ATHENA: THE FIRST-EVER ENCOUNTER OF (2) PALLAS WITH A SMALLSAT. J. G. O'Rourke[1,*], J. Castillo-Rogez[2], L. T. Elkins-Tanton[1], R. R. Fu[3], T. N. Harrison[1], S. Marchi[4], R. Park[2], B. E. Schmidt[5], D. A. Williams[1], C. C. Seybold[2], R. N. Schindhelm[6], J. D. Weinberg[6], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, [2]Jet Propulsion Laboratory, Pasadena, CA, [3]Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA, [4]Southwest Research Institute, Boulder, CO, [5]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA, [6]Ball Aerospace, Boulder, CO, *jgorourk@asu.edu.

Introduction: Pallas is the largest unexplored and most off-ecliptic protoplanet in the main belt and the parent of a populous impact family that includes many near-Earth asteroids. Discovered in 1802 by serendipity during the earliest observations of Ceres, Pallas is nearly the same size as Vesta. Protoplanets provide fascinating examples of planetary processes like volcanism, tectonics, and internal differentiation. Existing observations hint that Pallas fills an observational gap in terms of water content between Vesta and Ceres—the two protoplanets explored by NASA's Dawn Mission [1,2]. The orbit of Pallas is more inclined (~34.8º relative to the ecliptic) than any main belt object with greater than a tenth of its diameter, which indicates a unique dynamical history [3]. Notable members of the Pallas impact family include (3200) Phaethon [4-6], which is a small near-Earth asteroid that produces the Geminids meteor shower and perhaps collectable meteorites someday.

The Athena Mission takes advantage of a rare opportunity to perform a Mars gravity assist and encounter Pallas during its ecliptic crossing with a SmallSat designed and launched as a secondary payload.

Science Goals & Objectives: Exploring Pallas with Athena addresses three high-priority questions from the 2013 Decadal Survey for Planetary Science:

- How did differentiation vary on bodies with large proportions of ices?
- How have the myriad chemical and physical processes that shaped the solar system operated, interacted, and evolved over time?
- How did the current population of asteroids evolve in time and space?

Athena makes substantial progress towards achieving two broad, high-level science goals:

1. Understand the role of water in the evolution of Pallas.
2. Constrain the dynamical evolution of Pallas and asteroids in the Pallas impact family.

Athena targets and completes three science objectives focused on density, geology, and impact crater statistics:

A. Determine if the average density of Pallas is consistent with a water-rich bulk composition. Density is a first-order proxy for water content, but remains highly uncertain for Pallas because of the wide range of reported estimates for volume and total mass. Previous estimates vary between ~2400 and 3400 kg/m^3 [1,2]—a hugely consequential disparity that spans nearly the entire range from Ceres to Vesta. Ground-based telescopes with adaptive optics have improved shape models, but mass estimates still have uncertainties as large as ~22%. The Gaia space observatory will precisely measure masses of small asteroids. However, Gaia was designed to observe point sources and automatically discards images of large, spatially resolved objects like Pallas [7].

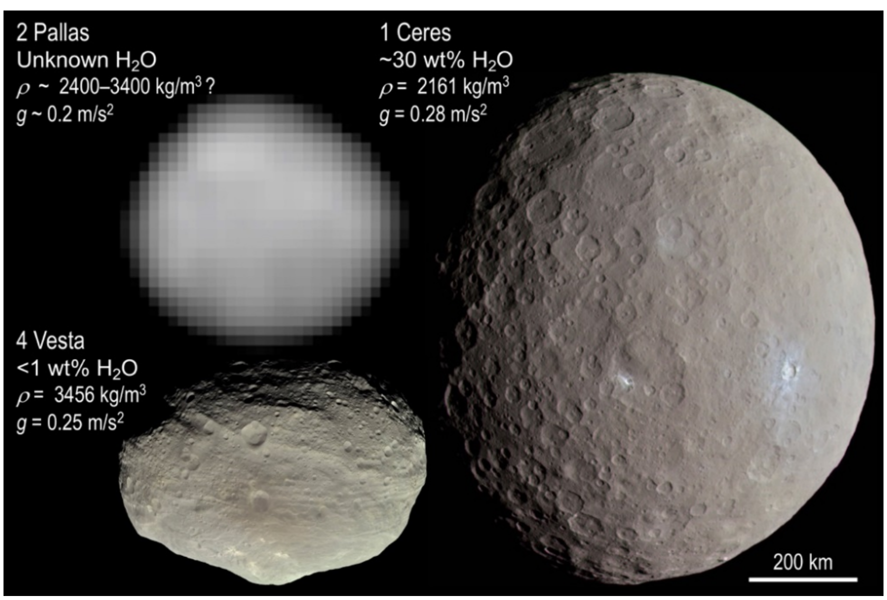

Figure 1. Pallas is the largest unexplored planetary body inside Neptune's orbit. Protoplanets Ceres and Vesta explored by Dawn serve as end-members in terms of water content with comparable geology given similar surface gravities. Athena maps geologic features on the surface and conducts radio science to infer whether Pallas contains substantial amounts of water ice and to determine relative ages and effects of high-velocity impacts on the imaged surface. Image of Pallas from Hubble [1].

B. Determine if the rheology and geology of the near-surface layers are consistent with a water-rich mantle and crust. Athena studies the geology of Pallas to answer one fundamental question: Do observations of widespread aqueous alteration on the surface signal that the crust and upper mantle of Pallas are ice-rich?

Various observations indicate that Pallas has a hydrated surface composition—perhaps a more thermally processed version of water-rich protoplanets like Ceres. However, a water-poor bulk composition would not necessarily conflict with the widespread occurrence of aqueously-altered materials on the surface. A surface layer of chondritic material (resembling CM chondrites, just like Pallas) could remain unmelted even as the underlying object differentiates into a silicate mantle and perhaps a small metal core [8]. There are several hints that the surface of Pallas has rheological strength and thus might not contain as much water ice as the uppermost layers of Ceres. Pallas has a populous impact family, while Ceres possibly produced interplanetary dust particles but birthed no known impact family or meteorite. Viscous relaxation reduced topography on Ceres but not Vesta, and Pallas appears to sustain at least some topography on scales of a few hundred km [1,2].

Abundant water ice would significantly decrease the rheological strength of the near-surface material. Athena infers the rheological strength by imaging the long-wavelength topography and the relaxation state and morphology of impact craters. Topography at spherical harmonic degrees 4 to 10 is diagnostic of viscous relaxation and constrained even without global imaging [9]. The critical diameter where impact craters transition from simple to complex morphology is ~7.5–12 km for Ceres but ~38 km for Vesta [10]—and more than 100 craters with diameters <40 km are expected to exist on the encounter hemisphere of Pallas. Finally, Athena observes a wide variety of geologic features whether Pallas is water-rich like Ceres or dry like Vesta.

C. Determine the history of impact bombardment on Pallas and the effects of high-velocity impacts on cratering. Athena determines relative ages of regions on the imaged surface with crater counting. Because Pallas has a relatively high orbital inclination and eccentricity, predicted impact speeds are ~11 km/s—more than twice the ~5 km/s average for impacts on Ceres. The Model Production Functions (e.g., the cumulative numbers of craters larger than a given diameter) for terrains with ages of 4 Ga on Ceres and Pallas are very similar. However, fast impact velocities on Pallas should produce vastly more melt production from impacts compared to Ceres and Vesta. If there is an ice-rich crust, Athena observes large and abundant high-albedo features similar to those in Occator Crater and other geologic settings associated with impacts on Ceres [11]. Fast impacts on a rocky crust would produce flat-lying deposits inside impact basins that are indicative of deep, ponded melt.

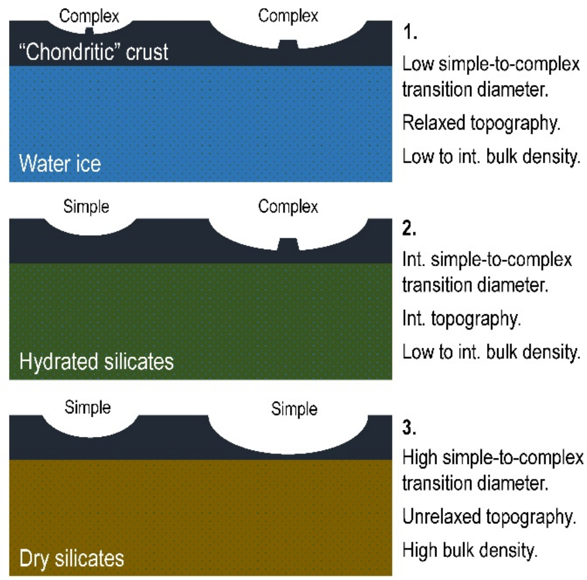

Figure 2. Athena tests three models for the differentiation of the crust and upper mantle of Pallas.

Data Collected During Pallas Encounter: Athena conducts radio science and visible imaging with a miniature color (RGB) camera. Continuous antenna pointing to Earth for two-way Doppler tracking enables <0.05% precision on the mass of Pallas. Athena images the encounter hemisphere for ~2 hours before and after closest approach (in total, more than one half of the rotational period of Pallas) at ground sampling distance <150 m (panchromatic) and <450 m (color) and obtains multiple (≥3) overlapping images at <200 m in geometries that are suitable for deriving stereo topography.

Because no spacecraft has yet visited Pallas, this dataset will enable unanticipated, high-impact science that goes far beyond our three targeted science objectives.

Synergies with Other Missions: The JAXA DESTINY+ Mission is planned to visit (3200) Phaethon close to when Athena encounters Pallas. As the largest B-type object in the main belt, Pallas also provides valuable context for exploration of a B-type asteroid with roughly ten billion times less volume—Bennu, the target for sample return by the OSIRIS-REx Mission.

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