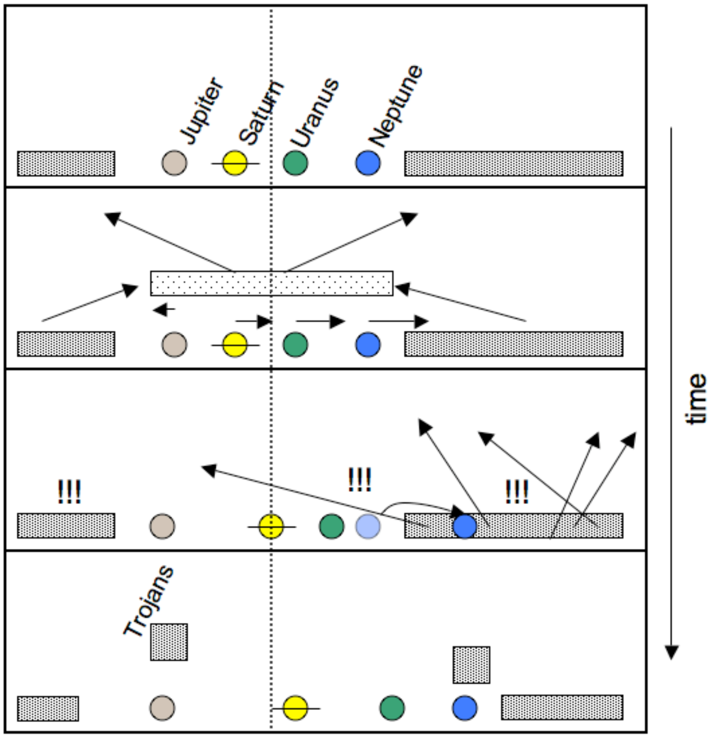
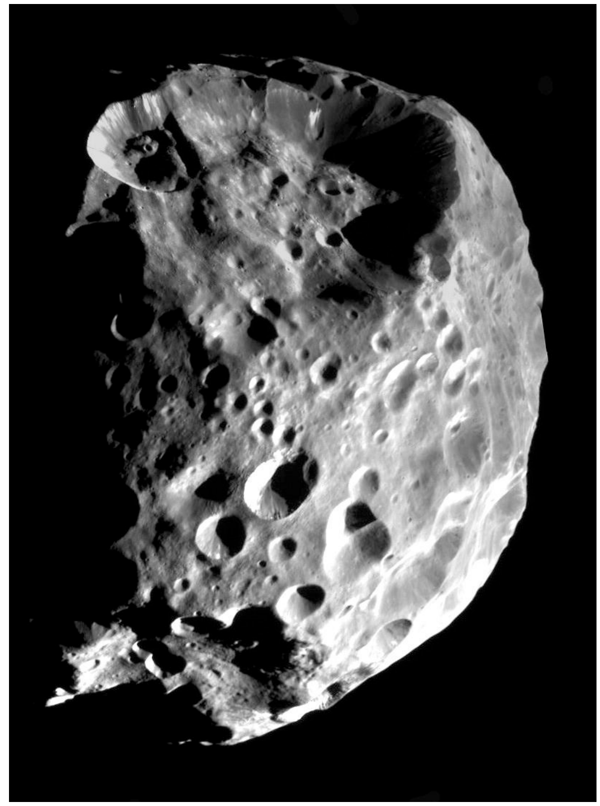
The Trojan Asteroids: Keys to Many Locks





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Executive Summary: The Trojan asteroids of Jupiter lie at the crux of several of the most interesting outstanding issues regarding the formation and evolution of the Solar System. Jupiter's companion asteroids hold the potential to unlock the answers to fundamental questions about planetary migration, the late heavy bombardment, the formation of the jovian system, and the origin and evolution of transneptunian objects (TNOs). Despite a population comparable in number to the main asteroid belt, they remain poorly understood. Dynamical studies over the last decade have provided evidence that they may have formed alongside TNOs and been captured into their current orbits early in solar system history, making them invaluable windows into TNO properties. Formation in place would make them equally compelling targets, as witnesses to the earliest history of the jovian system and the last remaining precursor material to the Galilean satellites. Spacecraft investigation of the Trojan population has been recognized as a current New Frontiers goal, should remain a very high priority for the coming decade, and most importantly is achievable now.

Motivation and Background: Jupiter shares its orbit with a host of small bodies. An estimated 600,000+ objects larger than 1 km in diameter librate about the L4 and L5 points in the Jupiter–Sun system (Jewitt et al., 2000, Yoshida & Nakamura 2005), the same rough order of magnitude as the number of similar-sized main-belt asteroids. *No mission* has gone through the regions in space where Jupiter Trojan asteroids are found (also called the "Trojan clouds"); every outer solar system mission has either remained at Jupiter or used a Jupiter gravity assist en route to points beyond. What we know about the Trojan asteroids is based on observations of these objects as point sources and analogy with spacecraft visits to objects believed to be similar. We can achieve full understanding of this compelling population only through a dedicated mission to the Trojan asteroids.

Compositional data from Trojan asteroids are scarce. The albedos that have been measured are quite low, with a mean optical geometric albedo of 0.04 found for a sample of 32 objects by Fernandez et al. (2003). These low albedos (among the lowest in the solar system), in conjunction with the Trojans' distance from the Earth, have made ground-based observations difficult. Visible and near-IR spectroscopy reveals featureless spectra with shallowly to steeply red spectral slopes, comparable to C-, P-, and D-type asteroids as well as cometary nuclei (Jewitt and Luu, 1990; Lazzarin et al., 1995; Dotto et al. 2008 and references therein). Despite the lack of detected absorption features, the Trojans' low albedos and red colors are consistent with, but not unique indicators of, macromolecular hydrocarbons, as on cometary nuclei. Similar lack of spectroscopic evidence for ices, organics, and other volatiles also occurs for comet nuclei, whose bulk compositions are icy, but masked by a thin, dark, refractory mantling layer. As smaller objects in the Trojan clouds have been observed, a wider spread in spectral slopes has been seen, and evidence for two distinct spectral groups has emerged (Szabó et al. 2007, Roig et al. 2008, Emery et al. 2009), although it is not clear whether the differences indicate a diversity of compositions or a diversity of regolith ages on Trojan surfaces (Bendjoya et al., 2004; Fornasier et al., 2007).

Two Trojan asteroids have been found to have satellites, leading to an estimate that multiple systems comprise a few percent of the population. A satellite orbit provides the additional information necessary for a density to be calculated for the primary, though the two Trojan systems show disparate results: the primary in the Patroclus system has a mean density of 1.08 g/cm^3 (Mueller et al. 2009), while the orbit of Hektor's satellite implies a density of 2.4 g/cm^3

for that object. As seen in Figure 1 (from Marchis et al., 2006), these values require significant porosity for Patroclus for any reasonable composition, while Hektor's composition conversely implies either a lack of ice and volatiles (perhaps lost during satellite formation) or a significantly lower porosity than Patroclus, or both.

The compositions inferred for Trojan asteroids from these studies are roughly similar to cometary compositions: ice-rich, organics-rich, largely pristine bodies. However, the exact composition expected depends upon the formation location of these objects.

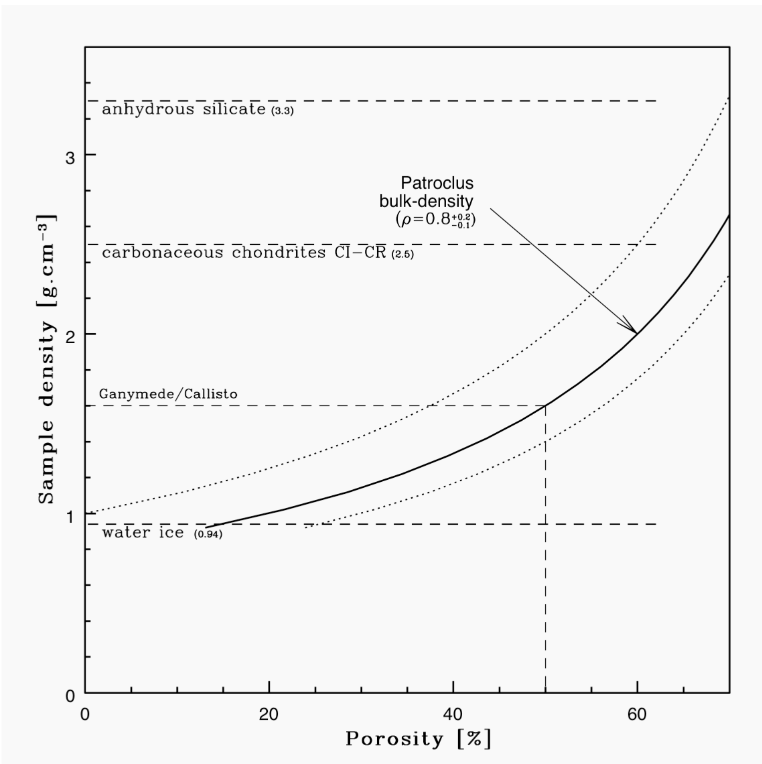

Figure 1 Patroclus' density is below that of water ice, and is represented on the figure by the solid curve, with dotted curves representing the uncertainties on that figure. Dashed lines represent the densities of representative solar system compositions: water ice, carbonaceous chondrites, anhydrous silicates, and the icy Galilean satellites. Each composition, read across to Patroclus' density curve, implies a porosity, read down from the curve to the x axis. For instance, if Patroclus has the same composition as Ganymede/Callisto, its implied porosity is 50%. Regardless of composition, Patroclus has an appreciable bulk porosity, with an icy, porous nature most likely. (from Marchis et al., 2006)

More recent work has cast some doubt on the conventional wisdom concerning the Trojan asteroids. The first observations of Trojan asteroid surfaces near 3 μm (Jones et al., 1990) found no evidence of organics, OH-bearing minerals, or ice, all of which have strong absorptions at those wavelengths. This was interpreted as evidence that any ice present was contained in the asteroidal interior and that Trojans never were heated to the point of melting water to drive aqueous alteration. Further observations and modeling of the largest Trojan (624 Hektor) by Cruikshank et al. (2001) showed that a few weight percent of water (or its equivalent in OH) could exist on its surface but that organics were not required to duplicate its spectral slope.

Emery and Brown (2004) further noted from 2-4 μm spectra of 8 Trojans that organics could not be responsible for the red spectral slopes due to the absence of corresponding absorptions near 3-μm (Figure 2). Recent Spitzer observations in the mid-IR (5–38 μm) by Emery et al. (2006) show evidence for silicates on Trojan surfaces and a surprising similarity to cometary comae interpreted as caused by either extremely underdense surfaces or silicates embedded in relatively transparent materials. Again, no organics were necessary for those fits. ***Existing spectra show no concrete evidence for volatiles or organics, only upper limits. This has been surprising, since our understanding of small bodies and nebular composition leads to a strong expectation that Trojans should be volatile- and organic-rich objects. Only through a dedicated mission to a Trojan asteroid can such enigmas be solved.***

The great promise of exploration of the Trojan Asteroids was recognized by the previous Decadal Survey and amplified by the NOSSE update of 2007, which elevated a Trojan asteroid mission to the list of New Frontiers-worthy missions, a recommendation followed by NASA in the NF3 round. While space considerations necessarily limit our discussion of the Trojan asteroids, we point the reader to the NOSSE report for their independent rationale.

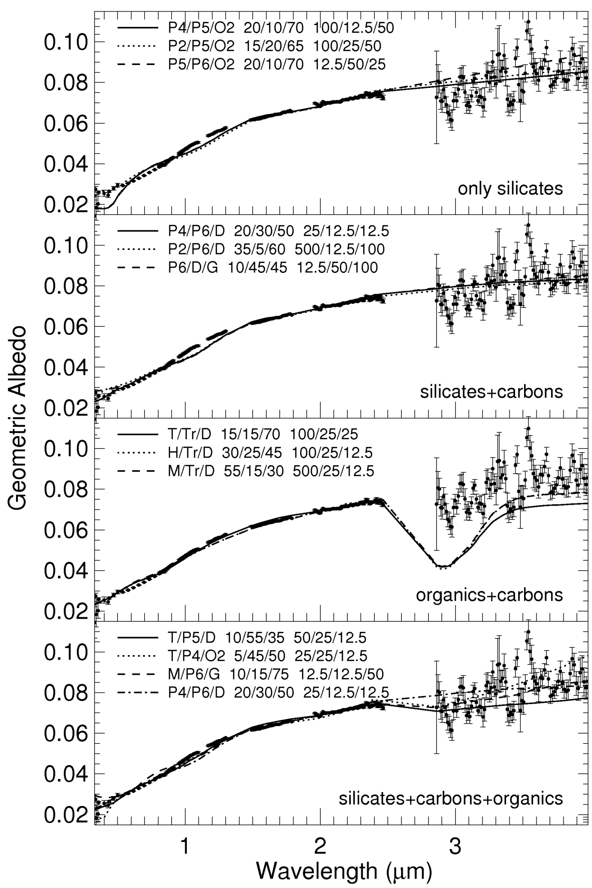

Figure 2 These fits to the spectrum of 624 Hektor show that while a small fraction of organic material may be present on Trojan surfaces, it is not required to explain the spectral data. In fact, the absence of any detectable absorption in the 2.8 – 4.0 μm region severely limits the type and abundance of organic material that is possible. Telescopic data alone are unlikely to provide detailed views of Trojan compositions. (from Emery and Brown 2004)

Relations and Origin of Trojan Asteroids: The similarity between Trojan and cometary surface properties has also been applied to the irregular satellites of Jupiter and Saturn and to the Centaurs and TNOs. However, dynamical connections between these groups seem to be statistically unlikely, and models suggest there is little movement from one group to another. Until recently, most dynamicists favored the idea that the origin of the Trojans were linked to the growth and evolution of Jupiter. In these scenarios, a gaseous envelope accreted onto Jupiter's core and quickly increased its mass. This allowed the libration regions near the L4 and L5 Lagrange points to expand, such that planetesimals wandering near these zones would be captured. As Jupiter increased its mass, the libration amplitudes of the captured planetesimals would shrink, forcing some objects into orbits consistent with known Trojans. Eventually, planetesimals with large libration amplitudes and shorter dynamical lifetimes escaped, leaving behind the Trojan swarms observed today. In this scenario, collisions or gas drag mechanisms may also play an important role in capture (Marzari and Scholl, 1998).. ***In this case, they would represent material from the middle part of the solar nebula where ice first began to condense, a region not sampled by any other class of primitive body, and akin to the starting material that formed Europa and the other Galilean satellites.***

An issue with this proposed origin is that the inclinations i of the Trojans are high (up to 40 deg in some cases), while the aforementioned mechanism would preferentially capture bodies with low (e,i) values. Thus, to explain the observed Trojans, some unknown post-capture mechanism that produced the high inclinations observed among the known Trojans is necessary. To date, no post-capture excitation mechanism has been found that can satisfy orbital constraints.

An alternative capture mechanism was proposed by Morbidelli et al. (2005), which is part of a trio of papers making up the so-called "Nice model" (Tsiganis et al. 2005; Gomes et al. 2005, presented in cartoon form on the cover). In the Nice model, the Jovian planets are assumed to have formed between 5-15~AU. Slow planetary migration was induced in the Jovian planets by gravitational interactions with comets leaking out of a ~ 35 Earth mass disk residing between ~16-30 AU. Eventually, after a delay of ~600 My (~3.9 Gy ago), Jupiter and Saturn crossed a mutual mean motion resonance. This triggered a global instability that led to a reorganization of the outer solar system. Uranus and Neptune were driven into and migrated across the comet disk, which in turn caused comets to be scattered throughout the solar system. Many ended up ejected or eliminated, but resonant interactions via a migrating Jupiter/Saturn injected a small fraction onto stable orbits within the Trojan, Hilda, and outer main belt regions (see also Levison et al. 2009). ***In this case, the Trojan asteroids would represent the most readily accessible depository of Kuiper Belt material.*** They would also be potentially related to those objects that brought water and organic material to the early, pre-biotic Earth. This scenario provides a natural connection between the Trojan asteroids, TNOs, Centaurs, and irregular satellites, implying a common origin in the outer solar system. It also leads to the interpretation that the spectral variability among the Trojans could be caused by compositional differences resulting from slightly different formation locations***. The Trojans offer a critical test of the planetary migration model of Morbidelli et al. (2005), which has implications not only for the Trojans but also for the dynamical evolution of the Kuiper Belt and the solar system as a whole.***

It is important to note that the thermal equilibrium temperatures at the two possible reservoirs are significantly different. The temperature at 5 AU is about 150K in contrast to T ~ 50K at the Kuiper belt. Observations have shown that objects formed under different temperatures are different in several aspects from surface properties to interior chemical composition. For example, objects formed at 50K should contain a much larger fraction of volatile ices than those formed at 150K (Bar-Nun et al. 2007). Therefore, physical properties of Jovian Trojans, like birthmarks, stand as a key test of the two competing formation scenarios. However, Trojans appear to be highly resistant to ground-based observations since decades of efforts have failed to detect any diagnostic features in these objects, using various ground-based telescopes (Jewitt and Luu, 1990; Dumas et al., 1998; Fornasier et al., 2004; Yang & Jewitt, 2007). As such, a dedicated mission to Jupiter Trojan asteroids is in great need, which will shed light on the physical properties, especially the chemical compositions, of these objects. If the compositions of Trojan asteroids were better matched to what we expect for objects formed at 30 AU than those formed at 5 AU, it would serve as strong support for the Nice Model and its implications about the dynamical and collisional evolution of the early solar system.

Outstanding Issues and Science Questions to Address: The Trojan asteroids are central to a number of major questions in planetary science. Their importance was noted in the previous Decadal Survey, with a potential flyby mission able to "sample primitive material from the Jovian accretion region of the nebula … allow[ing] an important recalibration of the bombardment flux on objects in the Jovian system, and … offer[ing] new insights into space weathering and other processes affecting asteroids" (Space Studies Board, 2002). Explicit connection to the Decadal Survey is detailed further in Table 1.

Two main questions encapsulate the scientific interest in Trojans:

1. *Did the Trojan asteroids originate near Jupiter's orbit or farther out in the solar system?*
2. *What do compositions of these primitive bodies tell us about the region(s) of the solar nebula in which they formed?*

These overarching questions are best addressed by characterizing Trojans and placing them in context with other primitive bodies and the outer solar system. In order to leverage our knowledge of these objects into a better understanding of the solar system as a whole, the following questions and issues must be addressed:

1. *How much and what types of ice and organics are present on and within Trojan asteroids?*
2. *What is the mineralogy of the silicates present on and within Trojans?*
3. *How do the geological processes that have occurred on the Trojans compare to those that have affected other small bodies?*
4. *What is the relationship between Trojan asteroids and comets, TNOs, outer planet satellites, and main belt asteroids?*
5. *Are densities and bulk compositions of Trojans diverse or homogeneous?*
6. *How are the spectral and physical properties of Trojan surfaces modified over time by the space environment?*

As mentioned above, our current understanding of the large reservoir of Trojan asteroids is shaped almost entirely by Earth-based observations. Those spacecraft targets that might be considered the best analogs to Trojan asteroids (the Saturnian satellite Phoebe [cover], cometary nuclei, primitive main belt asteroids) have only been visited briefly via flybys and also exist in significantly different environments than the Trojans. A dedicated mission to a Jupiter Trojan asteroid will be required to meaningfully answer these questions.

Recommendation: Because the Trojan asteroids are completely unexplored and largely unknown, any visit by a spacecraft will revolutionize our current understanding of these bodies, and by extension the solar system as a whole. The style of mission will, however, affect the ways and degree to which the above questions are addressed. A single-body flyby will provide valuable initial reconnaissance, including a view of surface composition, geology, and density. A well-instrumented orbital mission to a Trojan asteroid would provide science benefit far beyond that of a fly-by most importantly for its ability to measure the sub-surface composition and interior structure. The additional study time, opportunities for additional observation angles, global imaging and the suitability of additional instruments contribute to the increased benefit of an orbital mission. The ability to perform in situ experiments by a well-instrumented lander would provide the most science benefit of the three mission types. In addition, an investigation of the diversity of the Trojan asteroids is a critical aspect of addressing the two overarching questions listed above. We strongly encourage any mission architecture (flyby, rendezvous, or lander) to include encounters (flybys, etc) with multiple Trojans.

In addition to the insights provided by flyby and rendezvous missions, a landed mission provides the opportunity for more precise compositional measurements on meter scales. A mission that could return data via an instrument like an APXS or GRS on a lander, could discriminate among possible compositions and thus among possible formation locations. ***A mission to the Trojan asteroids with appropriate instrumentation could constrain the formation location of the Trojan asteroids,*** and in doing so provide a critical test for the Nice Model, one of the only such tests identified. ***This, in turn, would have profound effects on our understanding of early solar system history and processes, including the late heavy bombardment and large-scale transport.***

The technical feasibility for any of these mission architectures is well within our capabilities at the present time. Past missions to asteroids and other small bodies and recent developments in low-cost long-duration cruise operations are two successes that NASA can build on to realize a Trojan asteroid mission in the next decade. At a minimum, we ***strongly*** support the continued inclusion of a Trojan-focused mission in the New Frontiers list of eligible missions.

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