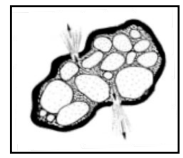
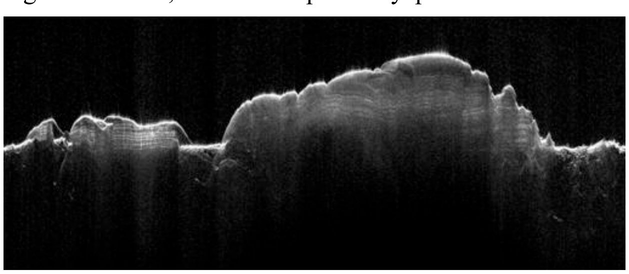
DEEP INTERIOR RADAR IMAGING OF COMETS. E. Asphaug (easphaug@ucsc.edu)[1], A. Barucci[2], M. Belton[3], S. Bhaskaran[4], D. Brownlee[5], L. Carter[6], J. Castillo[4], S. Chesley[4], P. Chodas[4], T. Farnham[7], R. Gaskell[8], Y. Gim[4], E. Heggy[4], K. Klaasen[4], W. Kofman[9], M. Kreslavsky[1], C. Lisse[10], L. McFadden[7], E. Pettinelli[11], J. Plaut[4], D. Scheeres[12], E. Turtle[10], P. Weissman[4], R. Wu[1]. [1]Earth and Planetary Sciences, University of California, Santa Cruz CA 95064, [2]LESIA, Paris, France, [3]Belton Space Exploration Inc., Tucson AZ, [4]Jet Propulsion Laboratory, Caltech, Pasadena CA, [5]U. Washington, Seattle WA, [6]Smithsonian Institute, Washington DC, [7]U. Maryland, College Park MD, [8]Planetary Science Institute, Pasadena CA, [9]CNRS, Grenoble, France, [10]Applied Physics Laboratory, Johns Hopkins University, Laurel MD, [11]U. Rome, Italy, [12]U. Colorado, Boulder CO.

Summary: The Deep Interior mission is designed to perform a comprehensive exploration of the interior, surface, and inner coma of 79P/du Toit-Hartley, a 3 km diameter Jupiter family comet, at high spatial resolution. It will relate the structures found there to the mode of formation of the nucleus, the history of its physical evolution, the geology of its surface, and the nature of its cometary activity. This shall be accomplished by an orbiting spacecraft capable of deep radar sounding, visible imaging, and imaging spectroscopy.

The next stage of comet exploration. The reconnaissance stage of the exploration of cometary nuclei, the most primitive of easily accessible solar system bodies, is in full swing with successful missions to comets Halley, Borrelly, Wild 2 and Tempel 1, and missions in progress (EPOXI and Rosetta) to Hartley 2 and Churyumov-Gerasimenko. This reconnaissance has so far yielded the discovery of an unanticipated range of diversity in geomorphic forms: multiplicities of pits, craters with vertical overhangs, global scale layering, mesas and plains. It has also revealed new geologic processes that are revolutionizing our concepts of the cometary interior – the discovery of repetitive mini-outbursts, of patches of enhanced H_2O ice, and of caldera-like depressions and smooth-flows. The first comet sample return (Stardust) has shown the mineralogy to be an unexpected mixture, incorporating highly refractory silicates from the inner solar system.

It is time to capitalize on these discoveries by moving into a new, detailed exploratory phase where we learn how comets work. We are presently refining a low-cost mission concept for a comet interior imager. The primary data product is a 3D image of the geologic underpinnings, at better than 10 m scales globally, comparable in many respects to a medical ultrasonographic brightness scan. With decameter scale radar imaging resolution, cometary structure can be revealed to a detail comparable to that seen in this cartoon.



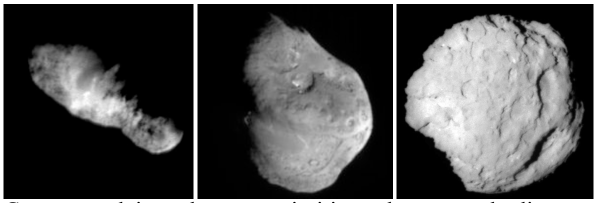


SHARAD reflection image of Mars North Polar Layered Deposits, ~1000 km track ([2]). With average thickness of ~2-3 km and a cold ice-rich composition analogous to comets, the NPLD provides an excellent basis for mission design. For Deep Interior, SNR shall be 20-30 dB greater due to proximity. Global illumination means that all signal in 3D contributes to advanced volumetric image processing.

Radar heritage. Radar reflection deep space missions now have high heritage thanks to the spectacularly successful Mars radar sounders, which have discovered detailed secrets deep beneath the ice (e.g.[1, 2]). On Earth, ice penetrating radars (IPRs) have been mapping the ice thickness of glaciers and ice sheets in Greenland and Antarctica. IPRs use a wide range of frequencies, depending on target of interest. Very low frequencies, 2-5 MHz, are used to probe warm outlet glaciers with very rough surfaces while 60-150 MHz systems map ice sheet thickness. On Mars two orbiting radar sounders have helped scientists discover layered ice deposits at Mars poles. MARSIS uses 1-5 MHz for deep penetration up to 3 km with a vertical resolution of 90 meters in ice while SHARAD (below left) employs a higher frequency 15-25 MHz to achieve a high vertical resolution of 9 meters to investigate ice deposits < 1.5 km.

Radar is thus a flight-heritaged technique capable of directly imaging the interior of comets, providing a first insight to their geophysical properties by imaging their structural, mechanical and compositional variations. Such information is crucial to understanding the evolution of comets as well as the potential of hazard migration associated to any potential collision with other celestial bodies. There is no doubt that comets are the first and best target for this experiment, owing to our understanding of ice dielectric properties, and to the rich science to be derived there. But the technique shall in the future be applied to assess the geophysical properties of potentially hazardous NEOs.

Nominal mission. Our nominal mission launches in 2016 to comet 79P/duToit-Hartley, an object which appears to have split in 1976, exposing some fraction of its interior.

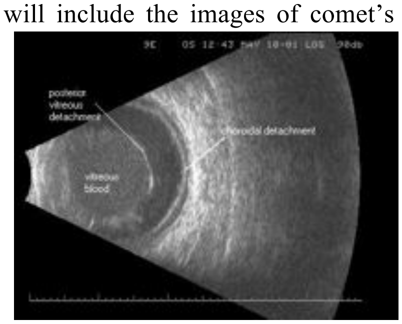


Comets nuclei are the most primitive solar system bodies accessible by spacecraft. We now have the technology to image their interiors at high resolution.

Other than this splitting event, which let to the transient appearance of a companion comet, the past five perihelia have been quiet compared to other comets, making this an ideal target for low-risk rendezvous operations. The diameter is known (~3 km) and its low level of activity, and pre-perihelion observations in 2013 shall provide more detailed information a few years prior to launch, for mission optimization.

Comets are composed of major volatiles including water ice, carbon dioxide, and carbon monoxide, plus silicates. The state of these ices, either in the form of crystalline ices and clathrate hydrates, or gas-laden amorphous ice is debated. It is generally considered that cometary water ice is in amorphous form. However, this hypothesis is challenged by models of water condensation in the early Solar system (e.g., [3]). The outer layer of the comet is expected to be a highly porous crust of refractory dust (e.g. [4]). Laboratory research by our team for this study and for Rosetta are ongoing, and while Deep Interior imaging is designed to be highly robust to all eventualities, we may be able to learn compositions from our combined investigations, and relate this to the strategy for sample return.

Data product: The radar reflection imaging (RRI) technique scans the comet's global structure from orbit: closely sampled radar echoes, acquired from a nominal 5-10 km distance as the comet rotates underneath, are processed to yield volumetric maps of mechanical and compositional boundaries, and to measure interior dielectric properties. To produce L1 data we will perform range compression on each data record using a reference chirp or tone signal. When stacked together, bursts in L1 product will form a radargram along the path s/c flew over the comet, something similar to MARSIS/SHARAD radargrams above. L2 will include the images of comet's deep interior and shallow surface reconstructed by using 10 and 60 MHz data sets. The comet image will be made using all the downlinked data. The quality of the image will increase with the accumulated radar data volume.

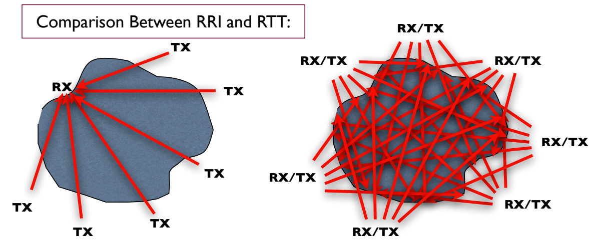


An injured eye, imaged by ultrasonographic imaging. The probe is to the left. By moving around the object a 3D volumetric image can be obtained.

B-scan imaging: We use a ray-tracing approach to a confined volume; this is analogous to a medical imaging technique called B-scan imaging which is used to image human internal organs such as heart (ultrasonic cardio echogram), eyes, and liver. The resulting image has a funnel shape as incident waves expand inside the body from the contact point with a probe toward the intended target of organ. By combining such 2D B-scan images taken around human body, researchers are able to construct a 3D ultrasonic tomography image. Several other kinds of advanced image processing can be done with the acquired data.

Complementary to Rosetta. Deep Interior is complementary to the CONSERT experiment [5] which is a 90 MHz bistatic transmission experiment operating for the duration of the Philae lander. Ours is a high resolution imaging experiment, and is sensitive to contrasts, while CONSERT probes slow variations in dielectric. Each shall yield information on the modes of formation and evolution of cometary nuclei.

Comparison Between RRI and RTT:



- Radio Transmission Tomography (RTT) collects data in the **transmission mode** (CONSERT)
- This means the radar wave that is generated by the transmitter is received at the opposite side of the object, or through reflections
- The information gathered with a single radar echo is the total **time of travel** through the object.
- The received wave also indicates the attenuation.
- The RTT is inherently low resolution dictated by basic physical principles of the transmission mode, but is more sensitive to slow variations.
- If the receiver is stationary (the case for CONSERT) the object can not be inspected from all angles, resulting in blind spots in the final image.
- **This type of tomography works well for smaller or transparent bodies and detects slow variations in dielectric**

- Radio Reflecton Imaging (RRI) collects data in the **reflection mode** (Deep Interior)
- The radar wave that is generated by the transmitter is received at a the same location by the radar receiver; thus, data is collected from all around the comet.
- The information gathered is the **dielectric contrast** information within the object with associated time delay.
- Time coherency between transmitter and receiver is readily established by co-location.
- SNR of 60 dB, capable of detecting 5% contrast.
- The received wave also indicates the attenuation.
- The RRI scheme provides much higher resolution images but is not as sensitive to slow variations.
- RRI images contrasts and reflectors, and is not as sensitive as RTT to gradual variation in dielectric.
- **The RRI scheme works well for all comets and is designed to reveal detailed images of contrasts and reflectors**

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