DEEP IMPACT: A LARGE-SCALE ACTIVE EXPERIMENT ON A COMETARY NUCLEUS

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Abstract. The Deep Impact mission will provide the first data on the interior of a cometary nucleus and a comparison of those data with data on the surface. Two spacecraft, an impactor and a flyby spacecraft, will arrive at comet 9P/Tempel 1 on 4 July 2005 to create and observe the formation and final properties of a large crater that is predicted to be approximately 30-m deep with the dimensions of a football stadium. The flyby and impactor instruments will yield images and near infrared spectra (1–5 μm) of the surface at unprecedented spatial resolutions both before and after the impact of a 350-kg spacecraft at 10.2 km/s. These data will provide unique information on the structure of the nucleus near the surface and its chemical composition. They will also used to interpret the evolutionary effects on remote sensing data and will indicate how those data can be used to better constrain conditions in the early solar system.

Keywords: comets, space missions, solar system formation, craters, chemical composition

1. Introduction and History

The Deep Impact mission was conceived as a proposal to NASA's Discovery Program because we know so little about cometary nuclei and because missions that either land or do remote sensing cannot easily make measurements far enough below the surface to have a chance to characterize primitive cometary material. When the comets formed 4.5 Gy ago, they formed at very low temperatures from a mixture of different ices that is expected to be very sensitive to the actual temperatures at which they formed (e.g., Bar-Nun and Laufer, 2003; and references therein). The comets also included a mixture of more refactory materials including a broad range of both organics and silicates (e.g., Langevin *et al.*, 1987), Because the comets are small ($<$100 km), whether they formed at their present sizes or represent fragments of somewhat larger Trans-Neptunian objects, they have not been subject to much internal heating and they therefore preserve a record of conditions in the outer half of the protoplanetary disk. On the other hand, the surface layers of comets have evolved (see Section 2.3), in some cases due to solar heating at previous perihelion

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passages and in other cases due to irradiation by galactic cosmic rays. The European Space Agency's Rosetta mission is now on its way to place a lander on the nucleus of comet 67P/Churyumov-Gerasimenko (up-to-date information on the status of this mission can be obtained in the internet at http://www.esa.int/export/esaMI/Rosetta). The Rosetta lander, which will probe into the uppermost meter of the nucleus, was an enormous engineering challenge because of the uncertainty in the cometary properties. The concept of Deep Impact arose while thinking about how to make measurements far enough below the evolved surface materials to have a substantial chance to probe cometary material that is essentially unchanged since the formation of the solar system 4.5 Gy ago. With current technology, the only method for sampling this material is to excavate a crater and this is the experiment of Deep Impact.

The primary goal of Deep Impact is to understand the differences between the material at the surface of a cometary nucleus and the material in the interior in order to understand the evolutionary processes that have taken place in the surface layers. These processes occur typically at previous perihelion passages (the companion paper by Yeomans *et al.* (2005) provides a detailed discussion of the orbital dynamics of our target comet). The material in the deep interior is expected to retain much of the original molecular abundances from the formation of the comet 4.5 Gy ago but theoreticians (Section 2.3) disagree about the depth to which this evolution has penetrated.

The general concept of Deep Impact is to recreate, using an artificial impactor, a process that occurs regularly throughout the solar system, namely the impact of one body into another. The impactor is a fully functional spacecraft that flies attached to the flyby spacecraft until 1 day prior to impact. When comet D/Shoemaker-Levy 9 (hereafter S-L9) was about to impact Jupiter (Chodas and Yeomans, 1996), astronomers worldwide made a wide range of predictions and carried out extensive observational programs aimed at better understanding both the nature of the comet and the nature of the Jovian atmosphere below the clouds. The biggest limitation in studying the Jovian atmosphere was in fact the huge lack of knowledge about the impacting bodies, not only the chemical composition (e.g., Crovisier, 1996; Lellouch, 1996) but even the size (Sekanina, 1996) of the impactors. Deep Impact is intended to impact a comet such that everything is known about the impacting body and the only unknowns are the properties of the comet itself. The scientific basis for the mission was first laid out by Belton and A'Hearn (1999).

Prior to the Apollo program, the series of Ranger missions impacted the moon in order to provide close-up photographs of the surface prior to manned missions to the moon. Deep Impact's impactor will take an analogous series of images. During the Apollo program, nine large impact experiments were carried out to study the seismic properties of Moon (Nakamura *et al*., 1982; see also the summary by Cook, 1980). These experiments delivered kinetic energies to the moon that range from 20–200% of the energy that Deep Impact will deliver. A similar mission concept to an asteroid was described by Clarke (1968), although this was not in our thinking at the time

Deep Impact was conceived. The actual heritage of Deep Impact, came in part from an early, unpublished, concept study led by M. Neugebauer (M.J.S. Belton, personal communication) for JPL as part of the work for the Comet Rendezvous Asteroid Flyby (CRAF) mission that was subsequently cancelled. Although, in that study, a hypersonic impact was not envisioned. Prior to the selection of Deep Impact by NASA, other proposals for impact experiments had been rejected on technical feasibility grounds or have failed. Since the selection of Deep Impact by NASA, there have been additional proposals to NASA's Discovery Program for other types of impact experiments on asteroids.

2. What We Don't Know

2.1. Mass and Related Parameters

It is not widely realized outside the community of cometary scientists, that we do not have a single, direct measurement of the mass of a cometary nucleus. That means, of course, that we do not have a single direct measurement of the density. Several investigators, beginning with Rickman *et al.* (1987), have cleverly used the measured, non-gravitational acceleration of comets together with models for the outgassing to deduce the masses of some nuclei, but the results are still very model dependent (a more detailed discussion of nuclear mass and density is given in a companion paper by Belton *et al.*, 2005). In the most recent case of comet 19P/Borrelly, for example, the location of the strongest active area on the surface and the orientation of the rotational axis are reasonably well known. Nevertheless, two independent determinations of the mass of Borrelly based on the same measured accelerations yield very different numerical results with reasonably large and only partially overlapping error bars (Farnham and Cochran, 2002; Davidsson and Guitérrez, 2004). All of the recent determinations, however, yield densities between 0.1 and 1.0 $\mathrm{g\,cm^{-3}}$, suggesting that cometary nuclei are porous, unless there is some still unidentified flaw in the approach using non-gravitational accelerations. The degree of porosity, however, depends critically on the ratio of ices to silicates, since these two components have different bulk densities. The ice-to-silicate ratio is also unknown. Estimates of dust-to-gas ratios by mass in cometary comae are currently tending to be of order unity or larger for typical comets, but this is model dependent, and the ratio in the coma is not necessarily representative of the ratio in the nucleus. The gas and dust coma of 9P/Tempel 1 is discussed in detailed in the companion paper by Lisse *et al.*, 2005.

2.2. Structural Properties

The structural strength is also unknown with one prominent exception. The tensile strength, at least on spatial scales of a kilometer or so, must be $<10^3\ \mathrm{dyn\,cm^{-2}}$ on the basis of the tidal fragmentation of S-L9 (Sekanina, 1996). The distribution of the fragments of S-L9 has been very well described by models that assume reaccretion of 100-m fragments, suggesting but not proving that the tensile strength is comparably small at 100-m spatial scales. It remains to be seen whether the strength becomes large for scales somewhat below 100 m, or for scales of 1 m or 1 cm or even less. The presence of a large quantity of debris detected during radar observations of near-Earth-approaching comets IRAS-Araki-Alcock (Harmon *et al.*, 1989) and Hyakutake (Harmon *et al.*, 1997) suggests that chunks of order 10 cm must have sufficient strength to be lifted by hydrodynamic or other forces. The spontaneous fragmentation of comets when far from any source of tidal stress (Sekanina, 1997) indicates that they are generally very weak on some scales, but without understanding the mechanism for spontaneous splitting, it is impossible to obtain strengths quantitatively. These numbers might be compared with numbers like 10^6 dyn cm^{-2} for solid ice and 10^8 dyn cm^{-2} for rock measured in the laboratory (both materials are usually much weaker on large geophysical scales). In addition to tensile strength, of course, there are other strengths that matter, including shear strength and strength against compression. Again, these are not known, although one commonly assumes that these strengths are also small in the case of cometary material. Further discussion of this topic can be found in Belton *et al*. (2005).

Closely related to this question is whether the structure, and thus the strength, has a characteristic size resulting from the original formation process. For example, Weidenschilling (1997) has suggested that cometary nuclei are made up of primordial cometesimals with preferred sizes in the range of 10–100 m. If this is correct, one expects significant changes in strength at this characteristic scale.

2.3. Differentiation and Evolution

Another interesting characteristic of cometary nuclei is that it is widely assumed that they must be differentiated, either primordially from extinct radio-nuclides (not very likely in our view based on the available evidence) or more recently from the effect of insolation at previous perihelion passages (see Belton *et al.*, 2005 for further discussion). Regrettably there are essentially no data to show this differentiation. In fact, the only differentiation that is well documented is in the outermost layer of Oort-cloud comets arriving in the inner solar system for the first time. These dynamically recognizable comets are also photometricly recognizable, brightening as r^{-2} as they approach the sun, a much shallower variation than exhibited by any other comets, including these same dynamically new comets as they recede from the sun (Whipple, 1978). This photometric behavior is generally attributed to the irradiation by galactic cosmic rays of the outermost layer of cometary nuclei beyond the heliopause, resulting in a highly chemically unstable layer that is blown off at some large heliocentric distance on the first approach to the inner solar system.

Evolution and differentiation during previous perihelion passages have been extensively studied with numerical simulations, but there are few data to constrain the models (see also the companion paper by Belton *et al.*, 2005). As a result, the simulations exhibit a wide range of depths to which the evolution proceeds and also a wide range in the variation of chemical and physical properties with depth. The evolution and differentiation are sensitive to the ice-to-dust ratio, the porosity of that mixture, the volatility of the ices, the mean free path of a vaporized ice molecule inside the pores, and so on. There are relatively few constraints on the models although some investigators have, for example, tried to reproduce the variation of brightness with heliocentric distance for Jupiter-family comets (e.g., Benkhoff and Huebner, 1995; Prialnik, 2002). The observations at radio wavelengths of many different species in comet Hale-Bopp show dramatic and systematic variations in relative release/production rates for different species as shown in Figure 1 (Biver

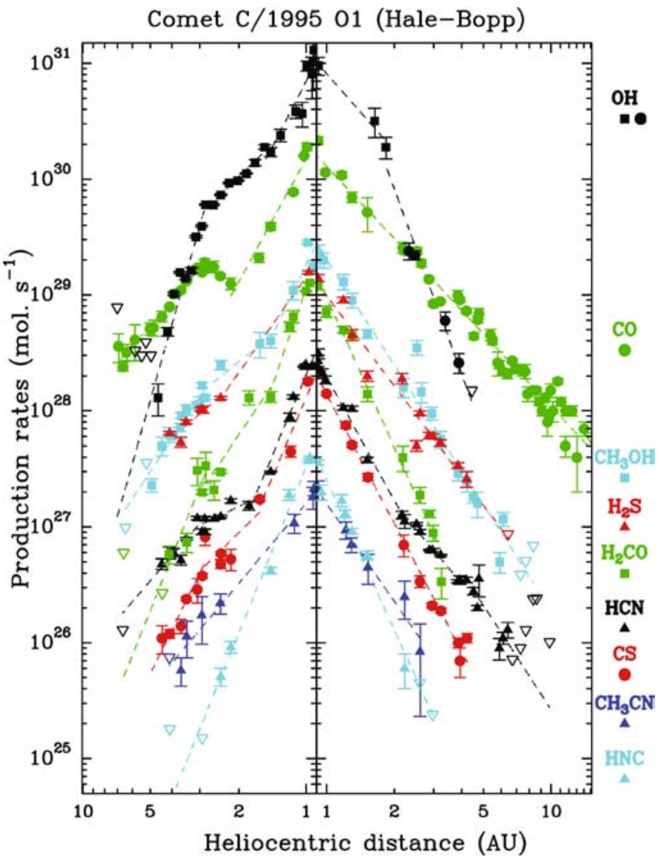

Figure 1. Molecular production rates by comet Hale-Bopp as a function of heliocentric distance both pre- (left half of diagram) and post-perihelion. Relative abundances vary systematically with distance suggesting either differentiation or processes in the coma. Diagram courtesy of Nicolas Biver (Biver *et al.*, 2002).

et al., 2002). This could be due to chemical reactions in the coma (proposed for HNC relative to HCN by Irvine *et al.*, 1997), or due to differentiation of volatiles in the sub-surface at some time prior to the observations, such as at the previous perihelion passage, or due to a differentiating process that was active at the time of the observations. These data might provide useful constraints on the differentiation in the nucleus, but detailed models to fit these data are still lacking.

A key issue in the modeling is the depth to which the evolution has penetrated. The cosmic ray irradiation of dynamically new comets from the Oort cloud is thought to have penetrated tens of meters (Moore *et al.*, 1983). For the comets of interest to Deep Impact (Jupiter-family comets, originally from the Kuiper belt), the depth of evolution is more uncertain. At the shallow extreme is the prediction of Kouchi and Sirono (2001).

2.4. End States

The ultimate evolutionary fate of comets after many perihelion passages is not known. Statistical studies of dynamical evolution suggest that some comets, particularly Oort-cloud comets, must disappear due to physical evolution before dynamical processes have time to eject them either out of the solar system or into a planet or the sun, but the nature of that evolutionary end-state is not known. The nuclei could either dissipate like comet LINEAR (C/1999 S4; see, e.g., Weaver *et al.*, 2001) or they could become inert and thus apparently asteroidal, much like the apparently dead cometary nuclei discussed by Fernández *et al.* (2001). If the latter is the dominant mechanism, there is a further question, namely whether the nuclei become inert because they have exhausted their supply of volatile ices or because they have developed a mantle that seals the volatile ices inside.

3. What Other Missions Are Doing

The 1990s led to a wide suite of missions to comets (and asteroids), ranging from the technology demonstration mission Deep Space 1, which flew past 19P/Borrelly, to ESA's mission that is *en route* to a rendezvous with 67P/Churyumov-Gerasimenko in 2014. The Stardust mission flew through the coma of 81P/Wild 2 and will return dust grains from the coma to Earth in January 2006. The ill-fated CONTOUR (the final status of the CONTOUR mission is available on the web at http://discovery.nasa.gov/contour.html) was slated to fly past two (a third was reduced in scope due to cost) comets with very different dynamical histories and possibly fly to a 'new' comet to assess what diversity exists in their physical and chemical properties and to put quantitative constraints on the origins of such diversity. The Rosetta Lander will sample material to depths of about a meter at the landing site and the CONSERT experiment (Barbin *et al.*, 1999). will perform radioabsorption sounding through the nucleus between the orbiter and the lander. The surface experiments are clearly important but they are limited in depth ($\sim$1 m) and/or spatial ($\sim$2 m) resolution and may not fully characterize the evolutionary processes of chemical and physical differentiation that are expected to occur. Most importantly, they will not be carried out for another decade. Deep Impact will be the first mission to sample to substantial depths (10–30 m) into the subsurface of a cometary nucleus. It is striking that a wide variety of missions to comets still allows each mission to address quite different scientific goals, a testimony to the progress that can be made in the field by means of a series of narrow missions, particularly when we know so little about cometary nuclei.

Differences among the topographies of cometary nuclei are obvious from the very limited sample of three comets for which we have *in situ* imaging. Wild 2 is clearly more nearly spherical, although the deduced semi-axes imply that it is really best described as a triaxial body (Duxbury, cited by Brownlee *et al*., 2004) than either 19P/Borrelly (Oberst *et al.*, 2004; Kirk *et al.*, 2004) or 1P/Halley (Merényi *et al.*, 1990), and it also has much greater vertical relief at scales $<$1 km than does Borrelly (Brownlee *et al*., 2004). Whether this is an evolutionary effect related to lowering of the perihelion distance of Wild 2 only a few apparitions earlier is unknown. Borrelly and Halley have both had many perihelion passages well within the orbit of Mars and they show substantial differences, Halley being nearly convex except for a narrowing at what might be termed the waist (Merényi *et al.*, 1990) while Borrelly has large-scale concavity on the side that was imaged. Thus the one technique, optical imaging, that is common to essentially all missions, shows substantial differences among comets that are not readily explained. Variations in gross shape for other comets are also inferred from the wide range of amplitudes observed for lightcurves if they are interpreted as being due to the varying cross-section of the nucleus as it rotates.

Finally, we note that Wild 2, for which we have the most complete set of images, shows many topographic features, some of which are nearly circular and may be impact craters, but which do not look like impact craters elsewhere in the solar system (a discussion of topography including our views of the enigmatic circular features on Wild 2 can be found in the companion paper by Thomas *et al.*, 2005). Deep Impact will provide at least one example of a crater that is known to be an impact crater and thus provide an important point of comparison for the craters on Wild 2.

4. Overview of Deep Impact

Deep Impact is the eighth mission in NASA's Discovery Program. It was proposed and accepted as a partnership between the University of Maryland, which provides the scientific direction and manages the science and the outreach, the Jet Propulsion Laboratory, which manages the project development and carries out the operations, and Ball Aerospace and Technologies Corp., which provides the spacecraft and instruments, other than some components that are provided by JPL.

4.1. Scientific Objectives and Success Criteria

The scientific objectives of the mission, as described in the original proposal and as quoted here from the relevant portion of the Discovery Program Plan, are

The Deep Impact mission will fly to and impact a short-period comet understood to have a nuclear radius>2 km (large enough so that it will sustain a crater of cometesimal size and ensure reliable targeting). The direct intent of the impact is to excavate a crater of approximately 100 m in diameter and 25 m in depth. The overall scientific objectives are to

1. Dramatically improve the knowledge of key properties of a cometary nucleus and, for the first time, assess directly the interior of a cometary nucleus by means of a massive impactor hitting the surface of the nucleus at high velocity.
2. Determine properties of the surface layers such as density, porosity, strength, and composition from the resultant crater and its formation.
3. Study the relationship between the surface layers of a cometary nucleus and the possibly pristine materials of the interior by comparison of the interior of the crater with the pre-impact surface.
4. Improve our understanding of the evolution of cometary nuclei, particularly their approach to dormancy, from the comparison between interior and surface.

The conversion of these goals into success criteria is more complicated than in many missions because of the very large uncertainty in what it would take to produce a crater of the size mentioned in the objectives, as discussed earlier in Section 2 and in more detail in the companion articles by Richardson *et al.* (2005) and by Schultz and Ernst (2005). For this reason, the success criteria are stated in terms of delivering a minimum mass at a minimum velocity, followed by success criteria based on the scale and sensitivity of images and spectra. The baseline success criteria are taken from the relevant appendix to the Discovery Program Plan (section numbering omitted) and are as follows:

i. Target a short period comet understood to have a nuclear radius >2 km.
ii. Deliver an impactor of mass > 350 kg to an impact on the cometary nucleus at a velocity > 10 km/s. The impact event and crater formation shall be visible from the flyby spacecraft and observable from Earth.
iii. Obtain pre-impact visible-wavelength images of the impact site including one with resolution < 3 m and *FOV* > 50 pixels.
iv. Obtain three visible-wavelength images, using at least two different filters, of the entire comet, pre-impact, with resolution < 50 m and average S/N >50 for the illuminated portion of the nucleus.

v Obtain five visible-wavelength images containing the impact site with resolution < 50 m and showing the crater evolution from within 3 s of time of impact until full crater development (assumed to take less than 660 s).

vi. Obtain five visible-wavelength images of the ejecta cone, showing the ejecta cone evolution at a resolution <50 m from within 1 s of impact until late in the cone evolution (assumed to take less than 60 s).

vii. Obtain five near-infrared (1.1 to 4.8 μm), long-slit spectra of the ejecta cone, showing the ejecta cone evolution with spectral resolving power > 200 from within 2 s of time of impact until late in the cone evolution (assumed to take less than 60 s).

viii. Obtain one image of the final crater with a resolution <7 m.

ix. Obtain one near-infrared (1.1 to 4.8 μm), long-slit spectrum of the impact region pre-impact and one post impact, both with spectral resolving power >200 and with noise-equivalent-surface-brightness <150 k Rayleigh per spectral resolution element at 3.5 μm.

x Obtain two near-infrared (2.0 to 4.8 μm), long-slit spectra of the coma, one before impact and one after formation of the crater (assumed to take <660 s), with spectral resolving power >200 and Noise-equivalent surface brightness <500 k Rayleigh per spectral resolution element at 4.7 μm.

xi. Obtain at least three Earth-orbital or ground-based datasets of two different types of data complementary to the data from the spacecraft.

The original baseline success criteria included a requirement to deliver an impactor of mass 500 kg, coupled with a minimum requirement of 300 kg. The descope to 350 kg was approved by NASA before CDR (Critical Design Review) in order to save considerable funds by using a smaller launch vehicle. If the project's favored scenario for the impact, gravitational control of the cratering, is correct, the difference in the size of the crater due to the reduction in scope will be very small, as one can see from the discussion of scaling laws in the accompanying papers by Richardson *et al.* (2005) and by Schultz and Ernst (2005). The baseline success criteria are otherwise unchanged since selection, despite numerous other reductions in scope taken between PDR (Preliminary Design Review) and CDR. The only other requirement from the original proposal that has been waived is the window for the launch date. Due in largest part to difficulty in developing the spacecraft's computer system, the launch was allowed to slip from the original window (opening on 2 Jan 2004) to the backup window (opening on 31 Dec 2004), which was outside the originally defined window for launch, but this had no effect on the encounter with the comet.

4.2. Overview of the Instruments and the Mission

The details of the flight mission are described in the companion paper by Blume (2005), details of the scientific instruments in the companion paper by Hampton *et al.* (2005), and details of the data expected to be returned and its archival disposition in the companion paper by Klaasen *et al.* (2005). This section provides only an introduction to those topics.

Deep Impact, which consists of two spacecraft – an impactor vehicle and a flyby vehicle that are initially mated and launched together, will reproduce the impact of a boulder into a cometary nucleus at a speed characteristic of collisions in the asteroid belt, delivering an impactor of 363 kg (plus whatever remains of the initial 8 kg of hydrazine fuel) onto the nucleus of comet 9P/Tempel 1 at 10.2 km s^{-1}. This kinetic energy, about 19 GJ, corresponds to the explosive power of 4.5 tons of TNT. We note that the speed is such that the kinetic energy per unit mass substantially exceeds the chemical energy per unit mass of the most efficient chemical explosives. Also, the localized and explosive liberation of this energy, which initially serves to accelerate the subsurface material in the vicinity of the explosion, ultimately causes the excavation of a large volume of material at much larger depths. The material left in the crater, which may have seen the passage of one or more shock waves, is not expected to have its chemical composition changed. The effect should be to produce, in roughly 200 s, a crater about 100 m in diameter and 25 m deep, although there is a large uncertainty in this prediction (see the companion papers by Schultz and Ernst, 2005 and by Richardson *et al.*, 2005). The impactor spacecraft has a camera for scientific imaging and autonavigation (see Mastrodemos *et al.*, 2005), a complete attitude control system using gyros and thrusters and a complete propulsion system using hydrazine. In order to minimize chemical reactions that might lead to species with bright lines in the spectrum, the use of copper, from the noble metals column of the periodic table, was maximized, comprising nearly half the mass of the impactor. The camera on the impactor has no filter wheel, taking only white-light images, which are both used on board for autonavigation and transmitted to the flyby spacecraft for retransmission to Earth (see companion paper by Hampton *et al.*, 2005 for details). As the impactor approaches the comet, we expect that dust in the coma will sandblast the primary mirror of the camera in the last minute before impact, while a single, major dust impact closer to the nucleus could destroy the camera. In either case, this is long after the last navigation maneuver (Figure 3). The last image, presumably only partially transmitted, will have a scale of 20 cm per pixel.

The flyby spacecraft is launched mated to the impactor, Figure 2, in a 30-day launch window beginning 30 December 2004, and remains joined to the impactor until it releases the impactor with a spring mechanism 24 h before impact onto a collision course with the nucleus. The flyby spacecraft diverts by about 2 arcmin in order to miss the nucleus by 500 km, our best estimate of the radius of the Hill sphere for the comet. (The Hill sphere is the volume within which orbits around the nucleus are stable against solar perturbations.) It also decelerates by about 100 m s^{-1}, passing closest to the nucleus 850 s after impact and providing an 800-s window for making all of our observations of the crater and its formation [our predictions of the formation time of the crater range up to 700 s for the lowest

Figure 2. The flyby spacecraft being lowered onto the impactor spacecraft in the clean room at Ball Aerospace and Technologies Corp. prior to system environmental tests. When the spacecraft are joined, the pentagonal gold-colored panels of the impactor are recessed entirely inside the flyby spacecraft. The white ring at the bottom of the impactor, here bolted to the top of a test stand, is the fixture that will join the impactor to the launch vehicle. Photo courtesy of Ball Aerospace and Technology Corporation.

assumed density of the nucleus]. The mission design, and particularly the short (800 s) window for observation after impact, require very intelligent auto-navigation as described by Mastrodemos *et al.* (2005). Instruments include a high-resolution camera (2 μrad per pixel) with a series of intermediate-band filters, an infrared spectrometer covering the range from 1.05 to 4.8 μm, and a medium-resolution camera (10 μrad per pixel) that is identical to that on the impactor except for the addition of a filter wheel. The medium resolution camera is intended to have a field of view large enough to image the entire nucleus near closest approach and provide geophysical context for the high resolution frames. The flyby instruments are body mounted and co-aligned so that tracking is achieved by rotating the spacecraft.

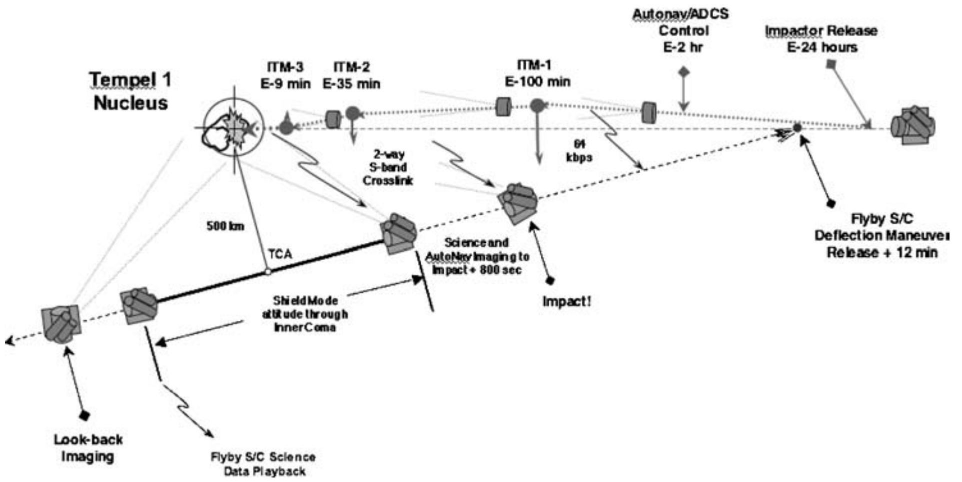

Figure 3. The encounter sequence. In this view, which is in the rest frame of the comet, the sun is behind the page at an angle of 63° to the plane of the paper and generally toward the upper right. In the heliocentric frame, the comet is moving down and to the right at about 30 km/s. Earth is also to the right and behind the page. The encounter sequence is described in detail in the companion paper by Blume (2005).

As the spacecraft approaches the comet, the spacecraft-fixed cameras are pointed by turning the spacecraft. The maximum spacecraft attitude turn rate of 0.6 deg/s occurs at a range of 700 km when the spacecraft has rotated 45° from the approach asymptote. Most of the shielding against dust being placed for this orientation.

The time of impact, on 4 July 2004, is determined to within a small window by the requirement for redundant linking of data from the spacecraft to two stations of the Deep Space Network coupled with the desire to observe the event in darkness from one of the major astronomical sites. The first constraint forces the astronomical site to be Hawaii and the onset of darkness there sets the earliest time for the impact. The window is roughly 05:50 to 06:30 UTC on 4 July, with the choice of time within that window to be made 1–2 months before impact in order to ensure that HST (Hubble Space Telescope) is on the correct side of the Earth to make observations.

The science team has developed a baseline scenario for the impact, and thus for its observation, assuming that the growth of the crater will be controlled by the low gravity of the cometary nucleus rather than, e.g., by the strength of the material. Depending on the size (effective radius probably near 3.3 km; please refer to the companion paper by Belton *et al.* (2005) for our latest estimates of the parameters that describe the nucleus of 9P/Tempel 1) and density (unknown) of the nucleus, the crater might be between 100 and 200 m in diameter (for reasonable assumptions about density) and 25 to 30 m deep. However, some colleagues have argued that the crater will be controlled by the strength of porous ice with the penetration being limited by the development of instabilities (Rayleigh-Taylor and Kelvin-Helmholtz) at the sides of the impactor (O'Keefe *et al.*, 2001), while others might argue that the energy will go primarily into compaction of the porous nucleus against moderate compressive strength as has been argued for Mathilde (Housen *et al.*, 1999). These scenarios lead to very different final craters. Many cometary scientists, on the other hand, have suggested that the impact might either break a piece off the nucleus or even shatter it to many pieces. Finally, although it seems very unlikely, the impactor might just bury itself very deeply if the density of the comet is much lower than currently accepted values, just as Stardust gently captures dust particles in ultra-low-density aerogel (Tsou *et al.*, 2003). The key point in designing the mission was to optimize our measurements for the baseline scenario but to ensure that our data would be robust in providing useful information about the other scenarios. Several of the alternative scenarios would require substantial revisions to prevailing ideas about the structure of comets such that even minimal data for the unlikely scenarios, as long as the data identify the cratering mode, will lead to fundamental conclusions about cometary structure.

An important aspect of the mission is the role of remote sensing from ground-based and space-based telescopes. The impact event is expected to be readily observable from Earth, and it was designed to allow convenient observation with many different techniques. On a spacecraft one is severely limited in the nature of the instrumentation one can carry to the target and, because of the fast flyby, the Deep Impact instruments are limited to a rather short observing window. Thus remote sensing will be important for applying the full range of techniques that astronomers use, from high-speed photometry through high-resolution spectroscopy and at wavelengths from X-ray to radio. The details of the Earth-based program are described by Meech *et al.* (2005) and the role of amateurs in this program is also discussed by McFadden *et al.* (2005).

4.3. Measurements to be Made

The instruments take a suite of measurements at different times (see Klaasen *et al.*, 2005) that we summarize here. The relevant scientific phases used here (different from the mission phases described by Blume, 2005) are approach, encounter, and lookback. Approach is from 60 days before impact (E-60d; the point at which we expect to be able to reliably detect the comet) until release of the impactor (E-24h). Encounter is the day from release of the impactor until closest approach of the flyby spacecraft to the nucleus (at E+850s). Lookback is from closest approach until end of observations of Tempel 1, nominally at E+2.5d. We summarize the types of data here as a function of instrument and phase indicating how they address our scientific goals. Many of the imaging data are also used for navigation, as described by Mastrodemos *et al*. (2005) but we discuss here the scientific use only. Details of the spectroscopic plans are given by Sunshine *et al.* (2005).

4.3.1. *Impactor Targeting Sensor (ITS)*
During encounter the ITS takes images at steadily increasing frequency. In order to maintain a minimum sampling interval corresponding to $\sqrt{2}$ changes in distance while not exceeding the telemetry bit rate to the flyby spacecraft, the images are gradually decreased in size from 1024×1024 by taking central subframes down to 64×64. These images provide the highest resolution ever obtained on a cometary nucleus and provide the context images of the surface immediately prior to impact which provide valuable input to simulations of the cratering process.

4.3.2. *IR Spectrometer (HRI-IR)*
During approach the spectrometer is used to study the coma, allowing us to determine the spatial distribution and abundances of numerous molecules as well as characteristics of the dust. Toward the end of the approach phase, the spectrometer is also used to study the rotational variation of the reflectivity characteristics of the spatially unresolved nucleus. During encounter, the spectrometer is used to study in detail the distribution of molecules in the coma and the variations in the dust with location in the coma. It is also used to study the rotational variation of the reflectivity characteristics of the cometary nucleus. As the range shortens prior to impact, the spectrometer maps the reflectivity of the spatially resolved nucleus. During crater formation, the spectrometer monitors the evolution of the spectra of the ejecta as material from successively greater depths is ejected from the crater, thus revealing compositional variations. Shortly before closest approach, the spectrometer studies the coma in detail to determine what the differences are relative to the pre-impact composition. The spectrometer is also used to make a spatial map of the reflectivity of the region including the crater to understand the differences between the ambient surface and the crater floor. During lookback, the spectrometer is used to study any continuing outgassing from the crater as well as to map the coma from a different direction thus allowing resolution of the three-dimensional structure and compositional variation.

4.3.3. *High Resolution Imager (HRI-Vis)*
During approach the HRI-Vis imager is used to photometrically monitor the comet's variations, both with rotation and with orbital position. Regular observations of the structures in the coma will provide the best data on the rotational state prior to impact. Once the nucleus is photometrically resolved in the central pixel, the rotational variation of the nucleus is monitored to study lateral heterogeneity of the surface. The nucleus becomes spatially resolved before the release of the impactor spacecraft. During the encounter phase, imaging is used to obtain colorimetry of the nuclear surface at steadily improving spatial resolution over half a rotation of the nucleus. This provides considerable information on lateral variation of the compostion of the surface. At the time of impact, images are taken as rapidly as possible in white light to study the evolution of the ejecta and determine the morphology of the ejecta cone. As the evolution proceeds, the image rate gradually

decreases since things change more slowly at the later times. These images of the ejecta cone will allow determination of the cratering mode as well as providing estimates of the amount of ejecta from optical depth consideration. Clumps of ejecta will be tracked in order to study the distribution of ejecta velocities thus providing a good test of structural properties that are important to the simulations of the cratering process. Very slowly moving clumps may allow an estimate of the local gravity if tracking continues through lookback. During the latest portion of the encounter phase, the HRI-Vis is used to study the properties of the crater and its surroundings, providing information on vertical stratigraphy, on any boulders that may have survived the shock and the excavation, and on colorimetric differences between the floor of the crater and the ambient surface. This will allow determination of differences between the surface and the interior. If natural outgassing persists from the crater, producing a new active area, this will indicate that comets become dormant by sealing ice in the interior rather than by exhausting the supply of ice. The last images will provide by far (5×) the highest resolution images ever of a cometary nucleus other than in those from the impactor. During the lookback phase, the HRI-Vis will take images to determine the three-dimensional shape, and thus the total volume, of the nucleus. The images will also track any continuing outgassing from a possible new active area by monitoring the jets at the limb of the nucleus (the crater itself will be on the far side at this point). Details of the geological approach are given by Thomas *et al.* (2005), while details of the interpretation of the cratering data are given by Richardson *et al.* (2005) and by Schultz and Ernst (2005).

4.3.4. *Medium Resolution Imager (MRI)*

The MRI is used during approach primarily to supplement the observations with HRI-Vis. At the end of approach and during encounter the MRI is used to take deep images of the coma in narrow-bands to isolate the gaseous and dusty structures in the coma, using filters that are not available in HRI-Vis as well as some of the same filters that are available in the HRI-Vis. At the time of impact, MRI provides higher-speed imaging of the impact than does HRI-Vis, although the crater itself is spatially unresolved by MRI at the time of impact. MRI provides a wide field of view for tracking clumps of ejecta that are seen initially in the HRI-Vis. The last images before closest approach image the entire nucleus and thus, combined with earlier images, provide the stereoscopic information to allow reconstruction of the three-dimensional shape of the nucleus. During lookback, the MRI will provide the wide field of view for studying the entire nucleus and much of the coma. As before impact, deep exposures in the narrow-band filters can isolate different gases and dust in the coma for detailed study.

5. Choosing the Target

The choice of a target for the Deep Impact mission was constrained by many factors including

- Launch in the window defined by NASA's Announcement of Opportunity (AO).
- A trajectory with sufficiently small launch energy per unit mass that a large mass could be delivered to the comet.
- Encounter at hypervelocity, i.e., more than a few kilometers per second.
- Encounter at low enough velocity that the flyby spacecraft can realistically decelerate enough to observe the entire process of crater formation.
- Approach from a moderate to small phase angle for approach navigation and crater illumination.
- Impact event readily observable from Earth, i.e., large solar elongation and moderate to small geocentric distance.
- Nuclear size large enough that self-gravitational energy should substantially exceed the delivered kinetic energy and large enough that targeting to hit the nucleus would not present a major challenge.

With these constraints there is a "good" target available for launches every few years and an acceptable target that meets most constraints available every year. Tempel 1 was chosen as the best target available for launches in the launch window allowed by the AO from NASA. To minimize the launch energy one should encounter the target near one of its orbital nodes and the descending node occurs on 7 July 2004, which is fortuitously close to the comet's perihelion on 5 July 2004. Thus impacts between late June and mid-July are energetically best and 4 July was selected. The dynamical history as well as the observational history of the comet are described in a companion paper by Yeomans *et al.* (2005). Details of what is known about the nucleus parameters and of the coma of comet Tempel 1 are given in the companion papers by Belton *et al.* (2005) and by Lisse *et al.* (2005), respectively.

Some of the alternative targets that were rejected for one reason or another included

- 4P/Faye – larger phase angle on approach, no backup launch window, higher launch energy,
- 58P/Jackson-Neujmin – launch too early without backup window, larger phase angle on approach, small nucleus,
- 10P/Tempel 2 – impact not observable from Earth, large phase angle on approach for backup launches,
- 41P/Tuttle-Giacobini-Kresak – erratic outbursts, small nucleus, higher flyby speed,
- 78P/Schwassmann-Wachmann 3 – small nucleus, long flight time,
- 2P/Encke – high launch energy,
- 37P/Forbes – high launch energy, high phase angle on approach.

Of all these targets, Schwassmann-Wachmann 3 was the most promising alternative and this was planned as one of the targets of the CONTOUR mission (primarily because it had recently undergone a major splitting event and a "young" surface might be observed). However, it was dropped from prime consideration for Deep

Impact because of the increased difficulty of hitting a nucleus with radius thought to be less than 1 km. The point of this discussion, of course, is to emphasize the fact that many targets are available for missions such as Deep Impact, and the choice of target is mostly a tradeoff between optimizing the science and minimizing the risk.

The choice of Schwassmann-Wachmann 3 would also have resulted in two missions to the same comet. In our view, the ideal mission, which is clearly not doable under the Discovery Program, would send two separate spacecraft to the same comet. An orbiter would arrive first and it would map the comet in detail, determining the mass and developing complete maps while the impactor is *en route*. The orbiter might then be used to adjust the targeting and the time of impact to hit a certain portion of the surface and the orbiter would also be used to study the impact process.

6. What We Should Learn

This section explains, in order, how we answer each of the questions raised in Section 2. However, we certainly won't answer all the questions raised there. Nevertheless, we organize the answers in the same way as the questions. As emphasized by Harwit (1984), and as exemplified in observations from Halley to Borrelly to Wild 2, the surprising results usually come from measurements in a new regime, in this case first an entirely new regime of experimentation, but also even traditional measurements in an entirely new regime of spatial resolution. We could only speculate on what might be learned from increasing the spatial resolution by an order of magnitude. We provide here only an outline. More details are in some of the companion papers in this volume.

6.1. Mass and Related Parameters

The mass, while of fundamental importance, will probably not be determined by the Deep Impact project, although we will certainly attempt to do so. Tracking of the spacecraft during a cometary flyby, as has been clear in previous flyby missions, is incapable of deducing a mass because of the combination of the small mass of the nucleus with the relatively fast flyby speed. Our hope for determining the mass lies in tracking clumps of ejecta that emerge at relatively low velocity and end up orbiting the nucleus or at least showing significant deceleration. A second possibility, if the geometry turns out to allow us a good view from the side of the ejecta cone, is to carefully determine the shape at the base of the cone when it expands beyond the edge of the crater and the base of the cone is falling back onto the surface Detailed discussion on the processes involved in crater formation and the resultant ejecta will be found in the companion papers by Schultz and Ernst (2005) and Richardson *et al.* (2005). Neither of these approaches can be characterized as having a high probability of success and this is not among our scientific requirements for success.

On the other hand, the morphology of the impact event may make it possible to constrain the porosity of the material being excavated, i.e., the porosity of the outermost 20–30 m. Extrapolating this deeper into the interior, however, would be inadvisable. Our detailed measurements of both the ambient coma and the ejecta, both gaseous and solid, may also allow us to better understand whether the ice-to-silicate ratio of the bulk material is the same as that of the solid nucleus.

6.2. Structural Properties

Perhaps the first step in understanding the results from Deep Impact will come from studying the morphology of the impact phenomena. We need to determine which physics is relevant to the event, i.e., to determine which physical processes control the formation of the crater and the distribution of the ejecta. Fortunately, the behavior of the ejecta cone with time is very different for gravitationally controlled craters (remaining in contact with the surface throughout the event) and strength-controlled craters (lifting entirely off the surface at an early stage) and the ejecta cone will be much weaker for a compression-controlled crater. All other things being equal, the opening angle of the ejecta cone is sensitive to the porosity of the target. Filling in of the conical shell occurs, for example, due to enhancement by buried volatiles. Thus simple morphology will be the key to understanding which physics is relevant to the cratering process and thus to the structure of the nucleus in its outer layers. Simply resolving which scenario of crater formation is qualitatively correct will dramatically reduce the qualitative uncertainty in models of the surface layers. The final crater is also diagnostic not only of the process but also of the values of certain parameters depending on which physical processes dominate. The challenge will be to use different types of measurements to separate the various parameters that we would like to determine. Details of our expectations are given by Schultz and Ernst (2005) and by Richardson *et al.* (2005).

6.3. Differentiation and Evolution

The ejecta from the crater are likely to have a composition that varies with time as material is excavated from deeper and deeper within the crater. This will be diagnostic of the differentiation in the outer layers. As noted earlier, the morphology of the ejecta is sensitive to whether volatiles are buried beneath the surfaces.

Spectroscopy and photogeology of the resultant crater will also be important in allowing us to investigate differences between the ambient surface of the nucleus and the material below the ambient surface – can we see layering in the walls of the crater? Can we see differences in spectral properties? And so on.

Spectroscopy of the coma, comparing the outgassing from the crater with the ambient outgassing, should allow us to determine whether the relative abundances of various volatiles is different in the interior and thus whether or not we are approaching primitive material. While it will be nearly impossible to determine whether we have gotten deep enough to reach primordial material, the differences should enable us to estimate the differences between primordial abundances and the abundances observed in the coma of many comets.

6.4. End States

Since we calculate that the nucleus has an active surface fraction of only a few to 10% (cf. the discussion in Belton *et al.*, 2005), the impactor will hit with very high probability in an inactive area. If the process of cometary inactivation is primarily one of sealing the ice inside by developing a thermally insulating and/or impenetrable mantle of refractory material, then one might expect the crater to become a new, active area, producing a jet with rather different ratios of volatiles than are observed in the ambient outgassing. Study of such a jet would be a key project for Earth-based observatories since the narrow window of the flyby observations limits *in situ* observations to the initiation of the jet and such a jet might last anywhere from hours to months.

6.5. Other Possible Results

The puzzling topographic features seen from Stardust at comet Wild 2 lead us to expect great advances in understanding the surface features with our higher spatial resolution. If nothing else, we will observe a feature that is unambiguously an impact crater that can then be compared with features seen at Wild 2 that might be impact craters. Details of these investigations are given by Thomas *et al.* (2005). We will also obtain unprecedented spatial resolution on the coma near the nucleus. This will enable us to better understand the processes by which both gas and dust leave the nucleus and expand into the coma where they can subsequently be observed from Earth. There should be advances, for example, in understanding the acceleration in the inner coma and in understanding the chemical changes that take place in the inner coma.

7. Summary

Deep Impact is unusual among space missions in several ways. It will conduct one of the very few active, *in situ*, experiments ever done and our range of predictions of the outcome of that experiment are so qualitatively different that simple, qualitative results can lead to a major advance in our understanding of cometary nuclei. Furthermore, the rich variety of phenomena that could occur makes Earth-based observations a crucial part of the experiment.

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