

DEEP SUB-SURFACE EXPLORATION OF COMETARY NUCLEI

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ABSTRACT

The surface regions of cometary nuclei are expected to be extensively modified by cosmic radiation and solar insolation. Induced state changes and associated sublimation and phase-change boundaries are expected to propagate deep into the interior. In the current exploration program a reconnaissance of the highly evolved upper meter of the cometary surface is comprehensively covered. However, the relationship of evolved surface materials to the pristine (*i.e.*, unchanged since emplacement in the comet) materials that may exist at greater depths remains to be explored. Except for the possibility of remote sensing by radar and microwave tomography, the problem of sampling the properties of deep (1–100 m) sub-surface materials has received little attention. We consider a concept for the scientific exploration of these deep sub-surface regions by means of excavation by hypervelocity impact. A massive (approximately 500 kg) impactor is delivered at hypersonic speeds to a comet nucleus to excavate a crater several tens of meters deep and over 100 m in diameter. We give two examples of such missions: one to a suspected dormant comet, 3200 Phaethon, and one to a currently active comet, 9P/Tempel 1. We show how a reconnaissance of the newly excavated crater structure from the flyby delivery spacecraft or an associated lander can yield new information about the physical and compositional structure of the deep sub-surface layers and about any lateral inhomogeneities that could be associated with the primordial cometsimal structure of the nucleus.

INTRODUCTION

Programs of solar system exploration place high priority on space missions to cometary nuclei because they are believed to contain relatively pristine samples of solar nebula materials present or accumulated during the time of planet formation. Knowledge of their compositions and physical structure is expected to yield insight into a wide range of processes that may have occurred in the solar nebula as the planets were being constructed. Past missions such as ESA's GIOTTO, the Soviet VEGA 1 and 2 missions, and the Japanese *Sakigaki* and *Suisei* missions to 1P/Halley, the NASA ICE mission to 21P/Giacobini-Zinner, plus the current development of ESA's *Rosetta* mission to 46P/Wirtanen, NASA's DS-1 (possibly to 19P/Borrelly), DS-4 (*Chimpollion*) (to 9P/Tempel 1), STARDUST (to 81P/Wild 2), and CONTOUR (to 2P/Encke, 73P/Schwassmann-Wachmann 3, and 6P/d'Arrest) are impressive testimony to the commitment of major space agencies to cometary exploration. The expected harvest from these explorations will be detailed knowledge of the state of materials on and just below (to a depth of approximately 1 m) the cometary surface as well as many unpredictable discoveries about their nature and diversity.

However, we see a significant deficiency in this excellent, but essentially two dimensional, exploration of cometary nuclei. Models of the surface regions of short period comets (*e.g.*, Benkhoff and Huebner, 1995; Prialnik and Mekler, 1991; Klinger, 1996) are in agreement that the upper surface regions will be highly evolved both physically and compositionally under the influence of solar insolation to depths well in excess of a meter. The nature and extent of these modifications is, however, far from settled. In addition, the flux of background cosmic radiation should have caused some compositional modification to material at depths of several tens of meters since the comet was formed (Strazzulla and Johnson, 1991). To understand how these evolutionary

modifications have affected the surface layers and to provide a basis for identifying the most primitive state of cometary material and to identify where such material might be located, a detailed exploration of the deep subsurface to depths in the range 1–100 m will be needed.

In Figure 1 we show our current appraisal of the surface structure of cometary nuclei. Substantial inhomogeneities are expected on linear scales of tens of meters vertically and hundreds of meters laterally. This expectation presents obvious problems for the interpretation of vertical cores sampled at a single, or limited number, of sites and that are limited to a depths near 1 m (as is apparently the case for currently planned missions according to Schwehm, 1996).

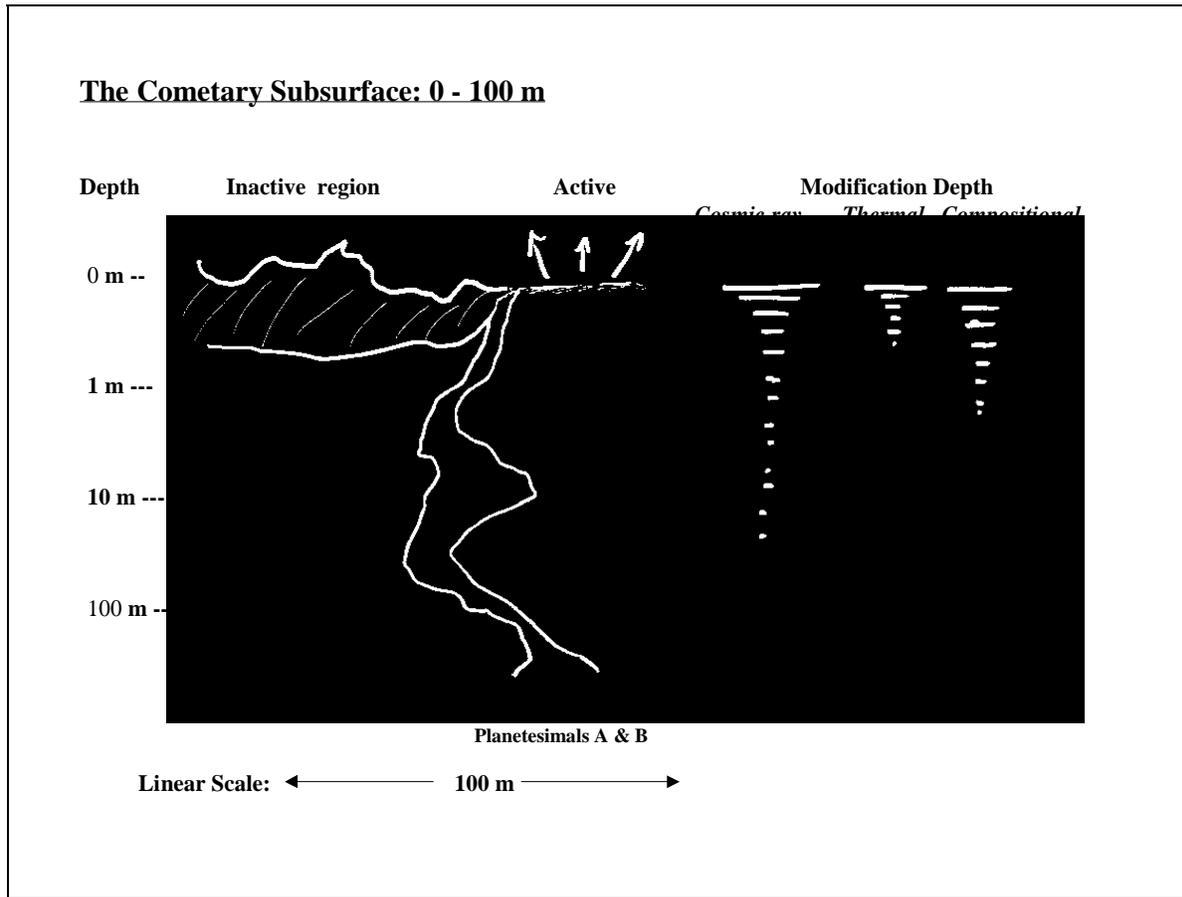


Fig. 1. Schematic cross-section of the surface regions of a hypothetical comet to a depth of 100 m over a linear scale of 100 m. The nucleus is presumed to be made up of smaller cometesimals as in the primordial rubble pile model (Weissman, 1986) which may have differing compositional make up. The sizes observed for active regions on 1P/Halley (Keller *et al.*, 1986) suggest that the lateral scale associated with major cometesimals may be in the range of 100 m to a few kilometers. The properties of the interface between two such regions A and B may have been modified in the accumulation process. The surface of A has built up a lag deposit and simulates an inactive region. The surface of B is that of an active region. To the right of the figure we crudely indicate the depth range of evolutionary modifications due to cosmic ray irradiation, solar insolation, and chemical differentiation through thermal diffusion.

Techniques that might be employed (but have yet to be studied in a cometary context) to sample properties of materials to depths of tens of meters and, in addition, explore laterally include automated burrowing machines, variable direction drilling without core preservation, impact excavation, microwave tomography, seismic exploration, etc. We have reached the conclusion that excavation by means of a hypersonic impactor followed by remote sensing from the flyby delivery bus, as described below, is the most effective way to begin. While this brute-force method of getting to large depths below the surface involves the propagation of strong shocks in the

immediate region of the initial impact site most of the affected material is removed from the crater. This happens either as crater flow ejecta or as ejecta lifted directly from the crater floor due to the initial sublimation of highly volatile cometary material. In the upper walls of the crater, particularly after any initial back slumping, the exposed material should retain its original stratification and have experienced little modification from impact induced, large amplitude, stress waves.

After the successful application of a few such impactors to a small, but diverse, selection of cometary targets, the general nature, stratification, and extent of the physical and compositional properties of sub-surface materials should become clear. The design of focussed, relatively inexpensive, missions to confidently sample the most pristine materials that cometary bodies have to offer (and that will presumably to be found at considerable depth), should then be possible.

MISSION CONCEPTS AND GOALS

Appropriate objectives for the initial phases of deep sub-surface exploration are: 1) to relate the properties of evolved surface materials to the properties of relatively pristine materials at depth; and 2) to determine whether comets lose all of their ice as the surface evolves or whether it is sealed within their interiors. To attain the first objective we estimate, on the basis of the modeling noted above, that the excavation needs to penetrate the mantle of an active comet to depths of at least 20 m, expose and (to the extent possible) maintain the integrity of any stratigraphy in the crater walls, and expose subsurface layers over lateral scales of at least 100 m. For the second objective the impact should attempt to induce cometary activity in a dormant comet by penetration of the mantle.

Parameter	3200 Phaethon	9P/Tempel 1
Orbit type (q, e)	Apollo (0.14, 0.89)	Jupiter (1.49, 0.52)
Activity state	Dormant/Extinct	Typical periodic
Diameter (km)	5.2	6.6
Rotation period (hr)	3.6	~ 25
Escape velocity (m.s ⁻¹)	<2.4	~2.2
Effective Surface gravity (cm.s ⁻²)	<0.07	~0.08
Flyby mission opportunities:		
Launch.....	January 1, 2001	January 6, 2004
Arrival.....	March 13, 2002	July 4, 2005
Impact speed (km/sec).....	33	10
Impactor type	Dumb	Smart
Impactor mass (kg)	500	500
Impact accuracy (+/- m 3σ)	300	600
Observation time (min).....	7	16
Crater excavation parameters:		
Diameter (m).....	~160	~100
Depth (m).....	~30	~20
Time of formation (s)	~270	~200

Table 1. Sample impactor missions to a suspected dormant comet (3200 Phaethon. The dimensions and period are by K. Meech, 1996) and to an active comet, 9P/Tempel 1 (cf. Lamy, 1998).

The key mission design element is the delivery of a sufficiently massive impactor at hypersonic speeds that is capable of excavating a crater with a diameter > 100 m and depth > 20 m. Impactors with a mass of several 100 kg delivered at speeds of order 10 km/sec are needed to accomplish this (see below). To minimize the impactor mass and to assure a high enough impact speed we find that delivery of the impactor from a flyby spacecraft is the cheapest solution. The speed of the delivery must be moderated by the further requirement that there must be enough time for instruments on the delivery spacecraft to survey the target area, the impact, the growth of the

excavation (which can take several minutes), and then survey the details of the crater and its final geological context. More complex mission modes could include association of an impactor/flyby mission with a subsequent, presumably more complex, lander mission, perhaps instrumented for micro-robotic exploration or sample return.

In Table 1 we give parameters for two possible missions that we have investigated. The first is the delivery of a dumb (uninstrumented) impactor to a suspected dormant (*cf.* Weissman *et al.*, 1989; Williams and Wu, 1993) comet, 3200 Phaethon. The second is to an active comet, 9P/Tempel 1 that is currently the target of the planned DS-4 cometary lander mission (expected to arrive in December, 2005). A dumb aluminum impactor is used for Phaethon. Delivered at 33 km/sec, the primary intention would be to penetrate the mantle and stimulate cometary activity. Note that the time for observation from the flyby bus is relatively short (~ 7 min), only twice as long as the estimated crater formation time. This is a general characteristic of impactor/flyby missions. At 9P/Tempel 1 we have used an instrumented (smart) impactor of copper construction to minimize contamination of spectrographic measurements. The impactor carries a camera that has two roles: the first to provide detailed information on the area to be impacted, and second to improve the accuracy of delivery. In this case the impact velocity is lower and the available observing time, both in absolute terms and relative to the crater formation time, is much longer.

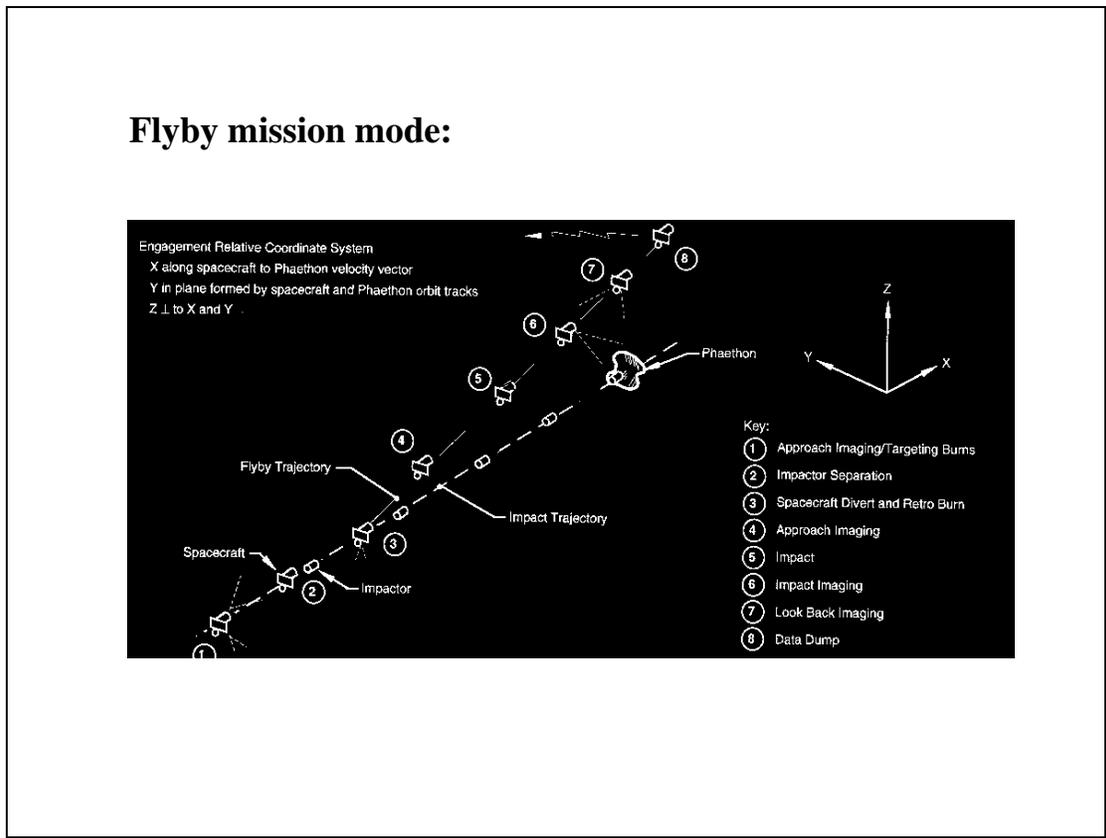


Fig. 2. Sequence of events that occur in an impactor/flyby encounter. Crucial to the success of both targeting and remote sensing is the inclusion of a high performance (~2 μradians/pixel), large format, imaging system, an autonomous trajectory correction system, and a powerful retro-propulsion module in the spacecraft payload. In the Phaethon mission the separation of the impactor occurs some 7.2 hrs before impact at a range of 855,000 km.

In Figure 2 we show schematically the sequence of events that would occur in a typical impactor/flyby mission. The 3-axis stabilized spacecraft is built around the relatively massive impactor, a high performance imaging system, and a powerful retro-propulsion module. On approach the imager finds the target and the spacecraft is automatically adjusted onto a collision course. This process continues repeatedly until an impact trajectory is assured (we estimate that a 3-sigma impact placement error of +/- 300 m is easily achievable) and gentle separation of the impactor from the spacecraft bus occurs. The spacecraft then diverts from the collision course

and fires the retro-propulsion system to slow the spacecraft and thereby allow the maximum time possible for remote observation of the target area, the impact, the subsequent crater, and its final geological context.

CRATERING PHENOMENA AND PROPERTIES

The nature of the cometary surface is poorly understood and this introduces some uncertainty into estimates of the response of the surface to hypervelocity impact. Except for being dominated by the presence of water ice and dust, the composition, the density, the material strength, the thermal properties are all grossly uncertain. It is inferred that cometary materials exhibit low strength ($\sim 10^3$ Pa) at large scales from the tendency of cometary nuclei to split, *e.g.*, comet Shoemaker-Levy 9 in the weak tidal field of Jupiter (Asphaug, and Benz, 1996), but locally they may be several orders of magnitude stronger, *e.g.*, in the vicinity of the evolved surface layers (Kuehrt & Keller, 1994; Moehlmann, 1995). Typical mean densities of cometary nuclei are expected to be low (~ 0.2 g.cm⁻³) because of their substantial response to jet reaction forces, *e.g.*, the delay of perihelion passage of 1P/Halley (Samarasinha and Belton, 1995), but the uncertainties are large. From the point of view of cratering mechanics (Melosh, 1989), these parameters suggest that the nuclei of typical comets are on the borderline of the strength/gravity scaling regimes. Assuming that the gravity regime applies, the size of a crater formed by hypersonic impact can be estimated by means of laboratory derived scaling laws. In Table 2 we give estimates of crater diameters and formation times for the 3200 Phaethon mission described in Table 1. Transient crater depths are typically 1/4 to 1/3 of the crater diameter, so the instantaneous crater may be 40 – 50 m deep.

Parameter				
Projectile Mass (kg; Aluminum)	200	Kilograms	500	670
		310		
<i>Diameters.....</i>	Estimated Diameter (m)			
Yield Scaling	124	141	163	178
Pi Scaling (see Melosh, 1989)	130	147	168	182
Gault (1974) Scaling	270	306	352	371
<i>Formation times.....</i>	Seconds			
Schmidt-Holsapple scaling (cf. Melosh, 1989)	238	253	270	281

Table 2. Estimated range of cometary crater diameters and formation times for a range of impactor masses applied to a 3200 Phaethon mission (see Table 1). Gault scaling is considered to give diameters that are too large. Thus, for a 500 kg impactor, we expect to create a crater ~ 160 m in diameter. The formation time is less certain. Low-g experiments (Cintala, 1989) indicate that formation times may be longer than those shown. Calculations by H. J. Melosh.

For a 500 kg impactor, contact with the cometary surface sets off a complex chain of events that ends up with the excavation of a small, circular, bowl-shaped excavation ≥ 20 m deep and ≥ 100 m wide some 200-300 sec later. The physical processes involved in these events are described in detail by Melosh (1989) but here we can only give a brief overview. At ≥ 10 km/sec, the velocity of the impactor is so high that the cometary material cannot respond through elastic wave or crack propagation. Fast moving stress waves of enormous amplitude propagate in both the impactor and the immediately surrounding cometary material. Within ~ 100 μ s, near a depth of a few meters, the internal energy of this material is unloaded into heat, vaporization, sublimation, and ionization creating a hot, dense plasma which produces a bright flash of UV, optical and thermal radiation that rapidly (\sim seconds?) fades as the plasma hypersonically expands up and clears the entry pathway into space forming a hypersonic vapor plume. The stress wave in the cometary material expands rapidly into the cometary sub-surface, shocking, collapsing the pores, fracturing, possibly liquefying and vaporizing H₂O and other high vapor pressure cometary materials until it can dissipate its energy through elastic wave and crack propagation. This entire process, which transfers both energy and momentum, sets a large mass of strongly modified material into motion that is ultimately ejected to space and accomplishes the excavation of the crater. The removal of crater material occurs as a transitory curtain of ejecta whose instantaneous surface falls on a (relatively) slowly expanding, ~ 45 deg half angle, cone. Because of the extremely low gravity all of this material is expected to leave the comet and

escape directly to space. After about 200-300 sec the ejecta curtain clears. Collapse may occur at the crater rim exposing strata of unmodified (this material could have seen relatively some low amplitude stress waves from the impact) sub-surface material in the upper crater walls and leaving a roughly circular crater with a final depth of ≥ 20 m. Because of the low gravity and the possibility of high vapor pressure materials in the debris and in the crater floor our experience with back-filling of the crater with rock breccia (as on the earth or moon) is probably not applicable. A cometary crater should easily clear itself to a much greater depth.

INSTRUMENT STRATEGY

The encounter distance (~ 500 km), size of the target nucleus (\sim few km), and the expected depth (~ 20 m) and morphology of the crater largely define the required performance of the remote sensing instruments. It is essential to obtain a record of the geological context of the crater before and after impact in order to locate the extent of ejecta emplacement and dimensions of blocks of material thrown out intact by the impact that may provide information on stratification and the strength of the upper surface layer. These surveys may also reveal lineations that trace cometesimal boundaries, lines of internal stress, etc., along which changes may occur as a result of the impact. At the crater itself it is essential to be able to resolve structures and layers in the upper walls where slumping may have exposed the first ~ 10 m of sub-surface material whose properties should reflect the evolutionary effects of solar insolation, etc. We expect that this material will have been left relatively unaffected by low amplitude stress waves propagating from the center of the impact (material that had been heavily shocked will have left as impact ejecta or slumped to the crater floor). The shape of the crater and the distributions of materials on its floor may also give information on lateral variations in the surface properties again reflecting cometesimal boundaries.

We therefore envision that the flyby spacecraft would support a high performance camera ($\sim 2\mu$ radians/pixel) capable of high resolution (up to 10% of the expected dimensions of the crater) mapping of the geological context of the target area in color ($0.35-1\mu$) on approach and then following the growth of the crater, the development of its ejecta blanket (with a time resolution of ~ 10 sec/frame), and, finally, resolving stratification in the crater walls at ~ 1 m/pixel resolution near the time of encounter (range ~ 500 km). A wide-field (~ 10 mradians) medium resolution camera is also required to cover the final geological context of the crater at encounter. A high spatial resolution, moderate spectral resolution ($\lambda/\Delta\lambda \sim 300$) near-infrared ($1-5\mu$) mapping spectrometer capable of mapping the basic distribution of composition in the crater and detecting parent molecules released from its floor and walls. Also essential are a high time resolution (sub-second) impact flash spectrometer and a dust impact mass spectrometer. The latter to analyze the minute amounts of material in the ejecta debris sheet that the spacecraft will transit (calculations indicate that this should be a minor safety problem, however, it would be prudent to carry a Whipple shield - a device to dissipate the energy of impacting meteoroids - on the spacecraft). In some cases the impactor could be uninstrumented. However, in others (*e.g.*, the 9P/Tempel 1 mission described above), a smart impactor with its own camera may be required. This camera would provide detailed coverage of the impact site while performing its primary duty to guide the impactor to the target.

If feasible, an impactor mission should be flown in conjunction with a lander mission instrumented to take advantage of the newly exposed subsurface materials within the crater. Space and the scope of this paper does not allow for a description of how these instruments would be designed, applied, or how the data would be returned.

CONCLUSION

The presently understood properties of cometary materials indicate that deep and laterally extensive excavations into cometary surfaces are possible at modest cost using the kinetic energy in a simple impactor delivered at hypersonic velocity from a flyby spacecraft. The excavation depths (≥ 20 m) and diameters (≥ 100 m) that are possible are consistent with the expected scales of vertical modification through processes induced by solar insolation and the background cosmic radiation. Investigation of exposed materials in the crater and induced cometary phenomena should yield information on the state, composition, and distribution of subsurface materials and constrain models of the evolutionary and transport processes that are expected to occur in the surface layers. As a result it should be possible to quantitatively gauge the degree of modification with depth and possibly locate the levels at which effectively pristine material resides. When applied to dormant comets, excavation to at least 20

meters may easily be sufficient to puncture the mantle to relatively fresh material below. For example, some models of mantle buildup indicate that a thin (~ 1 m) sintered, dust mantle may be sufficient to choke off cometary activity (*cf.* Keller, 1990).

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