DEEP INTERIOR: HIGH-RESOLUTION VOLUMETRIC RADAR IMAGING OF A COMET NUCLEUS.

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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. This need will be first satisfied by *Rosetta* at comet Churyumov-Gerasimenko for a landed mission. There is also a need to return to some of the comet nuclei that have presented the discoveries outlined above. And so *NExT*, a flyby, is enroute back to Tempel 1 to investigate the artificial crater that was excavated by *Deep Impact* and to see what changes have been wrought by a passage through perihelion. Ultimately we shall return to one of these nuclei for a surface sample return.

Back to the future: What is missing is high resolution volumetric imaging of a comet nucleus interior – a 3D tomographic picture of the geologic underpinnings, at better than 10 m scales globally. Radar reflection missions now have high heritage thanks to the spectacularly successful Mars radar sounders, which have discovered secrets deep beneath the ice.

Deep Interior will use the same high performance radar reflection technology at the *Stardust* flyby target 81P/Wild 2 (left), a comet that showed some evidence of layering but presented a massively pitted surface in stark contrast to that seen on Tempel 1. Of course, one of the greatest benefits of making a detailed reconnaissance with Wild 2 is that we shall discover the global context for the samples that were brought back to Earth from the *Stardust* mission's capture of its cometary outburst material [1].

While comparison is appropriate, our investigation is much more detailed than the radio sounding experiment that is offered by *Rosetta* [2]. The CONSERT experiment (Comet Nucleus Sounding by Radio-wave Transmission) is very different owing to its data acquisition mode (all pathways in transmission, retransmitted to the orbiter as part of the lander's function). It measures gross heterogeneity distribution affecting radio wave propagation, thereby detecting characteristic signatures leading to the identification of overall homogeneity and stratification. CONSERT has a strict data volume limitation, in comparison to *Deep Interior* whose radar is the primary science payload. The two investigations will provide complementary and not overlapping science data to the community.

Beyond Mars: The successes of the MARSIS and SHARAD planetary radars onboard *Mars Express* [3, 4], and the *Mars Reconnaissance Orbiter* [5], and LRS onboard *Kaguya* [6], have proven planetary radars to be the key to understanding subsurface geology, especially in ice-rich terrains where they penetrate to kilometers even at relatively high frequency. Among the most unambiguous of these radar imaging results is the revelation of layering in the Mars polar ice caps, where structure is resolved by SHARAD to ~10 m scales.

The investigation of the Mars polar caps is thus a most promising starting point for cometary science. With a SHARAD-class radar in orbit about a comet, or other ice-rich primitive body, it is proven that we can construct a global 3D radar image of the interior. Not only can we do this, but in the post-SHARAD era we know the specific instrument performance requirements, allowing us to design a mission that achieves, at global scales, better than 10 m resolution 3D images.

Better at a comet: We shall acquire 10 Tb of radar data – comparable to the SHARAD data acquisition of the Martian polar caps, but in the ~5 km diameter volume of the Wild 2 nucleus. It is a straightforward rendezvous mission, and is compelling for three reasons.

First, the radar instrument is now high heritage, and its performance over ice-rich terrains is well understood. Radar performance will be superior to that of SHARAD simply due to the fact that our primary observation orbit is ~5-10 km as compared to ~300 km.

That alone improves radar signal-to-noise ratio by ~20 db depending on the exact size of the comet.

Second, we will be able to collect data from all sides of the object in the reflection mode, allowing to accurately measure attenuation values and speed of wave in the comet (i.e. the complex dielectric values). So this is thus not just imaging of reflectors and scattering properties, but a direct volumentric measurement of cometary compositional properties.

Third, a reflection radar deployed in orbit about a primitive body will enjoy significant simplifying benefits, compared to using the same instrument for Mars or lunar radar science. The lack of an ionosphere makes for far simpler data modeling and analysis, compared with what is being required at Mars. Also, the body is globally illuminated during every data acquisition, and due to a complete aperture coverage around the object, with coherent processing, there is no longer a clutter noise signal. All signals are good signals and will be used in the 3-D volumetric imaging.

Mission design: The planetary radar imaging 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. Achieving our science goal of a 3D volumetric model to better than 10 m resolution requires the determination of spacecraft orbital position, a posteriori, to a distance of order 1 meter (1σ) at each data acquisition, and will require the return to Earth of approximately 10 Tb of radar data.

Payload: The baseline science payload of *Deep Interior* consists of a dual-frequency ground penetrating radar, a high-resolution visible imager, and a laser altimeter. Radar instrument development and testing are ongoing for a more powerful radar under a NASA PIDDP fund at JPL and the University of Iowa. A prototype of this radar has already flown numerous times in airborne configuration including one in January 2009 with deployment in Antarctica.

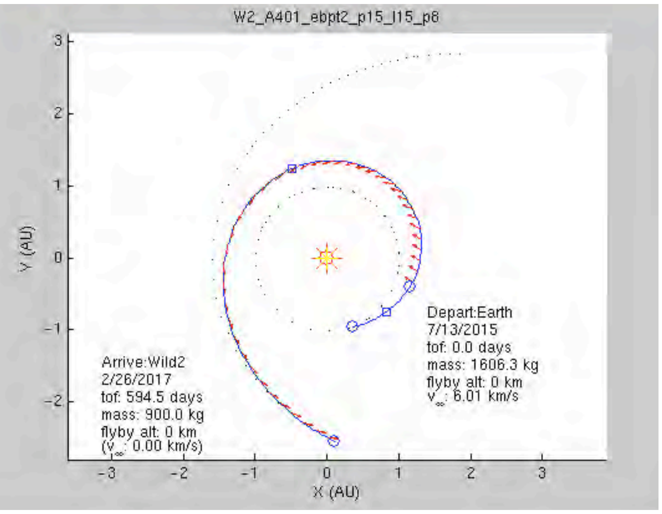
Tour and target body: The mission to comet Wild 2 (right) calls for a 2 year flight under solar electric propulsion, arriving in 2017, followed by a 120 day rendezvous. We have chosen this target for its high scientific relevance to NASA, and for its short mission duration. In the instance that the comet is active upon arrival, we maintain a holding observational position until the nucleus becomes quiescent and the dynamical system is understood. Note that Wild 2 is egressing at the time of the encounter.

Data acquisition. Data will be obtained in three modes: (1) from a holding distance of ~30 km, (2) via orbital or station keeping trajectories at an expected ~5 km distance, and (3) via flyover trajectories at speeds comparable to the escape velocity (~1 m/s), coming within 300 m of the surface.

Deep Interior utilizes a polar orbit, or else station keeping, while the comet rotates underneath; the result is to "peel the apple" with thousands of unique radar returns, providing global interior coverage. Camera images allow for the accurate reconstruction of spacecraft position at each radar acquisition. While not strictly required for the radar volumetric imaging, a laser altimeter reduces navigational uncertainty and allows for its own novel science.

Conclusions: *Deep Interior* uses a proven approach to resolve the whole-body geology of a comet to better than 10 m, using high-frequency radar in reflection imaging mode. This mission shall yield information on the mode of formation of cometary bodies and their possible evolution. It will distinguish between current competing theories of internal structure (e.g. layering vs. fractal aggregates) and will characterize the role of internal processes in producing cometary activity: H_2O phase transitions, fluidization, and sub-surface collapse. Perhaps most important, it will provide direct geologic context for the only samples we have from a cometary nucleus.

References: [1] Brownlee, D. *et al.* (2006), Science 314:1711. [2] Kofman, W. *et al.* (1998), ASR 21:1589 [3] Picardi, G. *et al.* (2005), Science 310:1925 [4] Plaut, J. *et al.* (2007), Science 316:92 [5] Seu, R. *et al.* (2007), JGR 112:E05S05 [6] Ono, T. *et al.* (2008), EPS 59.



Nominal trajectory for *Deep Interior* is a 1.9 year flight launching from Earth in mid-2015 and arriving at Wild 2 in early 2017.