TROJAN ASTEROID INTERIORS AS A TARGET FOR SPACECRAFT EXPLORATION. J.P. Emery[1], D.P. Cruikshank[2], K.S. Edgett[3], E. Dotto[4]. [1]NASA Ames / SETI Institute (jemery@mail.arc.nasa.gov), [2]NASA Ames Research Center (Dale.P.Cruikshank@nasa.gov), [3]Malin Space Science Systems (edgett@msss.com) [4]INAF, Osservatorio Astronomica di Roma (dotto@mporzio@astro.it).

Context and Properties: To date 2050 Trojans are known, with an estimated $5.9x10^5$ larger than 1km [1,2] (compared to ~$6.7x10^5$ for the Main Belt). An explosion of interest in physical studies of asteroids in the 1970s benefited the Trojans as well. They were found to have very low albedos [e.g. 3], which has been confirmed by more recent work [4,5], and the extremely high lightcurve amplitude (and therefore extreme shape) of 624 Hektor was quickly uncovered [6]. Despite this exciting result, lightcurves have been measured for relatively few Trojans, although one study concluded that Trojans with diameters < 90 km are fragments, while larger objects are primordial [7]. This is in agreement with interpretation of a change in slope of the size frequency distribution[1,2].

Reflectance spectroscopy at visible wavelengths failed to discover any absorption features, but revealed red spectral slopes, comparable to outer belt D-type asteroids [8]. The low albedo and red slope were modeled by mixtures of (hydrated) silicates, carbon black, and complex organics [8]. This result was incorporated into a solar nebula condensation sequence in which increasing organic content is responsible for red slopes in the outer belt and Trojan swarms [9]. Visible spectroscopy through the present has continued to show featureless spectra with slopes that range from neutral (gray) to moderately red [e.g., 10–13]. No ultra-red slopes comparable to many Centaurs and KBOs have been detected among the Trojans. Near-infrared spectroscopy has also failed to detect any clear absorption features, including no evidence for H_2O, no 1 and 2 μm silicate bands, and no absorptions from organics or hydrated minerals [e.g., 14–17]. Note that Vis-NIR spectra can be modeled without the use of organics (just silicates and amorphous carbon) [18,19], and the absence of absorptions in the 3-4 μm range may strongly limit the type and abundance of organics possible on these surfaces [19]. Discrete mineralogical features attributed to fine-grained (~few μm), anhydrous silicates were recently detected in mid-IR thermal emission spectra of three Trojans using the Spitzer Space Telescope. The mineralogy may resemble that of cometary silicates, and the spectral shape indicates that the surfaces are probably either very porous or that the grains are imbedded in a matrix that is relatively transparent in the mid-IR [20].

Although some significant uncertainties remain, we have learned a lot about the surfaces of Trojans from ground-based observations over the past three decades. Unfortunately, all of the studies summarized above only sense the upper few mm (at most) of the surface. With judicious choice of space weathering mechanisms, these results can be made to fit nearly any model for the interior composition and structure of Trojans. The observation with the most direct implication for internal composition of Trojans is the discovery and follow-up astrometry of a Trojan binary (617 Patroclus), which yielded a density of 0.8 ± 0.2 g/cm^3 [21]. The most straightforward interpretation includes both significant bulk porosity and a relatively significant ice fraction in the interior.

Motivation for a mission: Dynamical models of the origin and evolution of the Jupiter Trojans are equally intriguing. [22] showed using numerical techniques that the Trojan swarms are stable over >4.5 Gyr against gravitational perturbations from the other giant planets, though the region of stability is decreasing, and the overall diffusion of objects is out of rather than into stable librating orbits. Gas drag in the early nebula could reverse that trend, capturing objects. [23] found that a growing Jupiter would naturally capture objects into the Lagrange points without the need for substantial gas remaining after giant planet formation. In both of these scenarios, capture of objects already orbiting near Jupiter is most likely, though small fractions could come from scattering from the Main Belt or Kuiper Belt. Such scattering would be less likely before the giant planets fully formed, so the [23] mechanism would probably result in a more homogeneous population of mid-solar nebula objects than the gas drag model. More recently, [24] suggested a migrating giant planet model which predicts that, as Jupiter and Saturn pass through a mutual 2:1 resonance, the Jupiter Trojan swarms are first emptied of their initial residents, then repopulated with material primarily originating in the Kuiper Belt. In this scenario, the final Trojans pass through a high-eccentricity phase which brings them close to the sun, devolatilizing their surfaces. According to this model, the Trojans' bulk interior composition should then reflect the diversity of the Kuiper Belt, with only a small fraction of objects from the inner or middle solar nebula.

While these models are cast here in terms of the origin of Trojan asteroids, they have far broader implications concerning the formative stages and evolution of the Solar System (and, by extension, other planetary systems), including the structure of the Kuiper Belt, the properties of outer planet systems, and the impact history of the inner Solar System (i.e., late-heavy bombardment), among others. The interior compositions of Trojan asteroids are a key to distinguishing between these different hypotheses, providing a deeper understanding of the origin and dynamical evolution of the Solar System. Furthermore, linked analysis of surface and internal composition will illuminate important surface altering physical processes that can be leveraged in the continuing remote study of small bodies in both the inner and outer Solar System.

Ground-based observations remain critical to our understanding of Trojan asteroids, and continuing studies form the ground will certainly be beneficial. For example, very few phase curves exist for Trojans, and additional phase measurements would help constrain the structure of their surfaces. Similarly, lightcurve periods and amplitudes have been measured accurately for only a handful of Trojans, and only one (624 Hektor) has a reasonable pole solution. Deep searches for comet-like behavior (comae and/or tails) could help constrain the abundance of near-surface volatiles. Vis-NIR spectroscopy continues to uncover somewhat diverse spectral shapes. Spectra of small Trojans may offer the best ground-based hope of getting a glimpse of internal, primordial compositions. Additional mid-IR spectra would allow determination of silicate mineralogy, as recently detected by Spitzer on three Trojans, and whether it tracks with the diversity of Vis-NIR spectral shapes. While beneficial, particularly for determining surface properties, these ground-based studies will not reliably constrain internal composition, and, therefore, will not be able to unleash the full potential of the Trojans for testing hypotheses of Solar System formation and evolution. A spacecraft mission to the Trojans is necessary.

Discussion: The recognition of Trojan asteroids as important spacecraft targets is not new. The Decadal Survey ranks a Trojan mission as a high priority for NASA, with "deep ties to understanding the origin of primitive bodies" and offering "new insights into space weathering and other processes affecting" small bodies. The Outer Planets Assessment Group (OPAG) supports the Decadal Survey's priorities with respect to small bodies, and also specifically calls out the Trojans (along with Centaurs) as high priority targets for spacecraft missions. As introduced above, it is necessary that such a mission have the capability to investigate the internal composition of Trojans along with surface characterization.

As a target for a spacecraft mission, we note that the Jovian Trojans are not located "on the way to somewhere else." They are not accessible as flyby targets for typical outer Solar System missions (e.g., 2002 JF56 imaged by New Horizons), as the typical spacecraft will use Jupiter for gravity assisted acceleration. To study the Trojans requires a dedicated mission.

Key spacecraft investigations of Trojans necessarily must focus on both surface and interior properties. Visible wavelength imaging would focus on geology and geomorphology, including cratering and collisional history, clues to internal structure, and comparision of landforms with those on comets as well as other small bodies. Visible and infrared (near and middle IR) spectral mapping would focus on heterogeneities in surface composition, particularly impact-induced exposures that reveal subsurface composition. Radio science techniques will permit determination of asteroid mass; combined with shape information from images, this will yield bulk density. However, an active means of getting below the surface will be necessary for adequate determination of internal composition and structure. Experiments to be considered include (but are not limited to) a Deep Impact style collision; direct measurements by a lander with a penetrator, drill, or scoop; gamma ray spectroscopy, and subsurface radar.

Like the famous horse devised by Odysseus, a spacecraft mission to the Trojan asteroids would allow us to penetrate formidable barriers to knowledge and enter into a better understanding of our Solar System.

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