field of view and obscured underlying topography more than 700 s after impact (Fig. 11a). Fig. 11a provides an unannotated view, whereas Fig. 11b identifies key features of the ejecta curtain. Comparison between surface features before and after the impact reveals that the ejecta are optically thick at least 0.5 km above the surface if viewed face on and to much greater distances from the surface if viewed down, along the curtain in the foreground (Fig. 12). The amount of obscuration 6–10 crater diameters above the surface is inconsistent for a small crater (only 50 m in diameter); rather, this is consistent with a larger crater, two to three crater diameters above the surface. The stereo view (Fig. 11c and d) early on reveals two shadows emerging from the impact site from a high-angle plume: one cast on the interior of the ejecta curtain, the other revealed below on the surface as the curtain became transparent farther away.

Co-location of features in pre- and post-impact images appears to constrain the impact point within 50 m (Fig. 13a). Ballistic ejecta rays projected back to the surface converge on an elliptical footprint at the surface but significantly downrange from the impact point, based on other strategies (discussed above). At this time, however, the ellipse corresponds to the base of the ejecta curtain, rather than the final crater. A high-angle plume casts a shadow on the interior of the ejecta curtain (solid line) and hides the actual contact between curtain and the surface. The darkened region to the left of the trajectory, however, represents the shadowed base extending beyond the edge of the high-angle plume and is taken to be the approximate diameter (~370 m ± 50 m) of the ejecta curtain at this time. When projected onto feature-correlated SdN images, the downrange offset of the ejecta curtain becomes obvious (Fig. 13b).

This downrange offset of the ejecta-curtain base reflects an expected evolution of the ejecta curtain in a loose, porous particulate target. For vertical impacts, the ejecta-curtain base (or slice through the curtain, e.g., Anderson et al., 2004) expands in concentric circles centered at the impact point. For oblique impacts, however, the base of the ejecta curtain appears pinned to near the
impact point (Schultz et al., 2007). In under-dense (highly porous and compressible) targets, the impact point is just inside the up-range wall, rather than the crater center (Fig. 14a). Similarly, the shadow from the high-angle plume for the DI impact extends back to a point considerably downrange from the impact point (Fig. 13b). This migration reflects the downrange velocity component of individual particles within the late-stage high-angle ballistic plume, a motion also observed in laboratory experiments using highly porous and compressible targets (e.g., Fig. 18, Schultz et al., 2007).

Fig. 13b also clearly shows an opaque ray extending uprange. The persistence of this ray suggests that one component of flow relates to the initial penetration stage, in addition to both a cavity-directed high-angle plume and the inverted cone-shaped ejecta curtain, which widens with time. The initial stages of this process have been captured in high-speed imaging at the NASA Ames Vertical Gun Range (Fig. 14b and c). Hypervelocity impacts (30° at 5.3 km/s) into sand result in a brilliant self-luminous vapor plume that rapidly travels downrange, transitioning to low-angle ejecta initially directed downrange (Fig. 14b). Ejection angles gradually steepen and become more symmetrical. For a layered perlite target (Fig. 14c), the low-impedance of the surface layer initially results

**Fig. 11d.** Stereo MRI pair from (c) with dashed lines identifying discrete rays. Dark rays are actually gaps in the ejecta. These gaps disappear toward the surface where the ejecta curtain becomes optically thick.

**Fig. 12.** Comparison of features and terrains identified in the processed MRI image (Fig. 11) and ITS composite (a, right) and Stardust-NExT (b, right). Mapped features reveal regions where the ejecta are optically thick, which prevents features on the surface to be identified (black outline).
in a faint flash and downrange-moving self-luminous plume that completely decouples from the rest of excavation. In this experiment, a self-luminous uprange plume emerges 100 μs later. This reverse plume continues to expand throughout crater growth (e.g., Schultz et al., 2007; Schultz, 2009). At the same time, the opening cavity results in a high-angle plume of ballistic particles. The later re-emergence of the uprange plume for the DI collision (350 s after impact) may indicate gas-driven release from the deep penetration funnel initially created by the dense DI probe that re-opened after crater excavation had ceased. A separate contribution will detail factors that control the evolution of the reverse and high-angle plume. Here, these experiments illustrate observations from experiments that parallel observations from the DI flyby and provide evidence that this was a response to the impact.

Two additional observations implicate an excavation crater much larger than the relict 50 m-diameter pit. First, the small mound near the impact point altered the pattern of ballistic ejecta uprange. Second, an extension from the scarp downrange from the impact point created a gap in the ejecta curtain. These two observations document the limit of crater excavation.

For background, Fig. 15 shows a sequence of de-convolved HRI images during approach (from 8 to about 484 s after impact). Within the first 8 s, the ejecta emerge uprange in an axisymmetric fan-shaped pattern (Fig. 15a) but with a diffuse ray extending to toward the bottom in the image. The axisymmetric fan-shaped ejecta pattern is interpreted as a reverse plume (directed back toward the flyby spacecraft), which emerges from the penetration funnel during the initial, compression stage of cratering. Rays directed toward the camera widened due to foreshortening (increased scattering along the trajectory); conversely, rays on the other side should be narrower due to perspective. In the next frames (Fig. 15b), a narrow ray clearly appears to one side and grows, even though the axisymmetric fan-shaped ejecta pattern remains. Later, this ray rotates uprange around the trajectory axis until it becomes aligned with the initial trajectory (Fig. 15a). This evolution indicates that excavation flow encountered topography, consistent with the location of the mound relative to the impact point (Fig. 16). The delay in emergence reflects the slower crater growth in the uprange direction. If this mound had been more competent, then excavation flow would have been interrupted, resulting a gap in the ejecta curtain instead.

As excavation continued, the transient crater would have been disrupted had it encountered an uphill slope or the downrange scarp (e.g., Fig. 13b). If excavation had progressed uphill well into...
the impact-facing scarp, then the ejecta curtain would have been affected. Rarefaction waves off the free surface control ejection angles in particulate targets (e.g., Gault et al., 1968). Crater excavation progressing into an uphill slope (loose particulates) results in the same ejection angles with respect to the local surface. As a result, ejection angles would be higher with respect to a flat surface. From a distance, the ejecta curtain and rays would exhibit a distinct kink or bend. Instead, there is a clear (but narrow) gap in the ejecta curtain without distorted rays (or curtain).

ITS images more clearly show the ridge-like extension of the scarp approximately in the direction of the impact (Fig. 8b). Because ITS images are highly foreshortened, this feature should be more pronounced in the post-impact image as viewed from above (Fig. 8a); instead, the extension is barely visible. Consequently, excavation likely reached this feature. A gap in the ejecta curtain would develop if the transient crater had encountered a change in material properties (e.g., a competent structure); the wider the gap, the greater the interaction with the scarp. Fig. 16b reveals a narrow gap downrange (also see Fig. 11c, stereo; Fig. 12b, left). Because this gap subtends less than 6°, the transient crater just barely grew into (but was locally arrested by) a material contrast downrange. The interrupted growth correlates with the disappearance.

Fig. 14a. Evolving ejecta curtain illuminated by a laser-sheet. Image is a composite from three different times from a 30° impact into pumice. This illustrates how the base curtain widens while pinned to near the impact point uprange, thereby resulting in the center of the curtain being offset downrange. A similar evolution can be applied to the base of the DI impact ejecta curtain (Fig. 13b).

Fig. 14b and c. High-speed sequence (125,000 frames per second) showing selected images of a 30° impact into dry no. 100–140 sand with a density 1.7 g/cm³ (b) and thin layer (1.2 cm) of finely sieved perlite (0.12 g/cm³) over the perlite/dolomite mix (c). The impact into the perlite/dolomite mix resulted in a reverse plume emerging about 100 µs after impact. Double image in the first frame of (b) is an artifact of the imaging system.
of a portion of the ridge extending from the scarp downrange. Look-back images 15 min after close approach revealed that the gap widened as the ejecta curtain expanded, as would be expected. The asymmetry in the ejecta curtain at this time was interpreted as a combination of this gap, the rising high-angle plume (above the crater), and lighting (Schultz et al., 2007). A different interpretation, however, can be found in Richardson et al. (2007).

If these interpretations are correct, then the disrupted flow indicates that the scarp has greater strength than the rest of the DI target region, consistent with the resistant terraces and exhumed terrains in the region. Conversely, the complete obscuration of pre-impact features on the other side of the ejecta curtain is evidence that DI collision generally excavated very loosely bonded, fine-grained materials. Future reconstructions of the event (and viewing positions) would help in refining this interpretation.

In summary, the combined modifications to excavation uprange (small mound) and downrange (ridge extending from the scarp) requires the excavation crater diameter to be 200 m ± 20 m. Such a diameter is consistent with estimates for telescopically observed ejecta mass (>10^7 kg) lost to space (10–20%) and the estimated amount of ejecta returning to the surface (80–90%).

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**Fig. 15.** Evolution of the ejecta between 8 s and 484 s after impact. This sequence shows that uprange ejecta evolved from a symmetrical fan-shaped pattern (a–c) to an uprange (UR) arcuate ray (d–e). The UR fan is remains limited in extent due to foreshortening (heading back into the direction of the camera). While the UR rays are initially symmetrical (to either side of the trajectory axis in a through c), one UR ray (outward-directed arrow) extends farther to the right of the trajectory in (b through c). This ray is attributed to excavation of the small mound identified in the ITS approach images (e.g., Fig. 3b). HRI frames: 900910 at 8 s after impact (a); 900916 at 18 s (b); 900921 at 22 s (c); 900936 at 65 s (d); 900945 at 114 s (e); and 900985 at 484 s (f).

**Fig. 16.** Connection between emerging uprange ray to one side (UR in a) and downrange gap (b) with surface features in the pre- (c) and post-impact images (c, inset). The longer ray to one side is consistent with the intersection of the expanding cavity with the small mound to the left of (and slightly up from) the impact point (IP) in (c) resulting in excavation of additional material in that direction (a, UR). This small mound is missing in the inset from Stardust-NExT. Disruption of the downrange ejecta curtain (b, DR) may be related to interruption of crater growth downrange by an extension of the facing scarp (c), which appears to be partly removed (inset, c).
3.3. Nested Crater

The faint outer rim (180 m in diameter) identified in different look directions (Fig. 9) and stereo images (Fig. 2) resembles nested craters found on the Moon (Fig. 17a and b). The detailed evolution of ejecta captured in DI flyby images prompted the suggestion for a 5 m deep layer (Schultz et al., 2007). Ground-based observations (mid-IR) of the evolving dust components also implicated a dusty mantle of carbon-rich fine grain surface layer (10's of cm) over a silicate-rich substrate (Kadono et al., 2007). These two layers, however, likely represent two different processes. A thick (meters) surface deposit resulting in a nested crater is consistent with redistribution of materials (e.g., ejecta deposits from the nearby crater-like features), whereas the dusty mantle developed in situ in surface processes while in the trans-Neptunian region. Consequently, the stratigraphy at the DI impact site indicates multiple processes acting over a wide range of spatial and temporal scales.

On the Moon and in laboratory experiments, nested craters are produced by impacts into a thin, loose layer of particulates covering a competent substrate (Quaide and Oberbeck, 1968). In this case, the classical ejecta curtain still forms, but the width of the curtain is significantly reduced due to the arrested flow field. The muted appearance of topography and numerous layers inferred from close-up images by the ITS camera during approach indicate that a similar layering occurs at the DI impact site. Even small contrasts in target strength should limit downward displacement of the low-speed flow field due to the very weak gravity and weak shock conditions at large distances from the impact (porous target). Rather than a solid competent subsurface (as on the Moon), the substrate at the DI impact site simply could be more strongly bonded than a loose surface layer yet still produce a nested crater.

The nested-crater model could account for several observations of the DI impact crater from SdN. First, the faint narrow rim (Fig. 10) resembles lunar analogs (Fig. 17a). Second, the truncated cratering flow field during an oblique impact preserves asymmetry in the ejecta throughout crater growth (based on laboratory experiments). Third, a layered target would enhance the formation of arcuate uprange crater rays. Fourth, a slightly more competent substrate would ensure a deep penetration funnel by the DI probe and contribute to the late-stage emergence of the reverse plume. And fifth, the ejecta deposits would be thinner (e.g., Fig. 17).

Laboratory experiments reveal that a layer greater than about one projectile diameter retains the same diameter as a crater produced completely in the upper layer (Fig. 17b). For the DI nested crater, the central pit corresponds to a relict strength-controlled crater in the substrate, whereas the outer rim represents the gravity-limit for the ejecta flow field. Consequently, the diameter of the DI crater would have been about 130–150 m, had it formed in material characterizing the upper layer. The total amount of observed ejecta (including unobservable dust returning to the surface) is conservatively more than 10^7 kg. Such observations would be consistent with a target 1 m-thick layer (outer crater 200 m in diameter) or 2 m-thick layer (outer crater 150 m in diameter).

Fig. 17. Examples of nested craters on the impact melt downrange of King crater on the Moon (a and b). Nested craters form by impacts into a layered target. The inner pit results from penetration through a thin regolith into a competent substrate and reflects strength scaling. The outer rim forms by excavation of the overlying regolith, dominated more by gravity scaling. For vertical impacts (c), the diameter of the crater (D) in the regolith is significantly reduced (relative to a diameter, D_o, into just the regolith) if the layer is less than ~2.5 times the projectile diameter. For oblique impacts (here 30°), the diameter remains the same until the thickness becomes less that about one projectile diameter.
3.4. Ejecta deposits

The absence of an obvious ejecta blanket or surface alterations (e.g., scouring) created by the downrange expanding vapor plume or ejecta striking the surface could indicate a very thin ejecta deposit. Even though small lunar craters exhibit bright or dark rays, the low surface contrast for the near-surface materials on the nucleus left little trace. There are hints in SdN images, however. The disappearance of at least three small white patches (Fig. 8a) may be related to the effects of the DI ejecta, whether covered or disturbed.

This absence of an obvious ejecta deposit is attributed to both the limits of resolution and the nature of the ejecta (impact-excavated ices), which should not persist after 5.5 years. The very low speed of ballistic ejecta returning to the surface near the crater (due to the low gravity) also resulted in minimal surface disruption. If the DI collision produced a nested crater, then the ejecta thickness should have been thinner than the thickness around a nominal crater at the same scaled range due to cylindrical (rather than volumetric) crater growth of the transient crater and more difficult to detect on the surface.

4. Conclusions

The Stardust-NExT was an unprecedented opportunity to assess the consequences of a hypervelocity impact into an under-dense target in space. Comparison between clear images of the pre-impact surface (IT5 camera on the probe) and a record of the ejection sequence over 15 min (DI flyby) allows inferring the size of the DI crater and its fate. Four key observations constrain the DI crater: the 50 m pit at the projected impact site; the degradation of surface features identified in pre-impact images; the disruption of the ejecta curtain downrange; and published estimates for the total amount of ejecta observed during the DI collision. These observations result in two plausible scenarios for the DI crater observed in Stardust-NExT images. First, a large (~200 m in diameter) transient crater collapsed leaving behind a small 50 m pit. Or second, the DI impact produced a nested crater with a small inner pit (~50 m in diameter) surrounded by a shallow excavation crater (~180 m in diameter).

References


