DEEP IMPACT: THE FIRST SECOND. H. J. Melosh and the Deep Impact Team, Lunar and Planetary Lab (University of Arizona, Tucson AZ 85721, jmelosh@lpl.arizona.edu).

Introduction: The Deep Impact spacecraft hard-landed on the surface of comet Tempel 1at about 05:44:36 UTC on 4 July 2005 [1]. The earliest stages of the impact event were recorded in a series of 64 x 64 pixel subframes of the MRI (Medium Resolution imaging) camera system. Each exposure lasted about 51 msec and the field of view was nearly centered on the impact site, thus catching the earliest phases of the impact process. These frames witnessed the beginning of the conical ejecta plume's expansion. In addition, they caught the expansion of a cloud of incandescent, probably liquid silicate, droplets that sprayed away from the impact site

The Impact "Flash": The first indication of the impact was a tight group of bright, but not saturated, pixels centered on a single pixel (an area of roughly 80 m x 80 m on the comet's surface). In the next two frames the bright spot expanded from one to about four pixels in width, still not saturated. Then, in the frame exposed about 0.22 seconds after the impact, a group of 26 adjacent pixels became saturated and the image indicated bleeding of the electrons from the brightest wells in the CCD into adjacent wells. The brightness declined in subsequent images and an elongated, parachute-shaped, arc of bright material appeared downrange from the impact site while a bright, probably conical, plume of opaque material rose behind the arc and cast a prominent shadow on the comet's surface (Figure 1). The leading edge of the arc moved very rapidly, with an apparent velocity in the plane of the sky of approximately 4.8 km/sec (if the arc material is assumed to ricochet from the surface at an angle equal to the approach angle of about 30°, then it moved toward the camera at an angle of about 60° out of the viewing plane, implying an actual velocity of 9.6 km/sec relative to the initial bright pixel, similar to the velocity of the impactor itself). The arc also expanded in breadth at a velocity that is more difficult to define because of its changing shape, but appears to be roughly 3.3 km/sec. Although the arc expanded at constant velocity, within measurement errors (roughly ±100 m), extrapolation back to the origin suggests that expansion began about 0.1 sec *after* the first bright pixel was observed. This period of time is far too long to represent expansion of an initial hot volume of gas (this time scale is only a few ms, according to hydrocode simulations of an expanding sphere of SiO_2 vapor) and must therefore reflect the interval during which the impactor entered the surface and deposited its energy.

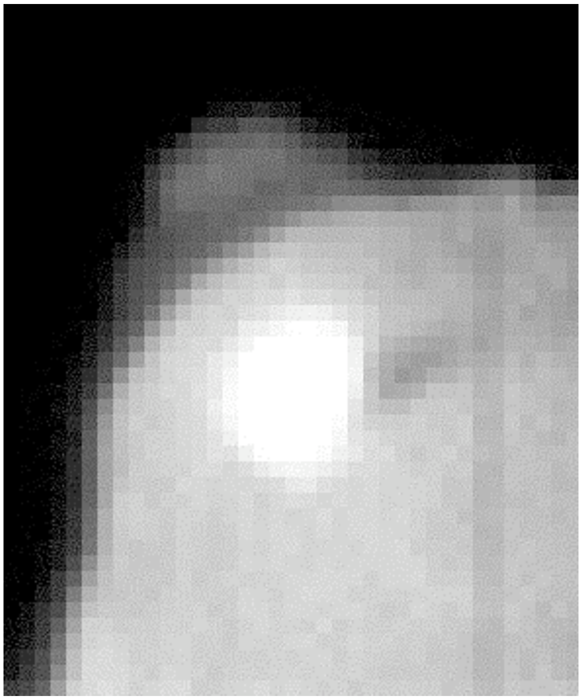

Figure 1. A fast-moving, parachute-shaped arc of incandescent material precedes the bulk of the impact ejecta 0.46 seconds after the first light recorded from the impact. The comet and the plume in this reproduction are slightly overexposed to highlight the arc in the upper portion of the image, just beyond the comet's limb. Portion of MRI frame mv9000910071.

Glowing Melt Droplets: Analysis of the brightness of the central region in this arc indicates that the initial brightness declined much too rapidly to represent the expansion of a cloud of particles reflecting sunlight. Only later, about 0.42 sec after impact, does the brightness decline as a function of t^{-2} (Figure 2), as expected for an optically thin cloud of dust expanding at constant velocity (the average density of such a cloud declines as t^{-3}, but the optical path length increases as t). However, the observed decline is consistent with blackbody radiation emitted from a cloud of incandescent liquid droplets expanding at a radial velocity of 1.7 km/sec (if this were the cloud's radial expansion velocity, then the leading edge velocity of 9.6 km/sec implies that the center of mass of the arc material moved at about 7.9 km/sec—in fair agreement with the apparent velocity of the arc's center of brightness).

Figure 2 indicates good agreement between the expected central brightness of a cloud of 150 µm diameter particles and the observed arc. The brightest point plotted (indicated by a ? symbol) is the overexposed frame, and the plotted brightness equals 26 times the saturated brightness of a single pixel, so probably underestimates the true brightness. The next brightest pixel was saturated, and is thus only a lower limit. The model, whose detailed parameters are described in the figure caption, is a good fit to all of the subsequent data, until the arc is lost in the background, about 1 second after the impact.

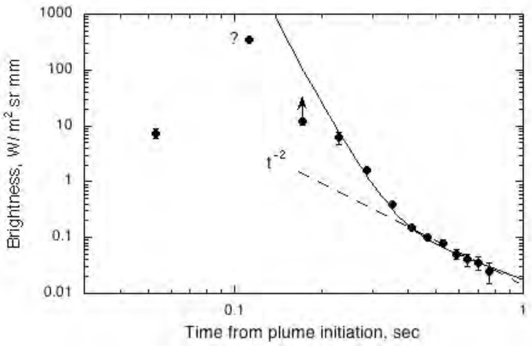

Figure 2. The central brightness of the expanding arc initially declined more rapidly than the t^2 law (dashed line) expected for a cloud of particles illuminated by sunlight. The points are measured from the calibrated MRI frames mv9000910066-78 (clear filter, 51 msec exposure). The data are well fit by a model that includes blackbody emission from a cloud of incandescent particles, up to a time of 0.42 sec, after which the brightness is consistent with reflected sunlight. The continuous curve shown is the brightness expected in the clear filter passband of the MRI camera system from a 4000 kg cloud of 160 µm diameter incandescent spherical liquid silicate droplets, density 2500 kg/m^3, expanding at a radial velocity of 1.7 km/sec. The initial temperature is 3500 K, and the droplet's albedo is 0.1. The droplet's temperature falls to about 1000K at the bend of the curve, where incandescence fades into the reflected sunlight. With these parameters the cloud becomes optically thin 0.03 second after the plume expansion begins, so it is transparent in all of the images except perhaps the first.

We conclude that the parachute-shaped bright arc that expanded rapidly away from the impact site during the first second after contact was an incandescent cloud of condensed, probably liquid, droplets that cooled from an initial temperature of about 3500 K down to 1000 K after about 0.42 second. It remained in view for another 0.4 sec, illuminated by reflected sunlight. Assuming an albedo of 0.1, appropriate for mafic silicate liquids, the total mass of the droplets was about 4000 kg. Because this is 10 times the mass of the impactor, we assume that the glowing material originated mainly from the comet and is thus probably silicate in composition. The delay in the peak brightness may represent the interval between formation of the hot vapor beneath the surface of the comet and its appearance at the surface. This delay, however, is one of the current mysteries of the impact event. The interval is too long for mere burial of the projectile in the target, or ricochet of projectile out of the crater. So what is happening during this interval?

Droplet Evaporation? An important question is whether such small liquid droplets could survive against evaporation long enough to cool below incandescence. An analysis using the Hertz-Knudsen equation and the evaporation kinetics of Forsterite [2] indicate a very short evaporation time of 0.01 second at the highest temperature of 3500 K. At this early stage the liquid must have been in equilibrium with its vapor at a pressure of a few bars. However, once it cools to about 3000 K the evaporation time drops to 0.1 second, and at 2700 K it is longer than the time over which the plume was observed. Thus, most of the expansion may have taken place while the droplets were in near-vacuum, the vapor pressure of the silicate being too small to prevent the relatively slow evaporation of the now-glassy mafic droplets.

References:

[1] A'Hearn, M.F., *et al.* (2005) *Science* **310**, 258.
[2] Hashimoto, A. (1990) *Nature* **347**, 53.