LESSONS FROM KINETIC PROBES: DEEP IMPACT, LCROSS, AND DART. P. H. Schultz, Department of Earth, Environmental and Planetary Sciences, Brown University, 324 Brook St., Box 1846, Providence, RI, 02912 (peter_schultz@brown.edu)

Introduction: The highly successful DART Mission follows two other NASA missions designed to use artificial kinetic probes as tools for planetary exploration: Deep Impact on July 4, 2005 and LCROSS on February 14, 2010. This invited review compares and contrasts the objectives and results of these three missions with implications for the future.

Deep Impact: This was an audacious Discovery-Class mission [1] designed to send a 360 kg probe into a cometary nucleus at hypervelocities (10.2 km/s). Nothing like this had been done before on purpose (excepting the Ranger series to the Moon) and there were many challenges: establishing a high probability of hitting the nucleus, even though it could not be imaged until just before arriving; not knowing the properties (surface structure, density, shape, etc.) of a cometary nucleus; coordinating an international network of 35 observatories in order to ensure multiple observations in case of bad weather; designing the impactor so that it would not contaminate any observations; and not knowing the near-nucleus environment. The flyby spacecraft would document the collision using medium and high-resolution telescopes and IR spectrometer.

The first challenge seemed simple enough since there were already images of Halley's nucleus. But in 2001, *Deep Space 1* returned images of Comet 19P/Borrelly, which dramatically changed the working assumption. Rather than a nucleus resembling a shriveled kumquat, it was now possible that 9P/Tempel 1 resemble a bowling-pin-shaped gourd. Under some illuminations, such a body could actually resemble two separate objects, and the probability that the spacecraft could miss its target was raised to unacceptable levels. Hitting the nucleus was based on autonomous navigation software (used for DS-1) that would guide the probe based on the target body's brightness centroid [2]. As a result, JPL had to embark on a new series of hit and miss statistical strategies, which then seemed like a video game. Optimal pointing was finally based on an offset from the brightest area on the nucleus. The second challenge was the unknown nature of the body. One pre-encounter prediction was that the probe would compress the target and disappear below the surface with minimal ejecta [3]. This contrasted with other predictions based on a range of properties and impact angles that provided more optimistic predictions [4]. The third challenge was to have enough observatories committed to observing the collision, just in case the flyby spacecraft did not survive its approach due to collisions with objects near the nucleus. Later results from the recommissioned DI spacecraft (EPOXI mission) to visit another comet (Hartley-2) revealed that this concern was well founded: a flotilla of mini-nuclei ranging in size from cm to a meter [5]. In the end, almost every observatory was able to contribute to the observing campaign [6] while other NASA assets made observations that were only possible if taken from space, e.g., Spitzer [7].

Just like DART, DI carried a camera on the kamikaze probe that not only characterized the surface but also established the impact point and geologic setting. In contrast with the DART mission, however, the DI was designed to return images of the actual collision, along with mid-IR spectral data of the plume, volatiles, and ejecta [8]. This capability proved critical in order to understand the event. Key observations included the downrange vapor plume, the well-developed ejecta curtain, obstacles interacting with the excavation, and a reverse ejecta plume [9,10]. The reverse plume prevented seeing the crater at closest approach but it cast a long shadow on the inside of the ejecta curtain. Such a plume was one of the predicted scenarios for a low-density target. Rapid-sequence imaging at the moment of impact also revealed the evolution of the initial flash, which provided key insight into the porous nature of the upper surface [11]. The total amount of excavated ejecta has been estimated to be from 0.5 x 10^6 to 6 x 10^6 kg. Another mission (Stardust-NExT) returned to 9P/Tempel 1 in 2014 revealed what appeared to be a nested crater about 150 to 200 m in diameter. This illustrates one of the important lessons from the Deep Impact mission: the ability to observe before, during, and after the collision.

LCROSS: Unlike the DI mission, the *Lunar Crater Observation and Sensing Satellite* (*LCROSS*) was a NASA Center demonstration mission through the NASA Ames Research Center [12]. Its objective was to excavate material hidden in the permanent shadow areas within Cabeus crater near the lunar south pole with the entire upper stage of the Centaur rocket (~2300 kg) serving as the impactor with a high-angle approach (with respect to the surface) at 2.5 km/s. LCROSS was actually a stowaway; the Centaur was designed to carry the *Lunar Reconnaissance Orbiter* (LRO).

When the ejecta emerged from the shadows into sunlight, emission lines from free atoms and molecules would allow determining the amount and type of trapped volatiles embedded in the ice-laden regolith. Measurements would be made from trailing

"*Shepherding Spacecraft* (SSc)" that was attached to the giant Centaur until separating about 9 hours before impact. The little SSc had a suite of instruments including one visible, two near-infrared (Near-IR), two mid-infrared imagers, photometer, and the critically important spectrometers (one visible and two Near-IR), all "off-the-shelf" technologies selected to reduce costs. In contrast with mission control for Deep Impact at JPL, the command center at NASA Ames was a tiny side room with just a few engineers, PI and Co-I.

This was a risky mission because there were concerns: (a) contamination from any remaining rocket fuel; (b) site selection to maximize the probability of excavating water-ice; and (c) the ability to launch enough ejecta to reach sunlight. In order to mitigate the first concern, LCROSS orbited the earth for 37 days as it adjusted its trajectory for a polar collision. During this time, most of the remaining rocket fuel was vented and maneuvers were made to bake out any residual water. For the second concern, prior results and LRO observations (H abundance and temperatures) were used to select the best possible site for mission success. But this amplified the third concern: the selected site (highest H abundance) was deep in shadow, 833 m below sunlight. Consequently, a relatively small crater (20 m to 50 m diameter) would have to launch ejecta higher than about 900 m in order to come into sunlight. Models using nominal crater excavation scenarios predicted very little material could reach this altitude. Initially it was hoped that LRO could observe the impact, but mission safety required positioning it on the other side of the Moon. The deep shadow also meant that earth-based observations would be difficult, if not impossible. If the SSc were not able to make the measurements, LRO and back-up using telescopes on earth would not be available for Plan B and C. (NB: Nevertheless, the impact plume was actually imaged with a 3.5 m telescope [13]).

LCROSS also met its objectives [12]. First, the amount of residual water was found to be minimal in comparison to the estimated 23 ± 11 kg of water vapor reaching sunlight (not including any solid ice). Moreover, the impact speed was too low to generate significant shock-released atomic and molecular species. Second, the LCROSS collision was not a "nominal" impact. About two months before countdown, experiments at the AVGR used hollow aluminum spheres in order to provide a better simulation of the Centaur and its emptied fuel tank. These experiments revealed that the earliest high-speed ejecta would form a nearly vertical plume, as well as early-time near-surface scouring, in addition to the classic conical shaped ejecta curtain during later stages of excavation [14]. This sequence is exactly what was observed by the SSc [14-16]. Moreover, the observations of the collision revealed unexpected atomic species (e.g., Ag and various organic molecules) indicative of impactor-delivered volatiles as well as long-term impact-recycling of the lunar regolith.

Lessons for NASA DART and Beyond: The DART collision on Sept. 26, 2022 involved a lower mass (579 kg) impacting at an intermediate speed (6.14 km/s) at a high-angle impact. Just like DI and LCROSS, the objectives for DART exceeded expectations: (a) the target site was well imaged prior to impact, a critical observation for understanding the results; (b) the accompanying CubeSat (*LICIACube*) captured the evolution of ejecta (but from the other side); and (c) most importantly, earth-based observations established a significant change in the orbit of Dimorphos that exceeded expectations. In the case of DI and LCROSS, impact experiments played a major role not only in predictions but also in understanding the results. Although computational simulations were performed at that time, they were limited by range of variables (e.g., high-resolution 3D modeling), resolution of the codes, and general availability. In contrast, DART took full advantage of much more widely available advanced computational modeling of expectations and an international team of contributors. Even though both DI and LCROSS missions demonstrated that laboratory experiments could be successfully scaled, DART used experiments primarily used for code validation. A key and significant difference from DI and LCROSS, however, is that the collision was not actually witnessed. Although *LICIACube* provided important insight as it passed at a safe distance on the other side of the impact, both DI and LCROSS demonstrated the value of actually observing the evolution of the event. This would be especially important for complex targets and crater collapse that could can mask the final result. This may prove important for the planned return to Dimorphos in 2026.

References: [1] A'Hearn M. F. et al. (2005), *Science* 310, 258 (2005); [2] Mastrodemos N. et al. (2005), *Space Sci. Revs*.. 117, 95-121; [3] Housen K. R. et al. (1999), *Nature* 402, 155; [4] Schultz P.H. et al. (2007), *Space Sci. Revs*. 117, 207-239; [5] A'Hearn M. F. et al. (2011), *Science* 233, 1396-140; [6] Meech K. J. et al. (2005), *Science* 310, 265-269; [7] Lisse C. M. et al. (2006), *Science* 313, 635-640; [8] Sunshine J. M. et al. (2007), *Science* 311, 1453–1455; [9] Schultz P. H. et al. (2007), *Icarus* 191 (2), 184-122; [10] Richardson J. E. et al. (2007), *Icarus* 191 (2), 176-209; [11] Ernst C. M. & P. H. Schultz P. H.(2007), *Icarus*, 190, 334–344; [12] Coloprete A. et al. (2010), *Science* 330, 468-472; [13] Strycker P et al. (2013), *Nat Commun* **4**, 2620; [14] Schultz et al., (2010), *Science* 330, 463 –468; [15] Hermalyn B. et al. (2012), *Icarus* 218 (1), 654-665; [16] Heldemann J. L. et al. (2015), *Icarus* 254, 262-275.