GRAVITY OR STRENGTH? AN INTERPRETATION OF THE DEEP IMPACT EXPERIMENT.

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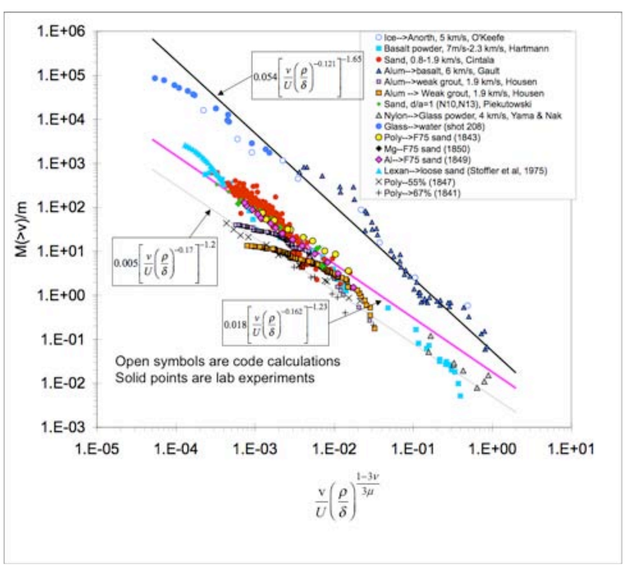
Introduction: We apply recently updated scaling laws for impact cratering and ejecta to interpret observations of the Deep Impact collision with Tempel 1. An important question is whether the cratering event was gravity or strength-dominated; the answer gives important clues about the properties of the surface material of the comet. Gravity scaling was assumed in pre-event calculations and predictions ([1], [2]) and has been asserted in initial interpretations of the mission results (e.g. [3]). Because the gravity field of Tempel 1 is extremely weak, a gravity-dominated event necessarily implies a surface with negligible strength.

The conclusion of gravity scaling was based in part on the interpretation that the impact ejecta plume remained attached to the comet during its evolution. We address that feature here, and conclude that even strength-dominated craters would result in a plume that appeared to remain attached to the surface. We then calculate the plume characteristics from scaling laws for a variety of material types and for gravity and strength-dominated cases.

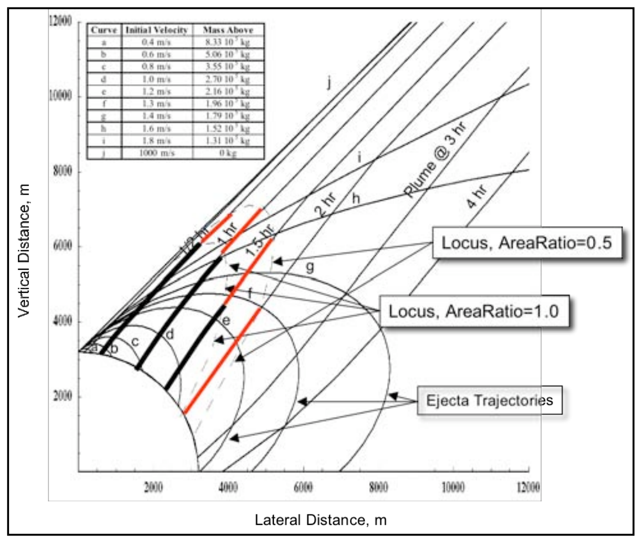
Ejecta Scaling Laws: The figure below (Housen and Holsapple, unpublished) presents a variety of data for the amount of ejecta in various conditions and materials. The data fall into four distinct groups. The first are dry soils: dry sand, lunar regolith and dry terrestrial desert alluvium. The second are non-porous materials: wet soils and rocks. The third is water, which is non-porous and has no strength. The fourth are materials with porosity larger than *~50%*.

We used these data to model the properties of the plume for various assumed material types for the



comet. We consider strength values from the almost negligible 50 Pa, the 3-12 kPa values for lunar regolith, and the 65 kPa strength of terrestrial desert alluvium.

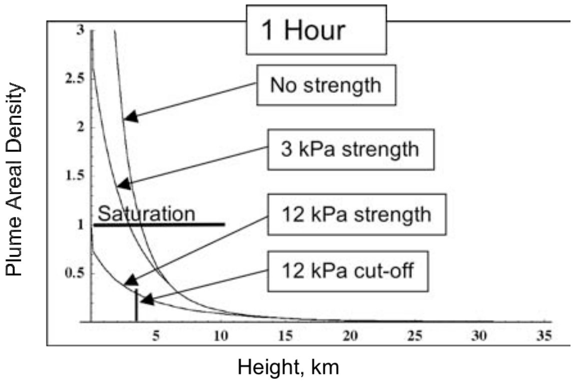
The Ejecta Plume, Sand Gravity Scaling: The characteristics of the ejecta plume can be found from simple ballistics and the initial velocities of the ejected material given by the scaling laws. The following typical figure, for zero-strength sand gravity scaling, shows the arcs of particle trajectories, the positions of the plume at different times. The legend shows the mass above each trajectory curve. For the speed and mass of the DI Impactor, the total mass of ejecta would be *1.1* 10^7 *kg*, although 90% of it would land within the first 20 minutes, and only 4% would remain aloft at *1 hr*.



The plume appearance can be estimated by calculating the "plume thickness", i.e. the ratio of the total particle cross-section areas to the spatial area the particles occupy. That is a measure of the opacity of the plume. The next figure shows the plume thickness at a time of *1 hr.* for a representative particle size distribution with maximum particle size of 10 μm. Near the surface, the plume is opaque, or "saturated", because the areal density is greater than unity.

The Ejecta Plume, Strength Scaling: For the case of a surface with strength, the same calculation gives a different result. At the *1 hr* time, the figure below shows the plume thickness for a material with *3 kPa* and *12 kPa* strength compared to the zero-strength gravity case.

Two differences are significant. The first is the much lower plume areal density closest to the surface



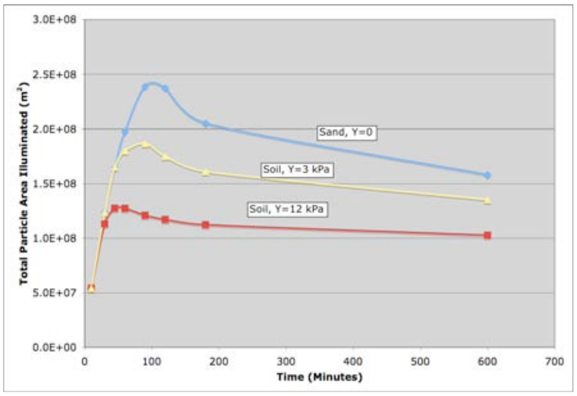
compared to the zero-strength sand case. Note however, that because of the near-surface saturation, the zero-strength case and the case of 3 kPa would be essentially indistinguishable at this 1 hr time.

Second, for the material with 12 kPa strength, a "strength cutoff" limit is indicated. Such a cut-off has been adopted by others (2). It is a consequence of using an idealized mass v. velocity relation from the ejecta scaling illustrated above that follows a power-law curve to a lowest velocity, and simply truncates there, without allowing any slower-moving material plotting below the power-law. That assumption results in a lower velocity limit for the ejecta, which is 1.7 m/s for this 12 kPa case. Then, at the 1 hr time, there would be no material below a height of 3.1 km. This cutoff has been used to conclude that, for a material with strength, the plume would detach from the comet surface.

In fact, experiments of the above ejecta data show, instead of a simple truncation, a gradual bend-over with significant mass (in fact, the *majority* of it) at lower velocities. For this 12 kPa strength, the ejecta velocities are as low as 0.4 m/s, meaning that the plume would reattach by 23 minutes, before the spacecraft was able to look back at the plume. So, even with the strength of 12 kPa, the plume would be attached to the comet surface for all times after about the first 20 minutes, and prior to that the height of separation is small and would be nearly impossible to observe.

If plume attachment cannot distinguish between gravity and strength scaling, then one must look to other aspects of the observations to make the choice.

Brightness v. Time: The observable "brightness" of the entire plume (or of any view window) at any time can be estimated from the total observable area of particles that can reflect light. The next figure shows that brightness measure as a function of time for the cases of zero, 3 kPa and 12 kPa cohesion. Because of the saturated opaque region, there is no essential difference in these three cases until about 20 minutes. Thereafter, the zero strength case continues to grow in brightness (because mass continues to exit the non-opaque region of the plume), but it does not reach its maximum until almost 2 hours. The 12 kPa case



peaks at about 30 minutes, and falls to about 1/3 of that to a time of 10 hr. For the assumed particle size distribution, the observable *mass* (*kg)* is about 10^{-3} times the areas shown.

Comparison to Observations: The actual plume appearance, shape and brightness have been measured in a number of ways at different wavelengths, from ground and space-based stations. Unfortunately, the pixel sizes are on the order of 100 *km*, so very little detail could be seen. The observations lead to estimates for total plume mass, brightness versus time, and brightness versus distance, generally for 100 km ranges and beyond. All of these observations, compared to the results for cratering, require that most of the plume mass was accelerated to much higher velocities during the process than the velocities of cratering ejection. That is, comet-like acceleration mechanisms are required to move the ejected mass to 100 km ranges in a few-hour time frame. But if there were such mechanisms, then up to *all* of the ejected mass could be transported to large ranges over an hour or two and observed. Then, to within the large uncertainties in particle sizes, albedo, ejecta scaling and so forth, any of the above strength cases, from 0 to 12 kPa, could furnish the amounts of total mass estimated. So, either gravity or strength craters can be consistent with the observations. Thus, the observations to date do not discern between the relative importance of strength and gravity in the DI event.

References:

[1] Schultz, P. H., Ernst, C. M., Anderson, J. L. B., 2005. Space Science Reviews 117, 137:160. [2] Richardson, J. E., Melosh, H. J., Artemeiva, N. A., Pierazzo, E., 2005 Space Science reviews 117: 241-267.[3] A'Hearn, M. F, Belton, M. J. S. , Delamere, W. A. , and 29 others, 2005. Sciencexpress, Sept 8.