THE DEEP IMPACT COLLISION: A LARGE-SCALE OBLIQUE IMPACT EXPERIMENT. P. H. Schultz[1], C. Ernst[1], M. F. A'Hearn[2], C. Eberhardy[1], J. M. Sunshine[3], and the Deep Impact Team. [1]Department of Geological Sciences, Box 1846, Brown University, Providence, RI 02912 USA (peter_schultz@brown.edu), [2]Department of Astronomy, University of Maryland, College Park, MD, USA, [3]Science Applications International Corporation (SAIC), Chantilly, VA, USA.

OBSERVATIONS: The DI collision was oblique: between 25° and 35° from the surface horizontal as established by the shape of nearby craters and location on the surface [1] and the shape models. The oblique trajectory also is clearly expressed by the evolution of the initial plume ejecta curtain asymmetry, and later curved ejecta ray systems. The following stages of evolution are divided according to observations of the observed ejecta, not the actual stages of excavation.

Early-time (first second): The early-time flash and vapor plume rapidly evolve along the trajectory: an initial faint "first light" uprange from the projected point of impact; a fading source along the trajectory that moves downrange (~100-170m) over the next 0.125s after impact (AI); gradual brightening over the next 0.62s; and then a sudden "flash" (saturated pixels) around 0.25s after the "first light." Over the next 0.12s, a plume emerges and travels downrange and evolves into an eyebrow-shaped, self-luminous leading edge. This leading edge expands laterally (with respect to the trajectory) and gradually fades [1,2].

Later Time (1 to 10 seconds): Over the next 9 seconds, the fast downrange plume decouples from the subsequent excavation stage of cratering and expands out the field of view. A diffuse plume of fine ejecta (scattered light) expands above the impact while radial rays emerge. Uprange, both a highly foreshortened fan-shaped ejecta segment and a shorter, narrower (collimated) ejecta plume emerge. The fan-shaped ejecta segment extends out at an angle less than the flyby-observing angle, i.e., comparable to the initial trajectory. The more collimated plume grows more slowly than the downrange and later ejecta plumes.

Late Time (10 to 200 seconds): Key later time features include (see Fig. 1): a) curved rays uprange with bilateral symmetry along the DI trajectory uprange and downrange; b) uprange plume; c) uprange "Zone of Avoidance" (ZoA), excepting the plume; d) high-angle diffuse plume (above the impact) identifiable in stereo images and in its shadow cast on the inner surface of the ejecta curtain; e) along-trajectory downrange ray; f) the beginning of a downrange ZoA expressed as a dark wedge. The curved uprange ray system evolves from the fan-shaped segment emerging during the first 10 seconds. This initial ray system decouples from inner ejecta after ~50 seconds and leaves behind a distinctive uprange ZoA that persists throughout the rest of the approach. A new set of curved uprange rays comprised of lower speed ejecta, however, emerges and persists to very late times (~800s AI). This new set begins with a very narrow ZoA. The curved rays are convex outward (with respect to the trajectory) both uprange and downrange, forming a spider-like, cardioid (heart-shaped) pattern.

Very Late Time: From 200 seconds to the end of the approach imaging sequence, the broad ejecta cone (subtending an angle of 165°) appears to result from very low angle ejecta with respect to the surface horizontal. Stereo imaging and laboratory simulations reveal, however, that this appearance likely results from the combined effects of the evolving uprange ZoA and the view angle for the flyby. As the flyby approaches the comet, well-defined rays continue to extend down to near the surface. Uprange, the ZoA remains pronounced with two well-defined rays on either side of the trajectory and subtends 160°, with fainter curved uprange rays subtending ~60°. A diffuse, narrow ray (or surface deposit) extends from the converging curtain base uprange. Downrange, the ZoA widened and formed a "butterfly" pattern. The sunward-side ejecta curtain casts a shadow on the interior of the opposite side as revealed in stereo imaging. Additionally, a high-angle plume emerging from crater casts a more opaque shadow across the curtain.

INTERPRETATIONS: The DI experiment closely resembles the evolution captured in much smaller scale laboratory experiments for oblique impacts into high-porosity targets prior to the encounter [3]. Similarities include the multi-component early stage diffuse plumes: downrange vapor; above-impact dust-entrained cloud; and back-trajectory plume. The later stage flow regime expressed by the bilateral uprange and downrange rays (forming the ZoA and a "butterfly pattern") is also reproduced in laboratory experiments (Fig. 2).

In the DI experiment, the initial back-directed plume rapidly (next 30s) dissipates as the number density decreases through expansion. This component is likely derived from the upper surface. Slightly higher angle V-shaped rays subsequently emerge uprange but also rapidly dissipate. The subsequent evolution of the ejecta shows that significant asymmetries persist to very late stages (800s). Moreover the two-staged evolution of the ejecta curtain (before 50s vs. after) may express the effects of layers in a very weakly bonded particulate target: an upper very low density volatile/non-volatile layer over a substrate of more volatile rich layer.

At late times, the low-velocity, high-angle diffuse plume above the impact contributes to the inability to see the final crater. Additionally, the late-stage uprange ray (800s) is attributed to a reverse plume, possibly deep seated.

The distinctive cardioid ray pattern is a direct consequence of the evolving flow field including changes in position and direction of ejecta through time [4] as illustrated in Fig. 3. For gravity-controlled cratering on a low-gravity body, however, the initial coupling stages should comprise a much smaller fraction of the total time for crater growth. This should be expressed by the rapid disappearance of the uprange ZoA as the cratering flow field transitions from non-radial to radially symmetric excavation flow. Laboratory experiments using highly porous targets, however, maintains a ZoA throughout growth. A layered stratigraphy would not only accentuate the persistence of the uprange ZoA but also produce the downrange ZoA and the resulting butterfly pattern as observed in laboratory experiments.

The observed evolution is important in order to place the ongoing spectral analysis in context and to understand the depth of origin for the various components [5]. Impact angle has a significant effect on such interpretations.

CONCLUSIONS: The DI collision produced ejecta with four components stretching out with time: a) early-time downrange plume that expanded while traveling downrange at a velocity slightly less than the initial impact velocity; b) downrange diffuse plume resulting from vapor-entrained debris; c) narrow plume directed uprange out of the initial penetration zone; c) low-angle, uprange ejecta fan related to excavation flow modified by the initial stages of penetration; d) high-angle plume comprised of low-speed ejecta above the impact; e) late-stage bilaterally symmetric butterfly pattern with a growing ZoA.The net result of these components is a cardioid-shaped ejecta fan flanked downrange by two rays and split uprange by a smaller ray. The evolution of the ejecta and the persistence in the asymmetry indicate that the near-surface is layered (> 20m) with a very low density ($0.2 g/cm^3$), independent but consistent with estimates based on the derived gravity [6].

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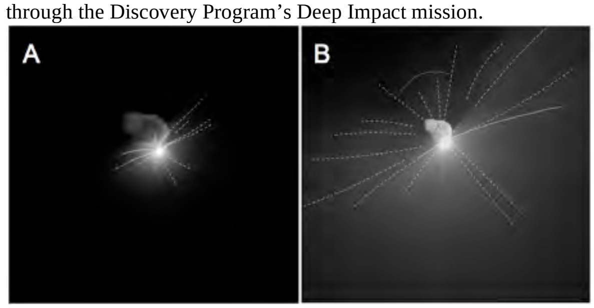

Fig. 1. Evolution of ray systems from the DI impact at different times. Fig. 1A shows the uprange (upper left) low-angle plume surrounded by a zone of avoidance as well as two downrange rays (~40s AI). Fig. 1B reveals the dispersal (arc to upper left), the cardioid shape of the ejecta, and a growing downrange gap (~200s AI).

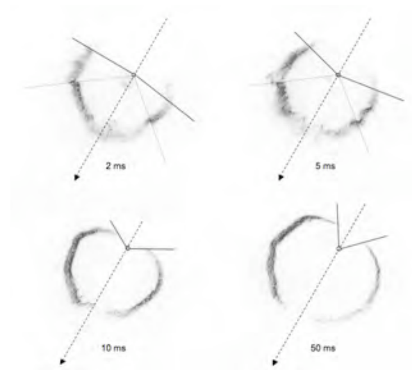

Figure 2. Evolution of uprange ZoA for a 30º impact into pumice at 1 km/s. Such asymmetry persists to later times for high porosity targets.

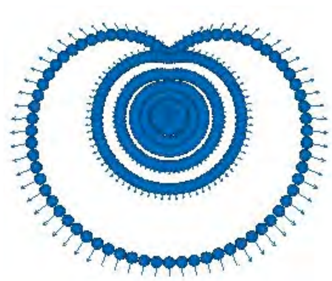

Figure 3. Cardioid shape of ejecta produced by asymmetries in the ejecta flow field from experimental oblique impacts using 3D-PIV[4].