

The TRACER mission: a proposed Trojan and Centaur flyby mission

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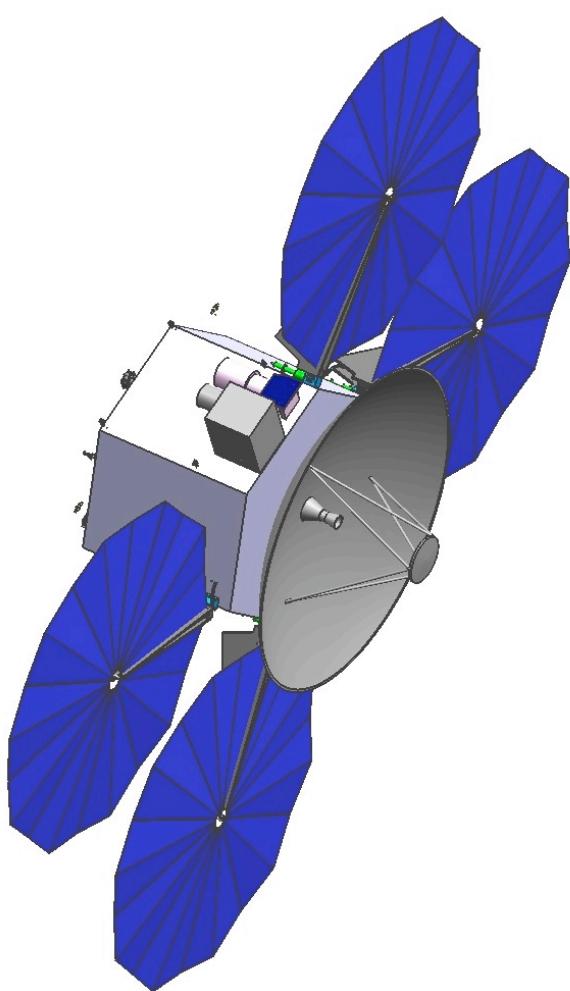
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This White Paper presents a response to the requirements for the Trojan/Centaur mission described in the New Frontiers Announcement of Opportunity, developed as a JPL Team X study in conjunction with the JPL Planetary Science Summer School. A mission including a flyby of one Trojan and one Centaur body can feasibly be designed within the New Frontiers guidelines, and will address fundamental questions about the history of the solar system. Using solar electric propulsion and JPL as the manufacturing center, the instrument suite can include cameras and passive *in-situ* experiments; a larger science payload would require the allocation of man-hours to be significantly reduced while the spacecraft is in cruise and/or funds to the mission to be increased with international participation.

Our solar system in context

The range of bodies in our solar system, from small rocky asteroids to gas giants, provides a window into the formation of a variety of objects, and allows us to test models of their formation and evolution. A number of recent studies with the Spitzer Space Telescope (Werner et al. 2004) of main sequence stars in the galaxy have shown evidence that nearly 14% of low mass main sequence stars harbor dusty debris disks (Beichman et al. 2006; Trilling et al. 2007) which have been associated with planet formation (Malfait et al. 1998; Crovisier et al. 1996; Hines et al. 2006).

The bulk of currently known extrasolar planets are gas giants with periapses of less than 1 AU. Gas giants are not expected to form so close to the parent star; planet migration is a potential explanation for the currently observed orbits of most extrasolar giant planets (Marcy and Butler 1998). Within our own solar system, there is evidence that the giant planets have migrated; for example, Jupiter is thought to have migrated inwards approximately 0.45 AU after accretion (Franklin et al. 2004). Additionally, the extrapolated protoplanetary mass density distribution could only be smooth and continuous if the current positions of Neptune and Uranus were swapped at the time of planet formation (Desch 2007). According to the Nice model of the formation of our solar system (Tsiganis et al. 2005; Morbidelli et al. 2005; Gomes et al. 2005), the gas giants formed in a more compact configuration than currently observed with locations between 5 and 15 AU. The planets later migrated under the influence of gravitational friction from trans-Neptunian planetesimals until Jupiter and Saturn crossed a mutual mean motion resonance. This event triggered a major instability in the outer solar system and the creation of distinct reservoirs of small bodies. This model has observable predictions, including the transport of carbon bearing bodies into inner solar system orbits (Levison et al. 2009). The Trojan and Centaur Reconnaissance (TRACER) mission outlined in this White Paper is designed to address fundamental questions about the formation and evolution of the solar system.

Importance of Trojan Asteroids

The origin of the Trojan asteroids has been a topic of debate since the 1970's, and potential sources include trapped comets (Rabe 1972) and near-Jupiter planetesimals (Shoemaker et al. 1989). Emery et al. (2008) shows clear evidence for two different color populations of Trojan asteroids with a weak correlation to inclination; this suggests that the orbital group contains two distinct populations with different parent reservoirs. To determine where Trojans asteroids may have originated, a number of ground based optical and near-IR observations have investigated

the potential presence of carbon bearing minerals and water ice (Emery and Brown 2003; Yang and Jewitt 2007).

The white paper of Rivkin et al. (2009) poses two major science questions regarding the Trojan population and their importance in understanding the solar system as a whole:

“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?”

Importance of Centaur Asteroids

The Centaur asteroids comprise an observational link between the Kuiper Belt (where they are thought to have originated) and icy bodies in the rest of the solar system. Compositionally, the Jupiter Family Comets and Centaurs are linked by the presence of methanol ice in both the JFCs and the Centaur 5145 Pholus (Cruikshank et al. 1998). Dynamical models of known Centaurs illustrate that these bodies are in unstable orbits with dynamical lifetimes ranging from ≤ 1 to ≥ 100 Myr (Tiscareno and Malhotra 2003). Models also indicate that Centaurs can diffuse into the inner solar system (Tiscareno and Malhotra 2003; Bailey and Malhotra 2009), thus replenishing the Jupiter Family Comet population.

The white paper of Fernandez et al. (2009) on Centaurs and trans-Neptunian Objects (TNOs) has identified 3 major categories of questions with relevance to Centaurs and their place in the solar system:

“What are the Physical Properties of TNOs?

What are the Compositions of TNOs?

What Physical and Chemical Processes affect TNOs, and How?”

Major Science Questions

- ***What are the physical characteristics of these bodies?*** Are they rubble piles or monoliths? Do they have satellites? Are they differentiated?
- ***Where in the solar system did these bodies originate?*** Did these bodies originate in the regions in which they are found now, or did they come from another source reservoir?
- ***Have these bodies migrated inwards from the outer solar system?*** This is certainly the case for the dynamically unstable Centaurs; the orbital evolution of the Trojans is unknown given their poorly defined source region.
- ***What evolutionary processes have influenced these bodies?*** Models of the Trojan asteroid population by Marzari et al. (1997) suggest that collisional evolution plays a significant role in shaping the size-frequency distribution of small Trojans. What is the extent of collisions within the Trojan population? Some Centaurs show evidence of out-gassing and dust production at high heliocentric distances. Which volatiles are responsible for this activity, and what can dust reveal about their thermal history of Centaurs? How are Centaurs thermally altered?
- ***Do these bodies have any evidence for organic material?*** Is there any evidence for the building blocks of life in the form of simple organics on these bodies?

To investigate these questions we have identified a candidate list of Trojan and Centaur asteroids for a flyby mission to be launched in the decade starting in 2015. The mission described below is a response to the New Frontiers 3 AO and is comprised of two flybys: the Trojan asteroid **Antenor** and the Centaur **2001 BL41**. A larger candidate list is included should the need for a later launch date arise.

Table 1: Level 1 Science Objectives for the TRACER Mission

Level 1 Science Objective	Data Required	Instrument(s)
What are the physical characteristics of these bodies?	<p>Medium resolution images to determine shape and presence of a satellite</p> <p>Time resolved imaging over a long baseline (~days) to determine spin rate and orientation</p> <p>Determine the mass via approach alterations due to the body's gravitational field</p>	Narrow Angle Camera Radio Science
Where in the solar system did these bodies originate?	<p>Optical and near-IR spectroscopy to determine mineralogy and bulk composition</p> <p>Near-IR spectroscopy and/or mass spectrometry to determine ice compositions</p> <p>Mass and Size estimates to determine Density</p>	Narrow Angle Camera Optical and Near-IR spectrophotograph Radio Science Ion and Neutral Mass Spectrometer
Have these bodies migrated inwards from the outer solar system?	<p>Near-IR spectroscopy and/or mass spectrometry measurements to determine the presence of ice and volatiles</p> <p>Optical imaging on approach to measure degree of outgassing activity</p>	Narrow Angle Camera Optical and Near-IR Spectrograph Ion and Neutral Mass Spectrometer
What evolutionary processes have influenced these bodies?	<p>High resolution imaging to obtain crater counts and ejecta colors for crater dating</p> <p>Mapping the density of dust due to collisions within the Trojan population</p> <p>Near-IR spectra to determine ice compositions and relative phase abundances to trace thermal alteration history</p>	Narrow Angle Camera Optical and Near-IR Spectrograph Ion and Neutral Mass Spectrometer Dust Counter

	Determine mass, size and composition of a potential coma	
Do these bodies have evidence for organic material?	Measure absorption due to 3.3 μm aromatic C-H stretch Measure absorption due to 3.4 μm aliphatic C-H stretch <i>In situ</i> measurements of composition of coma and/or ejecta material	Optical and Near-IR Spectrograph Ion and Neutral Mass Spectrometer

Candidate Targets

Candidate targets have optical red colors or low geometric albedos; the features are interpreted as evidence of surface organics. Centaurs are further constrained by their perihelion date, low eccentricities and inclinations. Jupiter Trojans from L4 or L5 are limited to those with ‘large’ diameters and Tholen D-type (i.e. organic rich) or P-type classifications that offer comparisons to similar bodies (i.e. TNOs, Plutinos and Centaurs) with strong red-sloped surface reflectances. Antenor, our prime D-type Trojan candidate at L4, is proximal to other Trojans allowing color and albedo sampling of this substantial asteroid family. Our principal Centaur candidate 2001 BL41 approaches Jupiter (~6.22 AU) during our mission timeline and with a strong V-R slope, is representative of most Centaurs and other TNO-like objects (Bauer et al. 2003). The final target list includes:

Trojans: at L4- Hektor, Nestor, Odysseus; at L5-Antenor, Anchises, Patroclus

Centaurs: 2001 BL41, Echeclus, Beinor

Trojan and Centaur Reconnaissance (TRACER) Mission Trajectory and Timeline

The TRACER spacecraft trajectory utilizes two Earth flybys before its voyage outward to Antenor and 2001 BL41 (Figure 1). A launch date of 12 Mar 2019, with a ± 10 day launch window, delivers our spacecraft to both targets within ~8 Earth years by 6 February 2027. Following launch on an Atlas V 541, the mission follows an Earth-Earth-Trojan-Centaur profile to provide the delta-V to propel the science payload mass. Earth flybys occur in 2020 and 2022 before an electric propulsion cruise phase ending on 26 August 2023, 3 months before the first encounter. Closest approach for Antenor takes place in November 2023, then to 2001 BL41 in May of 2027. Nominal flyby altitude for both bodies is 1000km for surface imaging, as well as possible ejecta and coma sampling (at the Centaur).

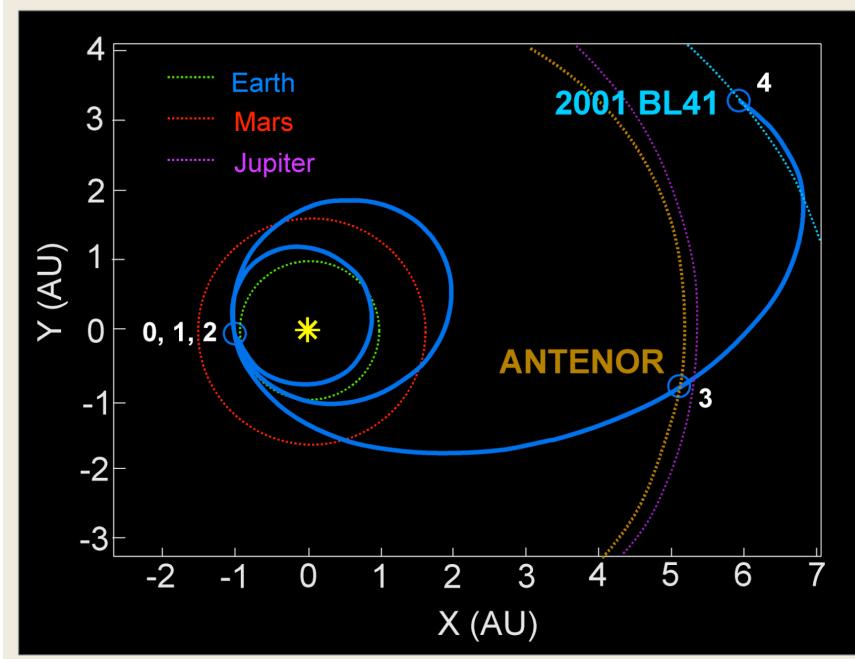


Figure 1: Trajectory of the TRACER mission. Major events are indicated by number: 0- Launch, 1- 1st Earth Flyby, 2-2nd Earth Flyby, 3- arrival at Antenor and 4-arrival at 2001 BL41. The orbital track for Antenor is in orange and the track for 2001 BL41 is in cyan.

The timeline for the development of this mission is shown in Figure 2 with the following milestones:

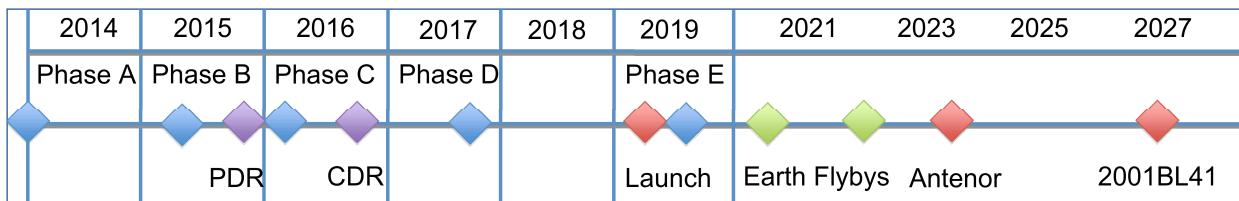


Figure 2: Milestones of the TRACER mission. Mission phases (blue diamonds), design reviews (purple diamonds), critical events (green diamonds), and major milestones (red diamonds).

Basic Payload

Based on the Level 1 science objectives described in Table 1, the core instrumentation package should include:

Table 2: Instrumentation for the TRACER spacecraft

Name	Capabilities	Heritage	Mass	Power
ASTERIA	0.4 to 5 micron spectroscopy	Moon Mineralogy Mapper (Chandrayaan-1)	27.5 kg	25 W

DELPHI	Narrow Angle Camera with 7 optical filters	AMICA (Hayabusa)	20 kg	10 W
GAEA	Ion and Neutral Mass Spectrometer	Cassini INMS	10.3 kg	23 W
ILIAS	Dust Counter	New Horizons VBSDC	1.6 kg	5 W
KLEIO	Radio Science using telecom antennas	NEAR-Shoemaker	75 kg	20 W

The selected instruments listed in Table 2 could be included for a mission using the New Frontiers cost cap of \$650M; we note that TRACER was \$26M over budget after preliminary mission design. Additional instruments that had initially been proposed for this mission but were eventually de-scoped include:

HECTOR/HERCULES: Two 75 kg impactors, one per target body. These were designed for use in tandem with GAEA, ASTERIA and DELPHI and allowed direct sampling of an ejecta plume and the study of more pristine sub-surface materials on our targets. They were de-scoped due to weight and cost considerations.

Expanded KLEIO: Bistatic radar experiment (Simpson 1993). This experiment would measure the dielectric properties of our targets at varying depths and infer density. It was de-scoped due to power concerns.

Expanded ILIAS: Dust counter and analyzer. The original proposal for this instrument also included a time of flight mass spectrometer for analysis of dust compositions and relative abundances of ion species. Dust analysis was de-scoped to the dust counter due to mass, power and cost constraints.

Magnetometer: Asteroid surface and exosphere magnetic induction experiment (Trotignon et al. 1999). Using the Magnetospheric Multiscale Mission heritage, an 11-meter boom is required to isolate this instrument from the spacecraft and it could not be fit into the AtlasV fairing without incurring additional costs.

Flight Systems

The spacecraft for the TRACER mission utilizes a hexagonal bus with 4 solar panels, 4 Xe engines, a fixed 4-m high gain antenna and a gimbaled 0.75 meter medium gain antenna. All data is transmitted at X band and the expected data transfer volumes are 18.2 GB (at 6 kbps) at Antenor and 10.7 GB (at 3 kbps) at 2001 BL41. This high data volume at a low data rate requires an 8-hour pass once a day on a 34 m DSN antenna for 105 and 125 days for the Trojan and Centaur encounters respectively. The mission review panel indicated that both X and Ka-band frequencies would be preferred to remove the plasma contributions to the Doppler measurement of the gravitational effects.

The accordance with the New Frontiers 3 AO guidelines, the TRACER mission design incorporates solar panels rather than radioisotope power sources. The TRACER spacecraft uses 4

MultiFlex solar panels with a total area of 58.8 m² in conjunction with 5 30A-hr Li-Ion batteries. At 1 AU the solar panels will provide 19.8 kW of power, with power availability decreasing with distance from the Sun to 540 W at the end of the mission. We note that the mission review panel indicated these flexible panels might cause some problems with spacecraft pointing and stability due to resonant vibrations.

Costs

The current cost cap for a New Frontiers class mission is \$650M in FY2009 dollars excluding the launch vehicle. TRACER is designed to launch on a medium performance range launch vehicle, the Atlas V 541, which increases the allowed cost cap by \$40M. The TRACER mission instrument development, spacecraft design and assembly and primary mission operations are all provided by JPL whose costs are estimated at \$716M (\$26 M over the cost cap). Competitive bidding of the spacecraft assembly, cost negotiation and defraying expenses through international collaborations and participation could reduce this cost, however these options were not considered in our mission design.

Conclusions

Under the guidelines set forth in the New Frontiers 3 AO, a flyby mission to a Trojan and a Centaur can be designed with a primary mission that includes imaging and mapping spectroscopy, as well as passive *in situ* measurements of dust and potential outgassing plumes or comas. Such a mission would yield significant science returns, providing data that would help to clarify and constrain models of solar system formation and evolution. A major limitation is the power available with solar panels, and it is recommended that radioisotope-based power sources are needed if a larger mission is desired to fit under the New Frontiers cost cap.

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