A MODEL TO DETERMINE COMETARY PROPERTIES FROM THE EJECTA PLUME BEHAVIOR RESULTING FROM DEEP IMPACT.
J. E. Richardson[1] and H. J. Melosh[2], [1]Center for Radiophysics and Space Research, 310 Space Sciences Building, Cornell University, Ithaca, NY 14853, richardson@astro.cornell.edu; [2]Lunar and Planetary Lab, University of Arizona, Tucson, AZ 85721. jmelosh@lpl.arizona.edu.

Introduction: On July 4, 2005, the Deep Impact mission successfully collided a 366 kg impactor with the surface of 6 km diameter Comet 9P/Tempel 1, at an oblique angle of about 56^o from the regional surface normal and a collision speed of 10.2 km sec^{-1} [1]. This impact produced a cratering event which was directly observed by a flyby-spacecraft which passed within 500 km of the comet, in two viewing windows: an approach phase of observations, made from 0 to 800 seconds following the time of impact; and a look-back phase of observations, made from 45 to 75 minutes following the time of impact [2]. The solid-particle ejecta plume produced by this cratering event rapidly emerged from the impact site and expanded to form a highly visible, cone-shaped cloud of launched particles, which dominates many of the subsequent images. This prominent plume remained visibly attached to the comet's surface as it rapidly extended longitudinally (away from the comet's surface) and expanded laterally (along the comet's surface) over the course of the observations made by the flyby-spacecraft.

Project Goal: During the first 800 seconds following the impact, the hollow interior of the ejecta plume was viewed as the flyby-spacecraft approached the comet. During the look-back phase of observations, 45-75 minutes following the impact, the conical exterior of the ejecta plume was viewed as the spacecraft departed the comet [2]. These later, look-back images permit measurements of the ejecta plume's lateral expansion rate over a time span of nearly half an hour, and thus provide a quantitative means for estimating the magnitude of Tempel 1's gravity field. This is because the observed ejecta plume consisted of billions of tiny ejecta particles, each one following its own ballistic trajectory under the influence of Tempel 1's gravity field, and as such, the lateral expansion rate of the collective ejecta plume is also a function of the comet's gravity field [3]. When coupled with a shape model for comet Tempel 1 [4], a reasonable gravity estimate also permits an estimate of the comet's mass and bulk density.

The Model: This gravity estimate for Tempel 1 is made by developing a first-order, three-dimensional, forward model of the cratering event's ejecta plume behavior [5], and then adjusting the parameters of this model (over many iterations) to match the spacecraft observations of the actual plume behavior, image by image (Figs. 1 & 2). This forward model is, in turn, based upon the Maxwell Z-model [6] and Pi-Group scaling relationships [7,8,9] for cratering events. In addition to gravity and density estimates for comet Tempel 1, this model also permits us to estimate the particle velocity distribution and total mass ejected by the impact, and obtain a rough estimate of the comet surface's effective strength at the impact site.

Results: This modeling exercise reveals that Deep Impact produced a reasonably "well-behaved" oblique-impact cratering event: one in which the impactor-spacecraft apparently struck a small, westward-facing slope of roughly 1/3-1/2 the size of the final crater produced (determined from initial ejecta plume geometry), and possessing an effective yield strength of not more than Y = 1-10 kPa (estimated via two different methods). The resulting ejecta plume followed well-established scaling relationships for cratering in a medium-to-high porosity target material, consistent with a transient crater of not more than 85-140 m diameter, formed in 250-550 sec, for the case of Y = 0 Pa (gravity-dominated cratering), and not less than 22-26 m diameter, formed in 1-3 sec, for the case of Y = 10 kPa (strength-dominated cratering). At Y = 0 Pa, an upper limit to the total ejected mass of 1.8 x 10^7 kg (1.5-2.2 x 10^7 kg) is consistent with measurements made via long-range remote sensing, after taking into account that 90% of this mass would have stayed close to the surface and then landed within 45 minutes after the time of impact. However, at Y = 10 kPa, a lower limit to the total ejected mass of 2.3 x 10^5 kg (1.5-2.9 x 10^5 kg) is also consistent with the remote sensing measurements: making this result somewhat ambiguous. The expansion rate of the ejecta plume imaged during the look-back phase of observations leads to an estimate of the comet's mean surface gravity of g = 0.34 mm sec^{-2} (0.17-0.90 mm sec^{-2}), which corresponds to a comet mass of m_t = 4.5 x 10^{13} kg (2.3-12.0 x 10^{13} kg) and a bulk density of ρ_t = 400 kg m^{-3} (200-1000 kg m^{-3}), consistent with the bulk densities estimated for other cometary nuclei, and where the high-end error is due to uncertainties in the magnitude of coma gas pressure effects on the impact ejecta particles in flight.

References: [1] A'Hearn, et al (2005). *Science*, **310**, 258-264. [2] A'Hearn, et al (2005). *Space Science Rev.*, **117**, 1-21. [3] Melosh, J.H. (2001). *32nd Lunar & Planetary Sci. Conf.*, 2135. [4] Thomas, P.C., et al (2007). *Icarus*, **187**, 4-15. [5] Richardson, J.E., et al (2005). *Space Science Rev.*, **117**, 241-267. [6] Maxwell D. & Seifert K. (1974) *Report DNA 3628F, Defense Nuclear Agency*, Washington, D.C. [7] Holsapple, K.A. (1993). *Annual Rev. Earth and Planetary Sci.*, **21**, 333-373. [8] Housen, K.R., et al (1983). *J. Geophys. Res.*, **88**, 2485-2499. [9] Richardson, J.E. (2007). *38th Lunar & Planetary Sci. Conf*, 1345. [10] Lisse, C.M. et al (2006). *Science*, **313**, 635-640.

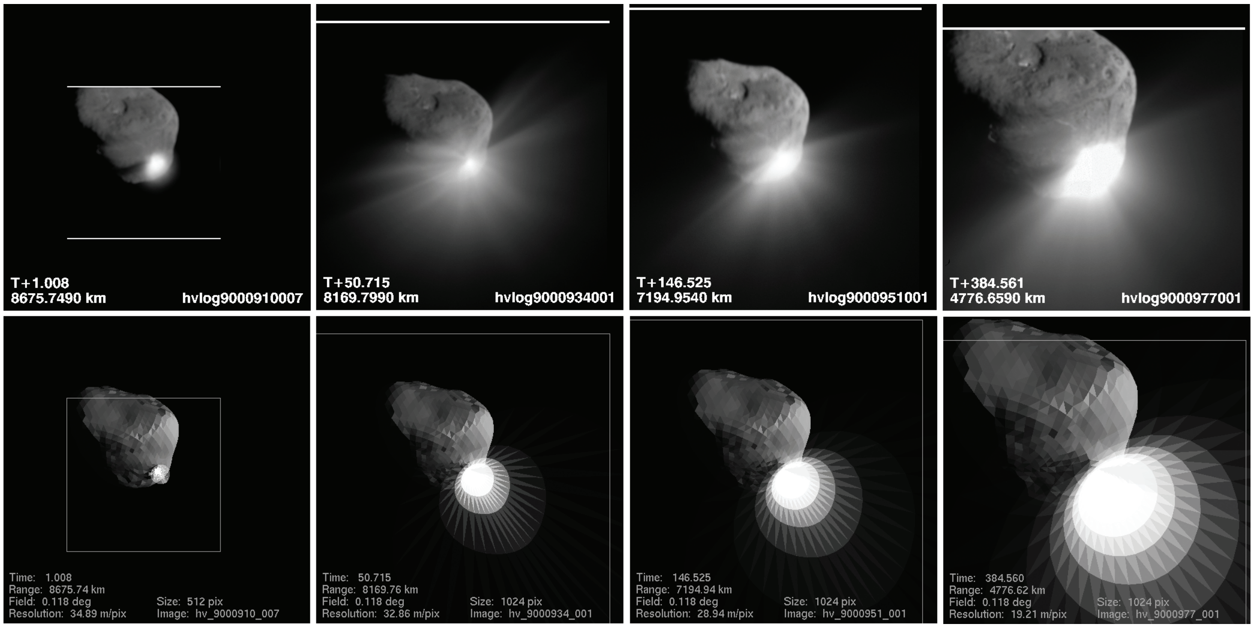

Figure 1: Deep Impact image sequence, part 1: a comparison between the actual HRI image sequence (*Upper Images*) and the best-fit modeled image sequence (*Lower Images*), using a Spitzer-based particle size distribution [10]. The two pairs of images on the left show the early interior view of the ejecta plume (phase 1), while the two pairs of images on the right show a near edge-on view of the plume's west (upper left) side (phase 2).

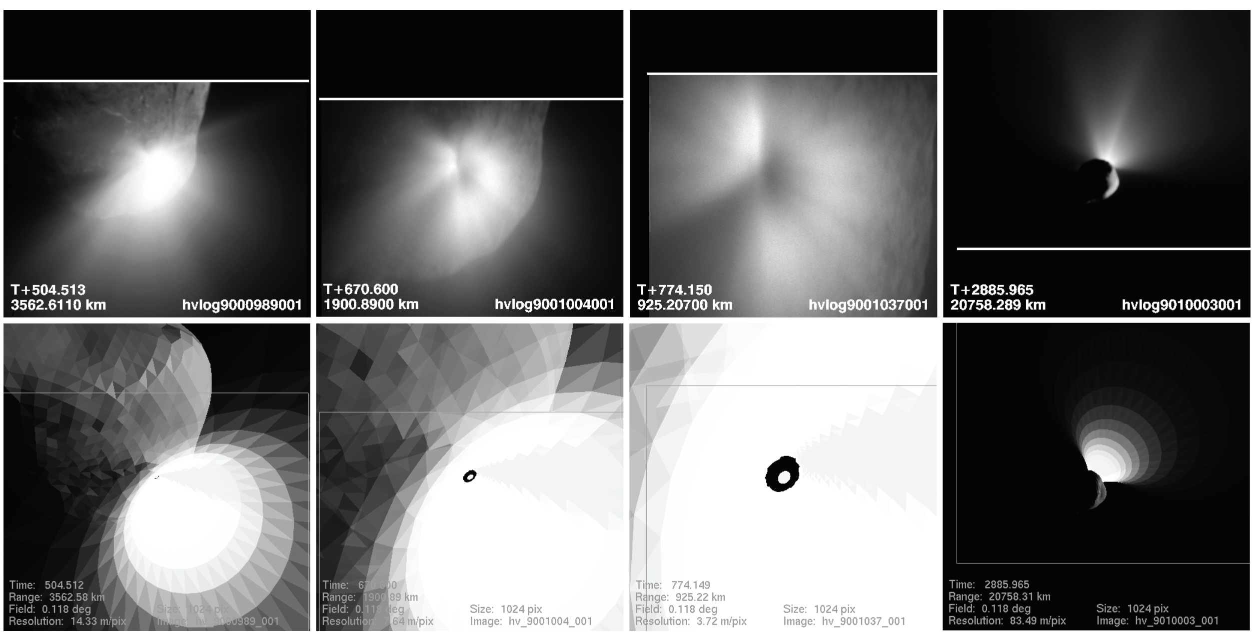

Figure 2: Deep Impact image sequence, part 2: a comparison between the actual HRI image sequence {*Upper Images*) and the best-fit modeled image sequence (*Lower Images*). The first pair of images on the left show the beginning of the transition from an edge-on view of the plume's west side (phase 2) to the late interior view of the plume's dark, oval base (phase 3), shown in the middle two pairs of images. The small grey circle near the center of the middle two synthetic images marks the impact crater, which the actual (upper) images failed to resolve due to obscuring dust. The final pair of images on the right show the beginning of the look-back phase of observations (phase 4).