In Situ Probe Science at Saturn

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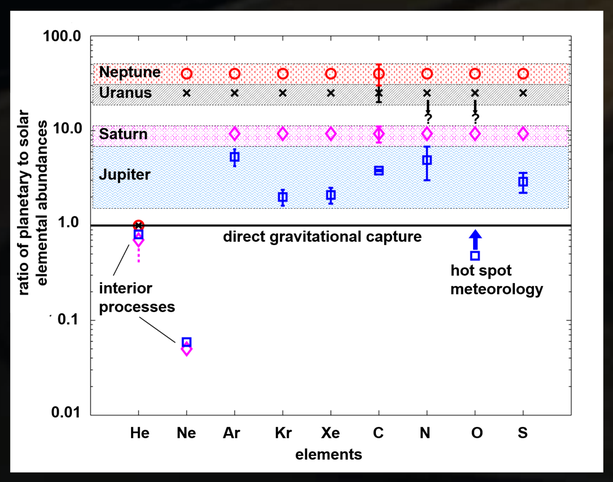
A fundamental goal of solar system exploration is to understand the origin of the solar system, the initial stages, conditions, and processes by which the solar system formed, how the formation process was initiated, and the nature of the interstellar seed material from which the solar system was born. Key to understanding solar system formation and subsequent dynamical and chemical evolution is the origin and evolution of the giant planets and their atmospheres.

The 2013 Planetary Sciences Decadal Survey "**New Frontiers in the Solar System, An Integrated Exploration Strategy**" defines three Overarching Goals for giant planet exploration, with specific Science Objectives and Science Questions to address the issues related to solar system origin and evolution. The PSDS Overarching Goals, and the Science Objectives and Science Questions most relevant to Saturn *in situ* exploration are listed below.

	Overarching Goal #1 **Giant Planets as Ground Truth for Exoplanets** *Explore the processes and properties that influence giant planets in the solar system in order to characterize and understand the observable planets in other planetary systems.*						**Overarching Goal #2** **Giant Planet's Roles in Promoting a Habitable Planetary System** *Test the hypothesis that the existence, location, and migration of the giant planets in the solar system has contributed directly to the evolution of terrestrial planets in the habitable zone.*		**Overarching Goal #3** **Giant Planets as Laboratories for Properties and Processes on Earth** *Establish the relevance of observable giant planet processes and activities as an aid to understanding similar processes and activities on Earth and other planets.*			
Science Objectives	**Understand Heat Flow and Radiation Balance in Giant Planets**				**Investigate the Chemistry of Giant Planet Atmospheres**		**Search for Chemical Evidence of Planetary Migration**		**Investigate Atmospheric Dynamical Processes in the Giant Planet Laboratory**			
Science Questions	What mechanism has prolonged Saturn's thermal evolution?	Does Helium rain play a role in reducing the H/He in Saturn's molecular envelope?	Why and how does the atmospheric temperature and cloud composition vary with depth and location on the planet?	Which processes influence the atmospheric thermal profile, and how do these vary with location?	How did the giant planet atmospheres form and evolve to their present state?	What are the current pressure-temperature profiles for these planets?	How and why do elemental and isotopic abundances vary as a function of distance from the Sun?	How & why do abundances of heavy elements and isotopes, the D/H and H/He ratios, and noble gases differ between the two classes of giant planets?	What processes drive the visible atmospheric flow and how do they couple to the interior structure and deep circulation?	What are sources of vertically propagating waves that drive upper atmosphere oscillations and do they play a role on all planets?	How does moist convection shape tropospheric stratification?	What are the natures of periodic outburst such as global upheaval on Jupiter and infrequent great white spots on Saturn?

Several theories have been put forward to explain the process of solar system formation, and the origin and evolution of the giant planets and their atmospheres. Each theory offers quantifiable predictions of the abundances of noble gases He, Ne, Ar, Kr, and Xe, and abundances of key isotopic ratios $^4He/^3He$, D/H, $^{15}N/^{14}N$, $^{18}O/^{16}O$, and $^{13}C/^{12}C$.



Only the Galileo probe has made *in situ* measurements of the composition of a giant planet atmosphere. Galileo arrived at Jupiter at a meteorologically anomalous location, found to be significantly depleted in water. Neon was also found to be depleted, likely due to rainout mixed with helium. Only carbon in the form of CH_4 has been measured by remote sensing in the atmospheres of Saturn, Uranus, and Neptune.

In the figure above, error bars on Jupiter abundances are based on Galileo NMS measurements. Symbols without error bars are based on the Core Accretion Model of giant planet formation. Note that N has been measured on Saturn. See Mousis, PSS (2014) for more information.

Many of the key atmospheric constituents needed to discriminate between alternative theories of giant planet formation and chemical evolution are either spectrally inactive or primarily located in the deeper atmosphere inaccessible to remote sensing. Abundance measurements of these key constituents, as well as the two major molecular carriers of carbon, methane and carbon monoxide (neither of which condense in Saturn's atmosphere), sulfur which is expected to be well-mixed below the 4 to 5-bar ammonium hydrosulfide (NH_4SH) cloud, and gradients of nitrogen below the NH_4SH cloud and oxygen in the upper layers of the H_2O and H_2O-NH_4 solution cloud, must be made *in situ* and can only be achieved by an entry probe descending through 10 bars.

Detection and measurement of the abundances of certain disequilibrium species such as CO, PH_3, AsH_3, and GeH_4 can be diagnostic of internal processes and dynamics including vertical mixing of the deep atmosphere, and would also help discriminate between competing theories.

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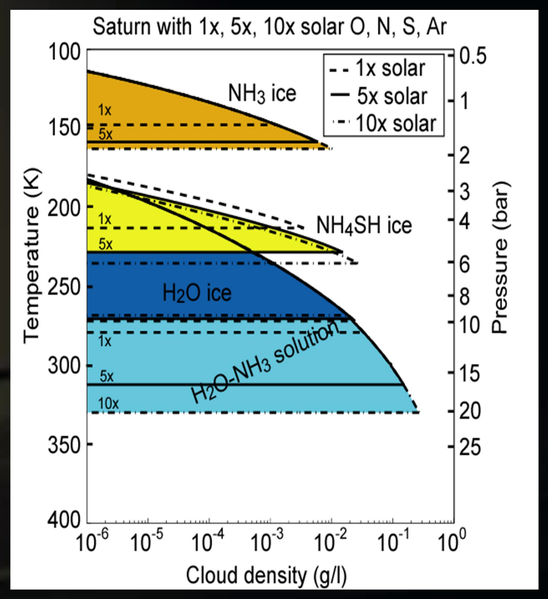
Measurements of elemental and isotopic abundances must be made in the well-mixed deep atmosphere, beneath multiple cloud layers. Dependent upon the abundances of nitrogen, sulfur, and oxygen, the base of the clouds are expected to be at 1-2bars/150-170K (NH_3 cloud), 4-6 bars/210-240K (NH_4SH cloud), and 10-20 bars/260-340K (H_2O/H_20-NH_3 cloud). See Mousis, poster#8094 and Mousis (2014).



Summary

The atmospheres of the giant planets serve as laboratories to better understand the atmospheric chemistries, dynamics, processes, and climates on all planets in the solar system including Earth, and offer a context and provide a ground truth for exoplanets and exoplanetary systems. Additionally, giant planets have long been thought to play a critical role in the development of potentially habitable planetary systems.

A small, relatively shallow Saturn probe capable of measuring abundances & isotopic ratios of key atmospheric constituents, atmospheric structure and dynamics, and cloud locations and properties not accessible by remote sensing can provide additional context to giant planet science provided by Galileo and Cassini and to be provided by Juno, and will help discriminate between competing theories of solar system and giant planet origin, chemical, and dynamical evolution.

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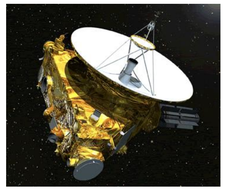

Potential Orbital Capture Missions to Trans-Neptunian Objects

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BACKGROUND

To date, New Horizons has been the only interplanetary mission undertaken with the exploration of a trans-Neptunian object (TNO) as its primary objective (Ref. 1). This remote region of the Solar System contains a large number of minor planets, at least one of which (Eris) is larger even than Pluto. Our group has previously analyzed high thrust missions using a single Jovian Gravity Assist (JGA) to several TNOs (Ref. 2-4). In the current study, we extend our previous work by examining the potential for the orbital capture of a probe. We also evaluate the possible benefits of using a Jupiter -Saturn Gravity Assist (JSGA) instead of a JGA.

Critical mission performance parameters include transit time to the target, potential flyby mass or orbital capture mass for launch on a given booster, arrival excess velocity at the target (which determines target observation time for flyby missions), and spacecraft radiation dose during the Jovian flybys. The last of these is important because of potential damage to electronics and the resulting shielding mass requirements.

OBJECTIVES

The main objectives of this project are:

- To design Jupiter Gravity Assist and Jupiter-Saturn Gravity Assist trajectories to several TNOs including Huya, Huamea, Ixion, Pluto, Quaoar, Varuna and Sedna;
- To identify the most favorable targets and opportunities for TNO orbital capture missions;
- To compare JGA and JSGA missions with regard to Jovian passage distances (a simple surrogate for spacecraft radiation exposure), arrival planet hyperbolic excess velocity, potential orbital capture mass, etc.
- To compare our results with historical missions in terms of transit time to the target, payload capability, Jovian flyby radiation exposure, etc.

METHODS

Interplanetary trajectory modeling was accomplished using Mission Analysis Environment (MAnE), a commercial software package developed by Space Flight Solutions (Ref. 5). Jupiter proximity trajectories were calculated using the Program to Optimize Simulated Trajectories (POST 3D, Ref. 6), and the Jovian radiation environment was analyzed using the European Space Agency code SPENVIS (Ref. 7). The calculated radiation environment is expressed via dose/depth curves, indicating the dose of radiation which would be experienced as a function of the equivalent thickness of aluminum shielding.

JGA trajectories are constructed by planning the second leg (Jupiter to the TNO) first, using a "pork-chop" plot which shows Jupiter departure and target arrival excess velocities; a near Hohmann Transfer from Earth to Jupiter in then added. This yields departure opportunities to a given TNO approximately every twelve years, corresponding to Jupiter's orbital period. Opportunities for JSGA trajectories to a given TNO occur less frequently due to the synodic period of Jupiter's and Saturn's orbits, with the Jupiter encounter typically occurring shortly before or near the time of those two planets' conjunction. Two such conjunctions occur in 2040 and 2060.

As an initial guess for JSGA trajectories, we set the Jupiter to Saturn transit time equal to 3.5 years (similar to that for Cassini) and use a near Hohmann transfer from Earth to Jupiter. MAnE is then allowed to optimize the encounter dates and distances. Potential TNO targets are limited for JSGA trajectories since the first two legs influence where a satellite can travel in an efficient manner.

Launch is accomplished on either a Delta IV HLV or an Atlas V, 551 with a Star 48 upper stage (analysis was done for both vehicles, and the better option was chosen). The performance of the launch vehicles is shown in Figure 1, taken directly from Ref. 10. Orbital capture is simulated assuming an impulsive burn. The interplanetary trajectories typically yield arrival excess speeds of 6 to 10 km/s, necessitating a two stage propulsive capture. The first stage assumes a solid rocket motor with an ISP's of ~286s and a tankage fraction of 0.05 (based on an average of ATK solid engine specs). The second stage is a liquid-fuelled HiPAT engine using mono-methyl hydrazine (MMH) and nitrogen tetroxide (N2O4). The engine is an upgraded version of the one used for Cassini orbital insertion and provides an ISP of 323s and tankage fraction of 0.113.

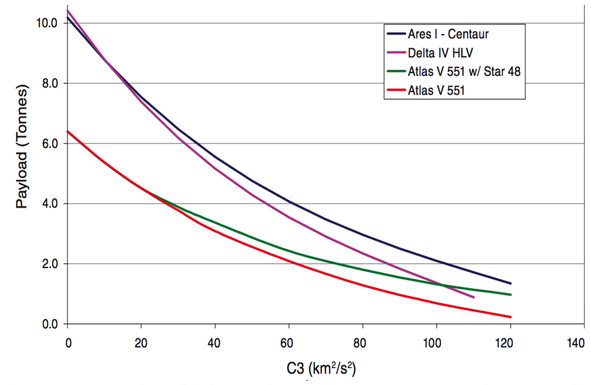

Figure 1. Launch Vehicle Performance Comparison for Interplanetary Missions (Ref. 10)

RESULTS

Table 1 shows potential orbital capture masses and other critical parameters for JGA missions with a time of flight of approximately 25 years to various TNOs. It is apparent that Huya, Pluto and Ixion are the most promising targets in terms of potential capture mass. These results assume departure at the minimum C3 and do not allow for schedule slippage (however, that issue is addressed below). The table also shows the impact of using a JSGA trajectory to Huya rather than a JGA. For the cases considered here, the JSGA permits a much more distant Jupiter flyby maneuver, but increases the arrival excess speed at the target, thereby reducing the time available for observation for a target flyby or making orbital capture less feasible.

	Earth Departure	Departure C3	Departure Mass (kg)	Jovian Periapsis Radius	Arrival V-Inf (km/s)	Capture Mass (kg)
Haumea	9-21-2025	103.14	1314	14.38	8.06	69.13
Huya (JGA)	10-28-2026	91.179	1560	9.28	3.93	380.6
Huya (JSGA)	9-28-2037	91.263	1558	33.08	6.54	133.4
Ixion	10-25-2026	88.6	1619	18.93	5.58	239.8
Pluto	12-19-2028	88.64	1618	18.25	5.22	295.6
Quaoar	11-21-2027	90.511	1575	17.64	6.5	149.4
Varuna	6-6-2022	88.2	1628	14.46	8.12	126.3

TABLE 1. Mission Comparison

Figure 2 shows the radiation dose/depth curves predicted to occur during the Jupiter flyby for several JGA trajectories to Huya, departing Earth in October of 2026. For comparison, the radiation encountered by the Voyager 1 and 2 probes is also shown (calculated using the same methodology). Figure 3 shows the potential orbital capture mass at Huya as a function of transit time for a mission departing Earth in 2026. The capture masses are shown both for the optimum departure date and for a 20% C3 margin above the minimum value to provide for schedule slippage The Jupiter flyby radiation dose behind 3 mm of aluminum shielding is also shown. This shielding depth was chosen as a point of reference since it is the value given in previous studies for the interior of the Pioneer probes (Ref. 11), where radiation doses were 4.5 (10^5) and 1.2 (10^5) rads for Pioneer 10 and 11 respectively.

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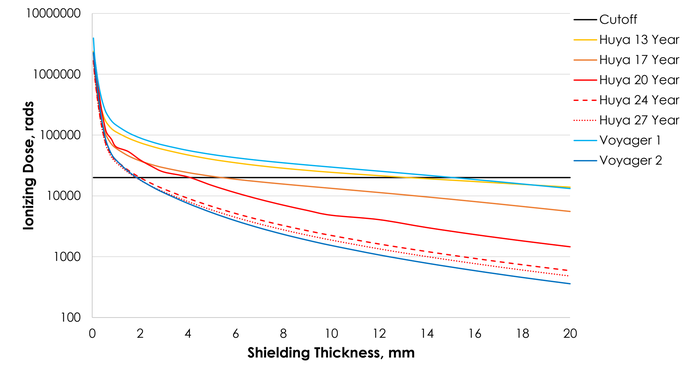

Figure 2. Jovian flyby radiation environment for 2026 departure to Huya with Voyager flyby radiation for comparison

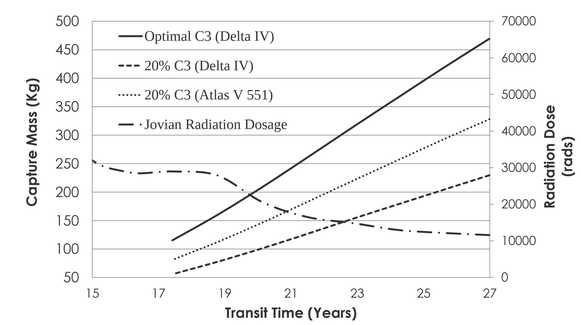

Figure 3. Transit time vs capture mass and Jovian flyby radiation for a mission to Huya departing in 2026

CONCLUSIONS

For selected TNOs, orbital capture of a small interplanetary probe appears feasible using a two-stage, traditional chemical propulsion system. The best targets identified to this point are Huya, Pluto and Ixion. Capture missions will typically require interplanetary transit times of approximately 25 years to have the low arrival excess speeds necessary to capture of a probe of reasonable mass. The interplanetary trajectory can incorporate either a Jupiter Gravity Assist or a Jupiter-Saturn gravity assist. For a wide range of Huya missions using a JGA, radiation exposure of the spacecraft during the Jovian flyby should be less severe than that encountered during previous missions including Voyager 1 and Pioneer 11. Use of a JSGA would allow more distant flybys of Jupiter and less intense radiative environments.

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SPLAT

The Sample Probe for Landing and Testing

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Abstract

Analysis is performed for the return of biological samples flown in space. Vehicle geometry is a 45° sphere-cone forebody. Spin stabilization is used to maintain passive stability and is supported by a drogue chute in the transonic regime. On-orbit maintenance and entry insertion is performed by a service module. The vehicle will land in the Utah Test and Training Range and be collected via helicopter to ensure rapid recovery of samples. The biological payloads placed restrictions of a maximum g-load of prolonged 16 g's and 20 g shock load. The trajectory was simulated as 3 DOF planar motion with landing dispersions being investigated through a Monte Carlo simulation. A pilot ringslot parachute provides initial deceleration and transonic stability and a main ringsail limits the final velocity. A hemispherical, vented airbag is used upon impact to meet g-loading requirements. SIRCA and Delrin compose the forebody TPS material and Li-900 is used for the backshell.

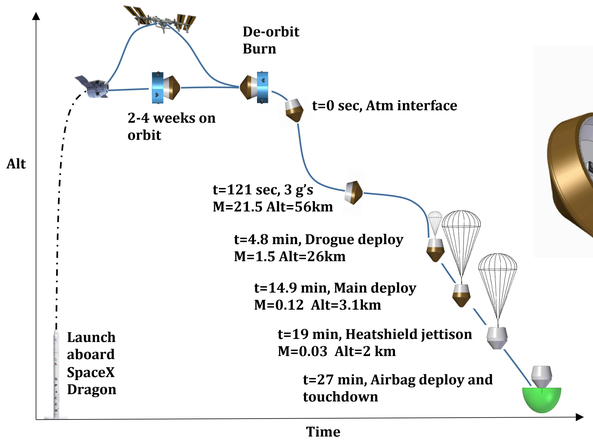
Introduction

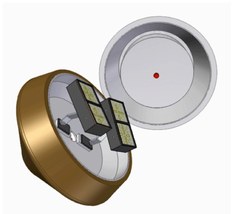
- Mission concept: small reentry system for recovery of biological samples flown in space
  - Free-flyer and ISS capable vehicle
- Heritage designs: Stardust, Mars Microprobe, SPORE
- Design constraints:
  - Strict constraints to allow for widest possible range of biological samples

Parameter	Limit
Shock g-load	20 g's
Sustained g-load	16 g's for 20s
Payload Temperature	25 °C
Recovery Time	< 6 hr

Concept of Operations

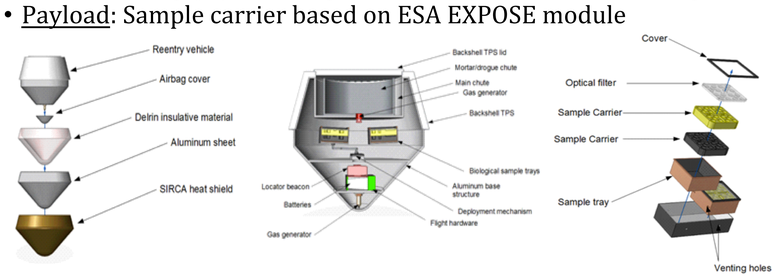
- Stowed in unpressurized trunk of SpaceX Dragon
- Configurable for attachment to ISS or as stand alone free-flyer
- Landing site: Utah Test and Training Range
  - Large, flat area to target with high-precision tracking
  - Fast helicopter recovery to minimize sample spoilage





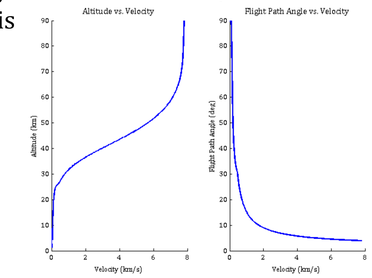
Geometry and Mass

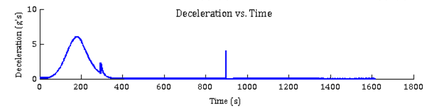
- Configuration: Service module (entry insertion, on-orbit maintenance), entry vehicle (payload and support)
- Geometry: 45° sphere cone forbody, truncated cone aftbody
  - Nose radius: 0.1m, max diameter: 0.48m
  - Mass: 26.5kg, payload: 2kg, TPS: 11.5kg, decelerators: 5.5kg
- Payload: Sample carrier based on ESA EXPOSE module



Trajectory

- Entry conditions: V = 7.8km/s, γ = -4° (for both ISS and free-flyer)
- Simulation: 3DOF planar EOM using US standard atmosphere
  - MER Trajectory dispersion analysis (3σ), UTTR nominal wind
  - Landing ellipse: 106 x 46 km (within UTTR)
    - Biggest effects: wind (under parachute) and γ
  - Maximum deceleration: 6.6g's
  - Peak heating: 403 W/cm²





Thermal Protection System

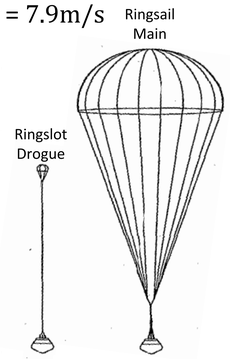
- Temperature constraints:
  - Payload: Expose (T<53°C), General biological sample (T<25°C)
  - Bondline: TPS (T<250°C), Insulator (T<150°C)
- Simulation: 1D heat conduction w/ surface heat flux balance and coupled ablation modeling
- TPS Sizing: 3cm SIRCA and 3cm Delrin on forebody, 2.4cm LI-900 on backshell (includes 25% margin)
  - SIRCA tested to 500 W/cm², but suggested for below 150 W/cm²

(unmargined)	Forebody	Backshell
PICA Thickness	8.18 cm	
PICA Recession	4.08 cm	
SIRCA Thickness	**2.41 cm**	7.63 cm
SIRCA Recession	0.13 cm	0.00 cm
Li-900 Thickness		**1.89 cm**
Peak Stagnation Heating	357 W/cm²	11 W/cm²
Peak Stagnation Pressure	0.86 atm	

Parachute

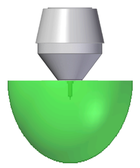
- Constraints: N_{max} < 20g's, V_{land} < 8.8m/s, transonic stabilization
- Drogue: 0.5 m² Ringslot, mortar deployed at M = 1.5
- Main: 9 m² Ringsail, pilot deployed after 10min (M = 0.12)
- Results: Inflation load = 14g's, Landing velocity = 7.9m/s

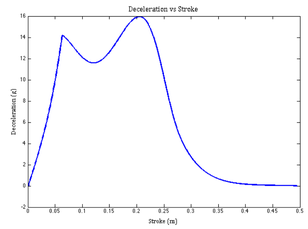
	Guide Surface	Ribbon	Ringslot	Ringsail
C_D	0.32	0.52	0.60	0.80
Average Oscillation	2°	2°	3°	7°

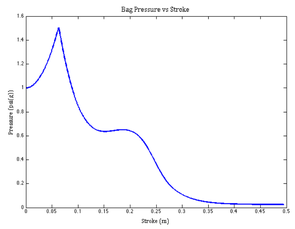


Airbag

- Design: Hemispherical vented airbag for off-vertical landing
  - 0.5m radius, 1 psi(g) pressure, vents open at 1.5 psi(g)
- Results: Maximum load = 16g's (nominal), Stroke = 0.34m
  - Load < 20g's for terminal velocity < 8.8m/s

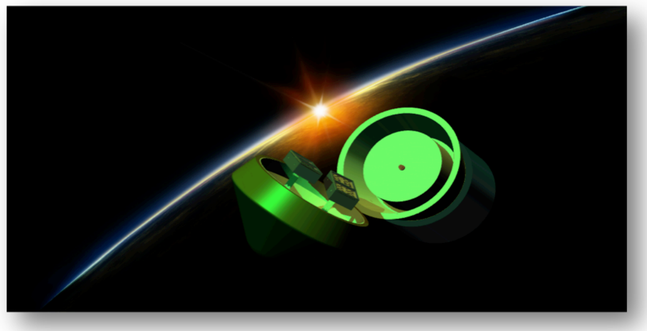






Conclusion

- Vehicle design for reentry of a wide range of biological samples
  - Analyzed: Mission, Landing Site, Geometry, Mass, Subsystems, Trajectory, TPS, Parachute, Airbag
  - Max deceleration = 16g's, Max sample temperature = 25°C
- Landing at UTTR: tracking capability, quick recovery



Images: spacex.com, goldbergauctions.com, deist.com, globalspec.com, NASA.gov, Parachute Design Guide

Planned Lunar Impacts: Scientific Value and Ground-based Observation Limits

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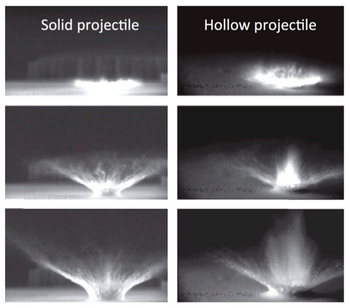
Abstract Number: 8100

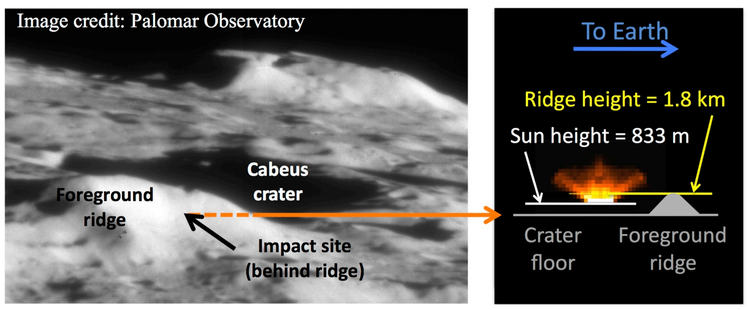
The LCROSS Impact

On October 9, 2009, the LCROSS mission entailed the impact of a 2300 kg Centaur upper stage onto the floor of Cabeus crater at a speed of 2.5 km/s and an impact angle of 85° to the horizontal [1][2][3]. The primary science goal of the LCROSS mission was to verify the presence of water in the lunar regolith thrown up into sunlight by the impact. This goal was achieved with observations from the *in situ* Shepherding Spacecraft that followed the Centaur impactor. A secondary science objective was to observe the time evolution of the ejecta plume from a side perspective from Earth-based observations. Pre-planned lunar impacts allow investigation of several issues through plume imaging:

- Determination of the ejecta mass from an impactor of known size, impact speed and angle.
- Verification of crater formation theories linking crater size and ejected mass to properties of the impactor.
- Comparison of large-scale impact plume morphology to results from laboratory impacts of high-speed projectiles to evaluate impact scaling assumptions.
- Evaluation of lunar regolith properties as a function of depth including albedo, particle size, and compressibility.



The figure above is a time series of images for laboratory impacts of solid and hollow projectiles at the NASA Ames Vertical Gun Range [4]. Hollow projectiles (right), representing the hollow Centaur impactor, produced multi-component plumes.

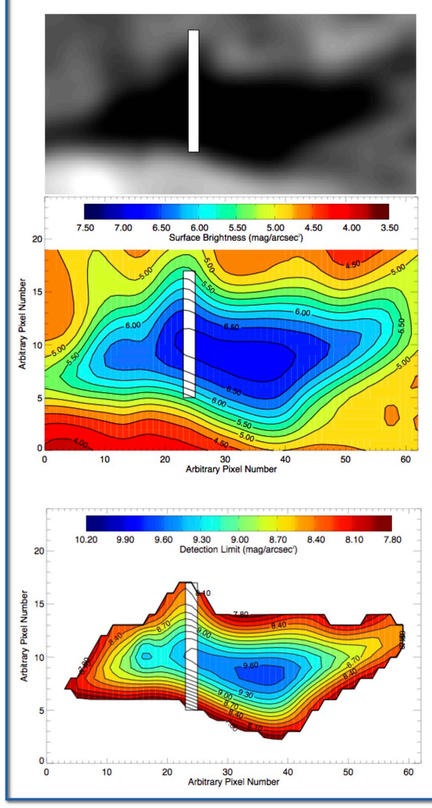


The impact site was optimized for detection of water from the Shepherding Spacecraft and was not ideal for imaging a plume from Earth. Surrounding bright lunar terrain increased the scattered light levels in the dark area of Cabeus. Although the plume was illuminated from a height of 833 m above the impact site, a foreground ridge obscured the view of the plume below 1.8 km. The scattered light from this bright ridge reduced the signal-to-noise threshold from the lower portions of the visible plume.

Ground-based Observation Strategy & Initial Results

We observed the LCROSS impact with the Astrophysical Research Consortium 3.5 meter telescope at Apache Point Observatory in Sunspot, NM. We used the Agile visible light frame transfer camera with a V-filter to obtain a continuous series of 0.5 s exposures throughout impact. We chose an ND=2.5 neutral density filter to produce images close to saturation of the illuminated lunar terrain in order to maximize the signal-to-noise ratio for a faint plume.

Our initial inspection of the images revealed no evidence of a visible plume, a negative result obtained by other facilities in the ground-based observation campaign [5]. We also found no visible plume in processed images where we subtracted pre-impact images from post-impact images to search for changes due to an evolving plume.



We subsequently calibrated the post-impact images to produce brightness maps of the Cabeus area and of the 3-sigma noise threshold above the impact site [6].

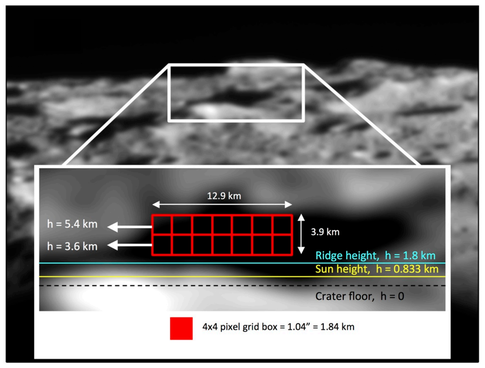
The figure at left is a V-band surface brightness map of the Cabeus crater LCROSS impact site from Agile imaging. The upper panel is a close-up view of the floor of Cabeus crater and the surrounding area. The middle panel is the per pixel V-band surface brightness. The white bar denotes the area directly above the LCROSS impact site. We found the minimum brightness above the impact site to be **6.75 magnitudes/arcsec²**.

The lower panel is the per pixel 3-sigma noise threshold of the data converted to calibrated V-band brightness values. This represents the upper brightness limit of a plume that could be detected through subtraction of pre- and post-impact images. As we found no detection of the plume using this method, we determined the maximum V-band plume brightness to be **9.5 magnitudes/arcsec²** at 4 km above the impact site.

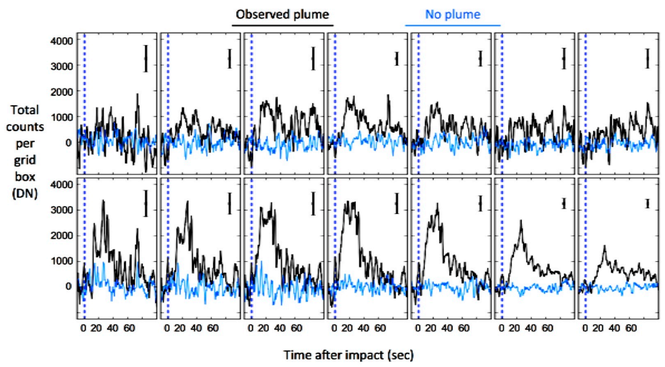
Plume Signal Detection Using a Principal Component Analysis Filter

In order to probe below the 3-sigma noise threshold, we employed a Principal Component Analysis based filtering method on our Agile image sequence. This involved removing the first 4 principal components that represented time-varying seeing distortions and sub-pixel horizontal and vertical image registration errors. We further increased the signal-to-noise ratio by co-adding 4x4 pixel arrays in a grid centered above the impact site and boxcar averaged over 5 frames or 2.5 s.

The diagram at right illustrates the examination grid used to detect the LCROSS plume using the PCA filtering method. The bottom row is centered at 3.6 km above the impact site. This was the darkest region in Cabeus crater in the Agile images. The scattered light from the foreground ridge reduced the signal-to-noise of the LCROSS plume significantly for heights below 3.6 km above the crater floor.

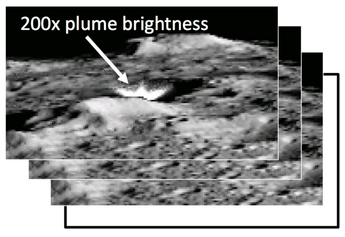


The figure below shows the measured brightness of each 4x4 pixel array in the examination grid as a function of time after LCROSS impact. The vertical bars are the 1-sigma noise values for each respective grid array. We found a detectable increase in brightness directly above the impact site (middle of bottom row). The brightness peaked at 17 s after impact, consistent with the time of peak brightness of the LCROSS plume observed *in situ* by the Shepherding Spacecraft [1].



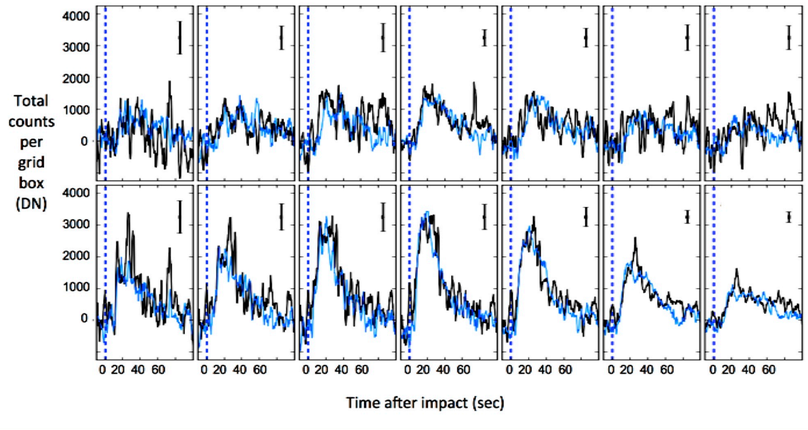
Plume Modeling & Characterization

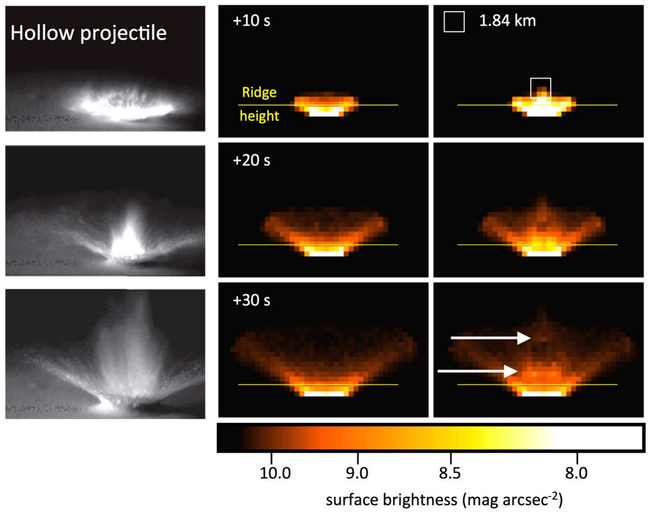
To establish that the signal found after PCA filtering was caused by an impact plume, we created a series of images incorporating output from an n-body ballistic particle plume model. We adopted the following procedure to create a synthetic image sequence and generate model brightness curves for comparison to our observations:



1) Ran 3-D n-body ballistic particle plume simulations and extracted plume brightness maps at 0.5 s intervals corresponding to the Agile image cadence.
2) Created a "perfect" sequence of plume capture maps combined with a computer generated lunar landscape (illustrated at left with plume shown 200x brighter than the actual best match result).
3) Added seeing distortions, frame alignment mismatches, and noise, then generated brightness curves using the same PCA filter and binning as with the observed data.

Below is an overlay of the brightness curves from our best match plume model (blue curves) with the curves extracted from out Agile image sequence after PCA filtering (black curves) [7].





The figure above shows a simulated single-component plume (middle column) and the best-match multi-component plume (right column). The best-match simulated plume resembled laboratory plumes produced by impacts of hollow projectiles (left column). The ejection angle of the LCROSS plume low-angle component suggested a regolith more compressible than pumice material used in lab experiments [3][7]. The white arrows highlight a brightness reduction seen in the best match model high-angle plume that may be due to either a mass reduction for particles with ejection speeds below 150-300 m/s or albedo variations with depth.

The maximum brightness of the best-match simulated plume was **10.0 +/- 0.1 magnitudes/arcsecond²** at 3.6 km above the impact site. Therefore, this analysis demonstrated the ability to detect and characterize a resolved ejecta plume **3.25 magnitudes/arcsecond²** fainter (20x dimmer in radiance) than the scattered light background using a PCA filtering technique. Simulation results indicated that the portion of the plume blocked by the foreground ridge was as bright as **8.0 magnitudes/arcsec²** at the sun height of 833 m above the impact site.

Implications for Future Impact Experiments

We used a PCA filtering method to detect and characterize a lunar ejecta plume with an estimated mass of 2000-4000 kg above the sun height of 833 m [1][7]. Other spacecraft of similar mass to the 2300 kg LCROSS impactor have been considered for lunar impacts at their end-of-life. A lunar impact site choice that would result in improved plume signal-to-noise ratio, either from increased visible plume brightness or reduced background scattered light, would allow for a more detailed characterization of plume dynamics and regolith properties.

Recommended impact site considerations are as follows:

- Impact as near as possible to the lunar limb – This provides a side-on view of the ejecta plume necessary for the evaluation of multi-component plume dynamics. Also, minimizing the area of illuminated lunar terrain in the impact site images reduces the intensity of the scattered light background.
- Clear line-of-sight from Earth and a solar illumination height of no higher than 1 km above the impact site.
- Lunar phase illumination – The solar phase angle at time of LCROSS impact was 65° (with lunar illumination of 71%), which was well suited for plume imaging. A higher lunar illumination phase would produce more scattered background light. A lower lunar illumination (with corresponding higher solar phase angle) would reduce scattered light with a possible tradeoff of a higher sun height at the impact site.

References & Acknowledgments

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[7] Strycker, P. D. *et al.* (2013) Characterization of the LCROSS impact plume from a ground-based imaging detection. *Nat. Commun.* 4:2620 *doi: 10.1038/ncomms3620.*

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Scientific rationale and concepts for an *in situ* Saturn probe mission

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Introduction: *In situ* exploration of Saturn's atmosphere would bring insights in two broad themes: our Solar System formation and evolution, and the processes at play in planetary atmospheres. **Here we summarize the science case for *in situ* measurements at Saturn (see also [1] for details) and discuss the possible mission concepts that would be consistent with the constraints of ESA M-class missions.**

Solar System formation: To understand the origin of the Solar System and the formation of giant planets, statistical data obtained from the observation of exoplanetary systems must be supplemented by **direct measurements of the composition of the planets in our Solar System**. By measuring a giant planet's chemical inventory, and contrasting these with measurements of (i) other giant planets, (ii) primitive materials found in small bodies, and (iii) the composition of our parent star and the local interstellar medium, much can be revealed about the conditions at work during the formation of our planetary system. In contrast with Jupiter, Saturn's **noble gas abundances are unknown** and their determination is missing to properly understand the planet's formation conditions. As in Jupiter, the missing piece of the puzzle remains **the measurement of O**. Precisely measuring the **He/H_2 ratio** in Saturn is also needed.

Planetary Atmospheric Processes: Saturn's complex and cloud-dominated weather-layer is our principle gateway to the processes at work within the deep interior of this giant planet. ***In situ* studies provide access to atmospheric regions that are beyond the reach of remote sensing**, enabling us to study the dynamical, chemical and aerosol-forming processes at work from the thermosphere to the troposphere below the cloud decks.

Mission concepts: Different mission architectures are envisaged, all based on an entry probe that would descend through Saturn's stratosphere and troposphere under parachute down to a **minimum of 10 bars** [1]. Future studies will focus on the trade-offs between science return and the added design complexity of a probe that could operate at pressures greater than 10 bars. Three possible mission configurations are currently under study (with different risk/cost trades):

- **Configuration 1: Probe + Carrier.** After probe delivery, the carrier would follow its path and be destroyed during atmospheric entry, but could perform pre-entry science. The carrier would not be used as a radio relay, but the probe would transmit its data to the ground system via a direct-to-Earth (DTE) RF link;

- **Configuration 2: Probe + Carrier/Relay.** The probe would detach from the carrier several months prior to probe entry. The carrier trajectory would be designed to enable probe data relay during over-flight as well as performing approach and flyby science;

- **Configuration 3: Probe + Orbiter** (similar to the Galileo Orbiter/Probe). As for Configuration 2, but after probe relay during over-flight, the orbiter would transit to a Saturn orbit and continue to perform orbital science.

In all three configurations, the carrier/orbiter would be equipped with a combination of solar panels, secondary batteries and possibly a set of primary batteries for phases that require a high power demand, for example during the probe entry phase.

Payload: To match the measurement requirements, a model payload (see Table 1) could include a mass spectrometer, a tunable laser system, a helium abundance detector, an atmospheric structure instrument, accelerometers, temperature sensors, pressure profile, Doppler wind and nephelometer instruments, etc.

Such a mission would greatly benefit from strong international collaborations.

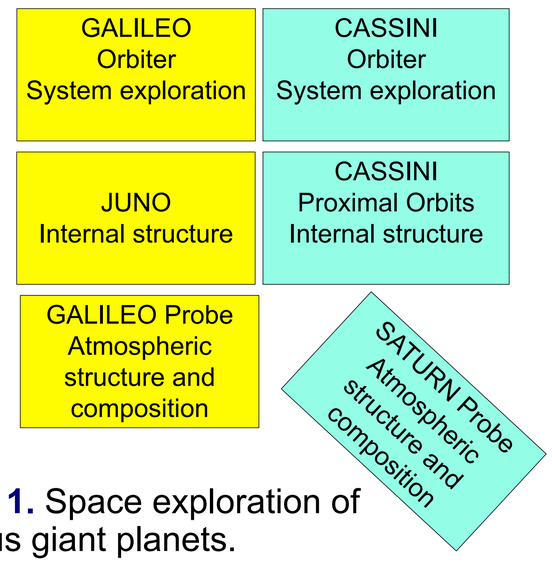
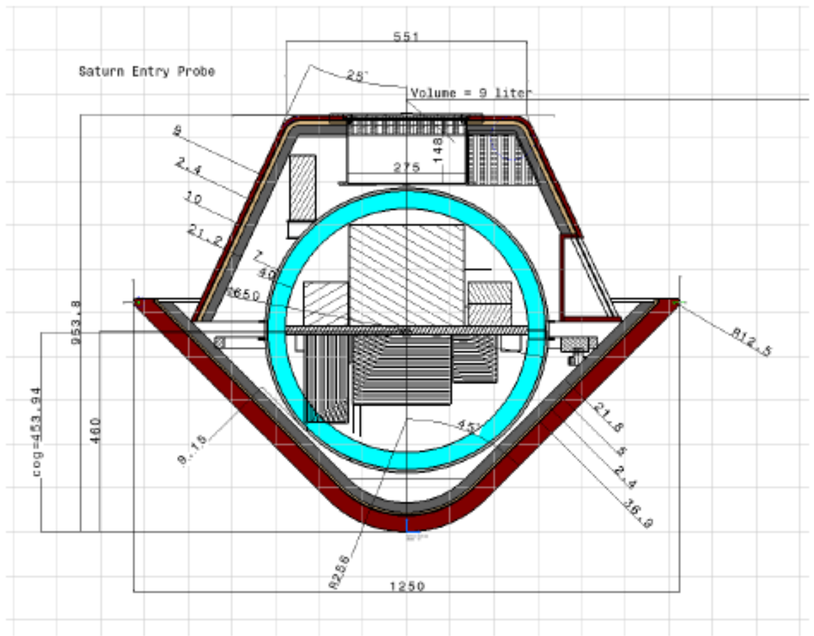


Figure 1. Space exploration of gaseous giant planets.

Table 1. Example of model payload

Instrument	Measurement
Mass Spectrometer	Elemental and chemical composition
	Isotopic composition
	High molecular mass organics
Tunable Laser Spectrometer	Stable isotope ratios
Helium Abundance Detector	Accurate He/H_2 ratio
Atmospheric Structure Instrument	Pressure, temperature, density, molecular weight profile
Doppler Wind Experiment	Measure winds, speed and direction
Nephelometer	Cloud structure
	Solid/liquid particules
Net-flux radiometer	Thermal/solar energy



References

[1] Mousis, O., et al. 2014, "Scientific Rationale of Saturn's in situ exploration", submitted to *Plan. Space Sci.* (and references therein).

A Saturn probe proposal is currently in preparation for the response to the ESA call for M4 mission. Any scientist interested in participating in this project is invited to contact Olivier Mousis (olivier.mousis@obs-besancon.fr)

The TechEdSat NanoSatellites and Exo-Brake De-orbit Mechanisms: Recent Flight Experience

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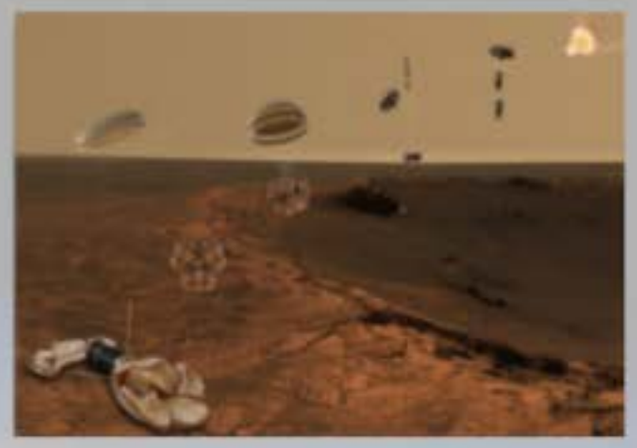
Applications

ISS/Oribital Platform Sample Return
-Recovering 0.1 kg to 3 kg samples

ATROMOS Mars Surface NanoSatellite Mission Concepts
-Exploring critical, high-risk regions of Mars



The Teams

Key Technology Advances

Exo-Brake
-Novel and 'Safe' de-orbit technique
-Advanced targeting through modulation

Advanced CubeSat Com
-Development of a 'TDRS-for-CubeSats'
(Obviating the need for ground stations; rapid uplink command capabilities)

ISS Design/Safety Process Nanosats
-ISS compatible design and testing process for rapid flight opprotunities

SCRAMP/TDRV (Tube Deployed Re-entry Vehicle)
-Self Stabilizing Re-entry Probe
-Shock/Shock interaction/Transpiration Studies

SOAREX-6
May 2008

>High-mach reentry test
>Shock shock interaction analysis

SOAREX-7
May 2009

>First flight of TDRV
>Highly stable self stabilizing reentry probe

TES-1
Oct 4, 2012

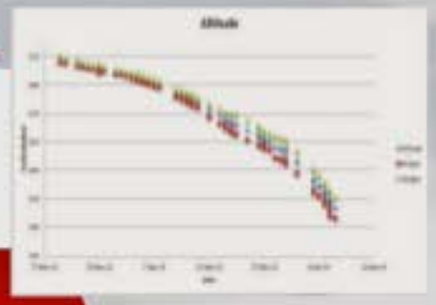
>First US CubeSat deployed from the ISS
>System Verification Test

TES-2
Aug 21, 2013

>First successful test of Iridium satellite to satellite communication

TES-3
Nov 19, 2013

>First 3U deployed from ISS
>First Exo-Brake flight test



TES-4
Expected July 2015

>Evolved Exo-Brake flight test
>Flight material and subsystem investigation

MARCHING TOWARDS TROY: EXPLORATION OF THE JUPITER TROJAN ASTEROIDS

PURDUE UNIVERSITY

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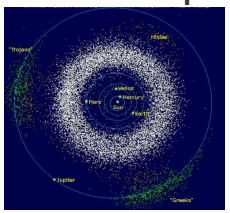
What are Jupiter Trojans? Why should we explore them?



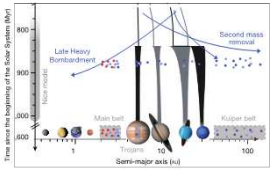
+ More than half a million objects larger than 1 km in diameter, called the Jupiter Trojans Asteroids
+ Librate about Jupiter's L4 and L5 Lagrange points
+ Potential source of insights into long standing questions on the origin and early history of the Solar System.

+ Very low albedos and great distance from the Sun have made ground-based observations very difficult
+ Two distinct subpopulations that are distinguishable in visible (redder) and near-infrared spectra (less red)
+ Spectral groupings not conclusively linked to physical characteristics or other observed parameters (e.g. albedo)

Formation Theories
1. Formation alongside Jupiter?
2. Interlopers from other parts of the solar system like the Kuiper Belt? – Nice Model - Chaotic Capture *(Morbidelli et al. 2005)* - Jupiter-Jump Capture *(Nesvorny et al. 2013)*

One of highest priority New Frontiers Class missions in the 2013 Planetary Science Decadal Survey

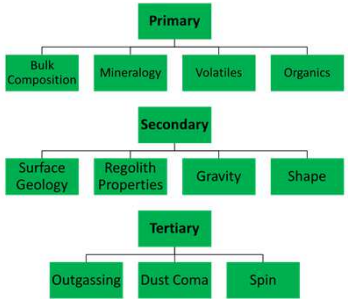
What we know about Trojans?



DeMeo and Carry (2014)

What We "Think" We Know	
Orbital Characteristics	a = Approx. 5 AU e < 0.3 i < 40°
Size	< 1km... >100km
Approx. Mean Collisional Velocity	5 km/s
Approx. Combined Mass	5.97×10^{20} kg
Systems	Binary/Non-Binary

Prioritization of Science Objectives



Prioritized according to the 2013 Planetary Science Decadal Survey

	Bulk Composition	Surface Composition	Surface Features	Regolith Properties	Gravity/ Shape	Outgassing	Dust Coma
Gamma/Neutron Ray Spectrometer							
Visible-Near IR Hyperspectral Imager							
Wide/Narrow Angle Camera							
Thermal Radiometer							
Laser Altimeter							
Ultraviolet Spectrometer							

Five instruments to achieve the science objectives

(a) surface mineralogical and elemental composition,
(b) interior structure,
(c) physical state of surface regolith: evidence and consequences of external modification processes

A New Frontiers Mission Concept: Science Drives Mission Design

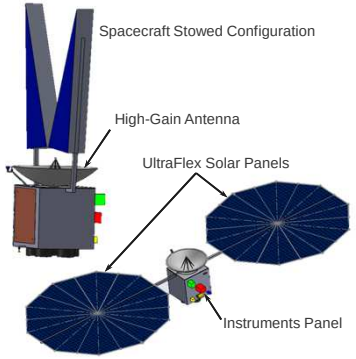
Mission that conducts science on two asteroid of different spectra

REDDER	LESS RED
Achilles	Diomedes
Hektor	Agapenor
Agamemnon	Deipylos
Neoptolemus	Kalchas
Teucer	Eurybates
Automedon	Amphilochos
Meriones	XO79

Mission Requirements

1. Rendezvous with two asteroids of different spectra
2. At least 6 months primary science mission at each target
3. Fulfill the science objectives highlighted in the 2013 Planetary Science Decadal Survey
4. Within cost constraints of New Frontiers mission class ($800 M in FY2015 $)
5. Use only solar power (no ASRG allowed)

The Mission is named "DUSK" as a tribute to the DAWN Mission

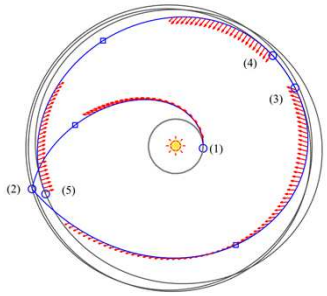


DUSK Spacecraft Details

DUSK is a 3-axis stabilized spacecraft	
S/C Bus	2x2x2 m
Thrusters	5 HiVHAc (Hall) Thrusters 0.3 – 3.9 kW, Xe Fuel = 2030 kg
Power	Solar (UltraFlex) 40kW
Dry Mass CBE/MEV	888 kg/ 1004 kg
Dry Mass Reserves	301 kg (30% of MEV)
Propellant CBE	1934 kg Xenon
Power	1.32 kW (at Trojan Distance)

INTERPLANETARY TRAJECTORY AND MISSION OPERATIONS

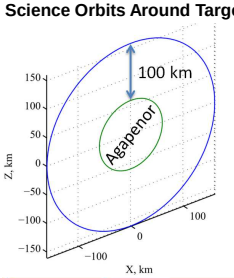
No orbit insertion maneuvers required at both Agapenor and Hektor

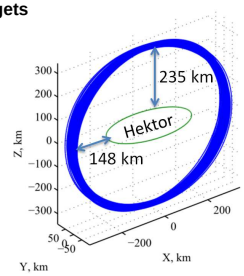


1. Atlas V 551used for launch
2. Launch date 9/18/2026 with an initial mass of 3439 kg
3. Jupiter gravity assists for maximum inclination change, 1/2029
4. Rendezvous with Agapenor in 10/2033, with a 7.05 year TOF
5. Approaches Agapenor at 0 km/s
6. 6-month primary science mission at Agapenor
7. Rendezvous with Hektor in 9/2038 followed by 6-month primary science mission (12 year TOF)
8. Prior to both Agapenor and Hektor arrival, opportunistic flybys of other asteroids possible

Science Operations, Risk, and Cost of the Mission

Science Orbits Around Targets

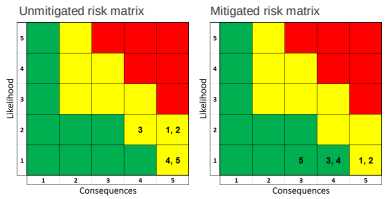




	Agapenor	Hektor
Model	Point-mass model	Triaxial ellipsoid (370x195x195 km)
Period, hr	~24	14.6
Velocity, m/s	10-20	40

+ Shapes of the targets are not properly known
+ Agapenor is modeled as a point mass and Hektor as a triaxial ellipsoid
+ Because of the shapes science orbits around the targets will need regular station-keeping
+ A 235 X 148 km orbit around Hektor is stable for around 30 days: ΔV needed to maintain orbit
+ The moon of Hektor is not considered while designing science orbits
+ Science orbits station-keeping and science operations drive attitude control propellant
+ Extra propellant is carried to account for uncertainties in the long-term propagation of science orbits
+ Velocities of spacecraft around Agapenor (~20 m/s) and Hektor (~40 m/s) helps in instruments operations

Risk Assessments via NASA's Priority Score System



#	Component/Mechanism Names	Risk Description	Type
1	HiVHAC Hall Thruster	If it fails, the system would not be able to control its movement direction.	Technical
2	Hydrazine Thrusters	If it fails, the system would not be able to control its movement direction.	Technical
3	Reaction Wheels	Medium. The system would not be able to make fine adjustments.	Technical
4	UltraFlex solar wings	Very low	Technical
5	Wing deployment mechanism	Very low	Technical

+ Risks can be mitigated via appropriate actions

COST

- The cost of the mission is $752 Million in FY2015 $ (cost cap of $800 M)
- Analogy-based, quasi-parametric, and grassroots models
- Reserves: 50% for Phases A–D, and 25% for Phases E and F

MISSION SUMMARY

- 13-year New Frontiers mission to two Trojan asteroids
- Time to commencing first science Ops: 7 years
- Rendezvous Agapenor and Hektor
- Opportunistic flybys of other asteroids
- 6x Instruments to answer science goals
- $752 Million (New Frontiers) - $48M to spare!

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