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Deep Impact – Exploring the Interior of a Comet

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Abstract. The Deep Impact Mission will send a 500 kg impactor to create a crater on the nucleus of comet P/Tempel 1 to reveal sub-surface materials. Our primary scientific goal is to understand the difference between the interior of a comet and its surface. Current and planned missions will investigate the heterogeneity of surface structure and composition, and will explore comet diversity. However, observations and theoretical models cannot tell us the depth at which cometary pristine material lies. The DI mission will provide information about the interior of a comet by excavating a crater to: (*i*) observe how the crater

forms, (*ii*) document the final state of the crater, (*iii*) measure the composition of the hot ejecta from the crater, and (*iv*) determine the changes in the natural outgassing produced by the impact.

1. Introduction

Cometary nuclei are the most pristine objects from the era of planetary formation that are observable at close range, and as such provide a link to study the birth and evolution of the Solar System through their compositional and physical properties (Weidenschilling 1997; Lissauer & Stewart 1993). Studies of comets are telling us how much the interstellar material is processed in the solar nebula prior to its incorporation into planetary bodies. However, numerous perihelion passages will deplete the surface layers of volatiles, and can lead to differentiation. While the depth to which these effects go is very uncertain, calculations suggest that this effect will reach depths of as much as ten meters (Prialnik & Mekler 1991; Benkhoff & Huebner 1995; Klinger 1996). Comets have also played a role in bringing volatiles to the early Earth (Owen 2000) and possibly organic materials which lead to the emergence of life (Oró 2000; Becker 2000). The *Deep Impact* mission is the eighth Discovery mission. It will be the first experiment to probe beneath the surface of a comet to study the pristine interior material – initiating a new dimension in the study of cometary nuclei.

2. The Mission Profile

Deep Impact will be launched on 2004 Jan 1 by a Delta II rocket, and will swing by Earth on 2004 Dec 30. The spacecraft will carry a 500 kg copper impactor. The impactor will be released on 2005 July 3 when the spacecraft is about 24 hours from closest approach. The flyby spacecraft will then slow down by 120 m s^{-1} to fall 10^4 km behind by the time of impact. This delay will give the flyby spacecraft approximately 16 min to view the impact, the ejecta and the crater before the flyby at 500 km closest approach. The impactor will hit the comet nucleus at a velocity of 10.2 km s^{-1} excavating a large crater as in a meteoritic impact. The properties of the crater will be sensitive to the unkown properties of the cometary nucleus, but for a particular, plausible model of the nucleus, the crater will be $>$100m in diameter and $>$25m deep, taking approximately 200 seconds to grow to this size. At the time of encounter, the spacecraft will be at a heliocentric distance, r, of 1.495 AU and a geocentric distance, Δ of 0.905 AU.

2.1. Instrumentation

The instrumentation complement includes a high resolution imager (HRI) and a medium resolution imager (MRI) in the visible and near-IR. The MRI will provide the scientific context of the mission (along with simultaneous ground-based observations), will image the ejecta plume and perform the targeting. The HRI will provide high resolution images and spectra ($\Delta\lambda/\lambda\sim$216) of the coma, comet and crater in the visible and IR. The impactor will also have an imager and active guidance system (Fig. **??**). Table **??** lists some of the instrument specifications. The optical detectors are 1024^2 split frame

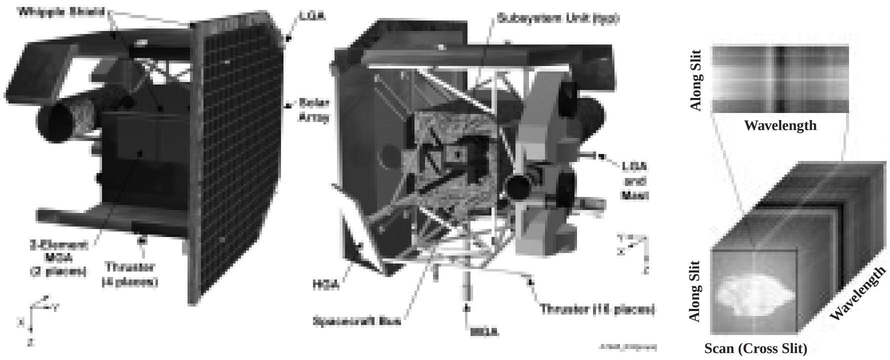

Figure 1. (a) Two views of the spacecraft and scientific payload, (b) Sample spectral image cube of the nucleus of 9P/Tempel 1.

transfer CCDs with 21μm pixels, and the near-IR has 512^2 HgCdTe detectors with 37μm pixels.

Table 1. Deep Impact Instruments.

		HRI	MRI	Impactor
Telescope	Diam [cm]	30	10	10
Visible	FOV [deg]	0.118	0.587	0.587
	res/pix [m]	1.4 at 700 km	7 at 700 km	0.2 at 20 km
IR	FOV [deg]	0.29	1.45	–
	Spectral range	1.05–4.8 μm	1.05–4.8 μm	

2.2. Timeline

The current mission baseline calls for impact on 2005 July 4. This data is appealing for reasons of public outreach – since we expect the impact flash to be visible from the ground through small telescopes and are planning a vigorous network of amateur observers for mission support. The time of impact, controlled by a Δv at Earth encouter, will be adjusted for optimal rotational phase and for optimal coverage by space observatories in LEO (e.g. HST, AXAF and SIRTF) and ground-based observatories (Tenerife, La Palma, Paranal, La Silla, Cerro Tololo, McDonald, Kitt Peak, Mauna Kea and Siding Spring) tentatively chosen for darkness in Chile and the Canary Islands, with daylight observations at infrared wavelengths in Arizona and Hawaii (Fig. **??**).

2.3. Cratering Physics

Our model for the crater predicts that the ratio of excavated mass to impactor mass is more than an order of magnitude larger than for terrestrial craters. We have used scaling

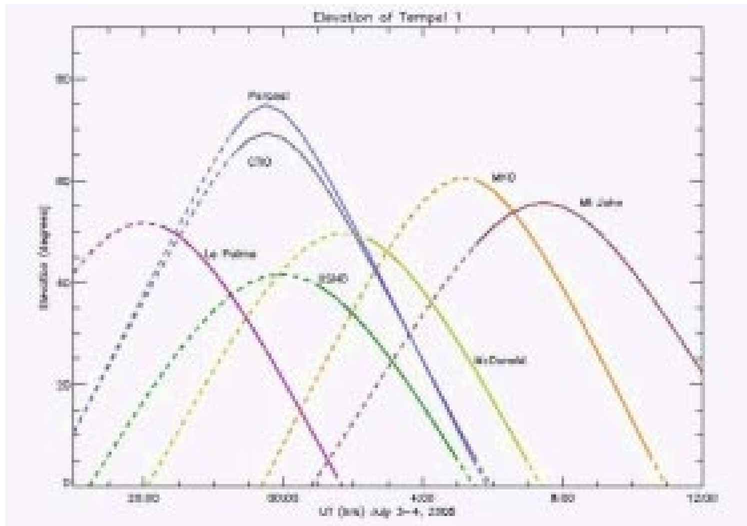

Figure 2. (a) Elevation of comet 9P/Tempel 1 for a 2005 July 4 impact as seen from several observatories world-wide. The dashed lines indicate that the sun is still up.

laws which have been widely tested in the laboratory, however, we must extrapolate by > 2 orders of magnitude due to the very low surface comet gravity. As the crater grows, it will expand at a fraction of the impact velocity. The depth of vaporization will depend upon the shape and density of the impactor as well as the nature of the surface properties of the comet (Melosh 1989). The shock release state during the impact, will also depend on the porosity of the material. The crater morphology and the growth rate of the crater will provide clues related to the nature of comet 9P/Tempel 1's surface layers (Melosh 1989; Stewart-Mukhapathy 2000).

3. Target Characterization

Prior to the encounter, the science team will conduct a vigorous program of ground- and space-based observing to characterize the nucleus of P/Tempel 1. The comet was discovered in 1867, and observed in 1873 and 1879, but then lost until 1967. Dynamically, the comet appears to be a typical Jupiter-family short-period comet ($P = 5.5$ yr, which has probably spent considerable time in the inner solar system ($\sim 3{\times}10^5$ yr; Levison & Duncan 1997). Thus, we expect that the surface layers will be highly evolved by exposure to solar insolation. The level of activity of the comet appears to have been fairly stable since the 1960's (Kresák & Kresáková 1989). The composition also seems to be fairly typical of the JF comets (A'Hearn *et al.* 1995).

3.1. Current Observations

The spacecraft will likely detect the comet 1-2 months prior to impact but will not spatially resolve the nucleus until about 2 days before impact. In order to design the autonomous targeting software and mission instrumentation, it is crucial to know what the expected observational environment will be upon arrival. This includes the size and reflectivity of the nucleus, its axial ratio, rotational state, and surface brightness relative to that of nearby dust. Critical among these parameters, possibly the hardest to determine and most demanding of telescopic observing time, is the nucleus rotation state – particularly if it is in an excited state.

Simulations show that targeting precision (circular 3-σ) will be $\sim$250 m for a 3 km-radius bare nucleus of 4% reflectivity. This precision will be degraded by concave nuclear topography, by variations in the reflectivity, and by ambient coma. In order to choose a day of impact relative to rotational phase to maximize the targeting cross section, it is essential to know whether there are significant variations in reflectivity. In addition to the targeting issues, knowledge of the spin state may be critical for determining nucleus mass (*e.g.* from the motion of large low-velocity ejecta released in the late stage of crater formation).

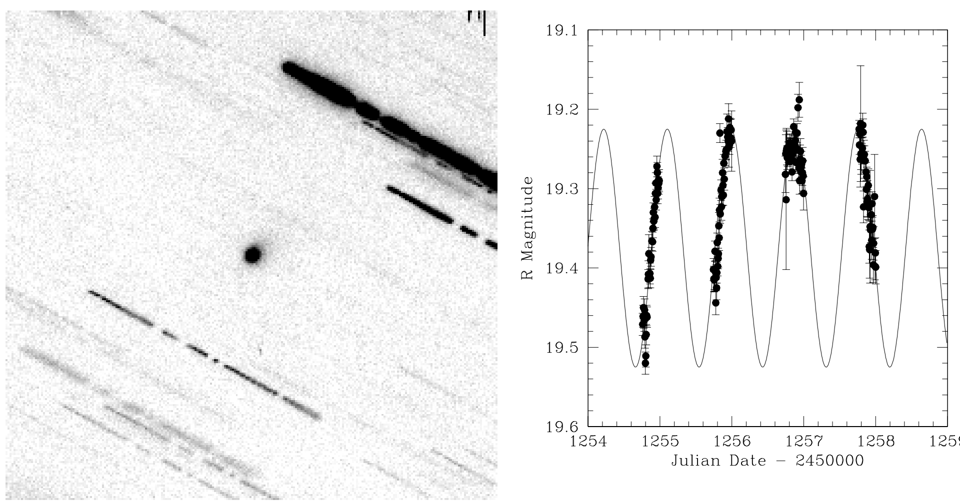

Figure 3. (a) Composite 10,500 s image of P/Tempel 1 from 1999 March when the comet was at r = 2.88 AU (b) Composite lightcurve from 4 nights during 1999 March (Meech *et al.* 2000).

To date we have very little information about the target. Rotational light curve observations obtained during 1999 Jan and Mar using the UH2.2 m telescope on Mauna Kea showed a rotational light curve, shown in Figure **??**. The data suggest that the mean effective radius is about r_N = 2.5 km for a 4% albedo, and the nucleus is highly elongated ($>$ 2.5 : 1). We searched for periodicities in the data using the Window-CLEAN algorithm, and have a preliminary fit to the data of $\sim$40.7 hrs for a 2-peaked light curve. Observations obtained during 2000 Sep-Nov using the UH2.2 m, the NGT 3.6 m (La Palma), the Lowell 72″, and the ESO 1.5 m Danish telescopes should help refine this period.

3.2. Planned Coordinated Observing Program

Between the present time and the encounter, we plan to characterize the rotation state of the nucleus, determine its size and albedo, look for reflectivity variations on the surface, determine the outgassing rate of various species, and model the dust environment of the coma. This will involve a large coordinated international ground-based observing effort.

Rotation State – We are proposing to get data (*i*) to get the rotation period and determine if the comet is in an excited spin state, and (*ii*) try to obtain the rotation pole of the comet (important for targeting). The rotation pole determination requires 3-4 light curves obtained with minimal coma contamination when the comet is at low phase angle ($\alpha < 10^\circ$) over a range of ecliptic longitudes, e.g., when the comet is at large r. The observations will be a coordinated effort from several observatories (Mauna Kea, NOAO, ESO, Lowell, and La Palma) during 2000 Oct, 2001 Nov, 2002 Dec and 2004 Jan.

Dust Environment – Flying through a cometary coma is not the safest of undertakings, as was proven by the Giotto and VEGA spacecraft during flights through 1P/Halley's coma (Reinhard 1986; Sagdeev *et al.* 1986). The best possible models of the dust environment are needed, both to allow for proper protection of the spacecraft and to understand the dust environment. Finson-Probstein dust dynamical modelling can give us information about the dust size distribution, relative dust ejection velocities and the onset and cessation of activity. Combined with spectroscopic observations of the gas coma and radio measurements of volatile production rates, we can also get the dust/gas mass ratio. Accurate dust models require both short timescale imaging to constrain the small grains which move rapidly away from the nucleus vicinity, and longer timescales to constrain the large grains. Optimal observation times will occur during the fall 2000 and again in early 2004.

Nucleus Size – The current size of P/Tempel 1 is an estimate based on an assumed albedo. The probable error in assuming the albedo can lead to a factor of $\sim$2.5 in radius uncertainty. The unknown surface albedo distribution can potentially severely affect the impactor targeting, which is carried out autonomously based on measurements of the center of brightness. Time resolved simultaneous optical/IR ground-based observations of the nucleus can constrain the albedo distribution, as has been studied for only 3 comet nuclei. The only possible time to obtain these observations in time to affect mission planning, when there is minimal coma, but the comet is bright enough for detection is during August 2000.

Gaseous Species – We will monitor the development of several gaseous species as the comet becomes active. The molecules of primary interest are those that exist as ices in the nucleus – H_2O, CO and CO_2. It is important to establish a baseline of chemical abundances in 9P/Tempel 1 so that we may interpret the abundances seen in the outburst which will be caused by the impactor. Any changes observed would imply that there is chemical heterogeneity not just among different comets, but within individual nuclei, and will have implications for the conditions in which comets formed. It is also important to establish a baseline for the velocity structure of the various chemical species. The velocity structure reveals information about the physical conditions in the coma which the impactor will pass through. More importantly, any changes will help us to understand the physical effects of the collision.

This is not an intrinsically bright comet, and at radio wavelengths [OH] we will only have one period in which to observe before the impact beginning in 2005 Mar or Apr. Unfortunately, it will not be possible to get CO – even from Mauna Kea because of the faintness of the comet. However it should be possible to monitor HCN beginning in 2005 Mar. (We did attempt to see HCN during 2000 Jan near perihelion, but will only obtain upper limits).

In order to accomplish all of these goals, a large-scale international coordinated observing plan is being undertaken to fully characterize the nucleus (see Fig. **??**).

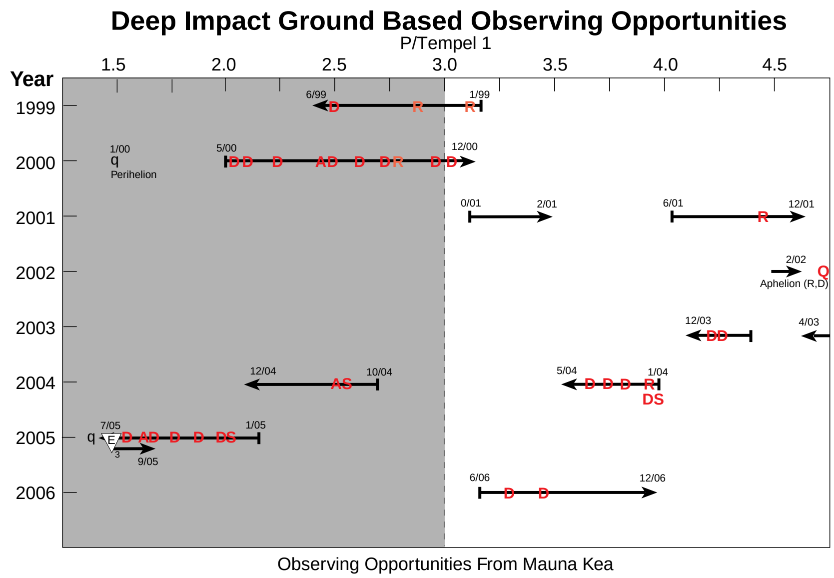

Figure 4. Timeline for critical 9P/Tempel 1 observations. **R** = rotation determination, **A** = albedo (simultaneous optical/IR), **S** = spectroscopic observations, **D** = imaging the dust coma for particle dynamical models.

4. Conclusions

This mission represents the first investigation of the interior of a comet nucleus. Our goal will be to determine how deep the ices and pristine material is, the structure of the outer layers of the nucleus, and to understand the relationship between cometary pristine material and information we will get from future lander missions.

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