

The Case for an Enceladus New Frontiers Mission

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It is unlikely that a flagship mission devoted to the study of Enceladus will occur in the next few decades but Enceladus remains a compelling science target for a future mission. A limited, well-focused New Frontiers class mission to Enceladus can make major contributions to answering some of the fundamental questions we have about the satellite's activity, the solar system, its formation and evolution, and the likelihood that other habitable environmental niches occur outside the Earth's biosphere. We recommend: 1) the acknowledgement that limited, well-focused missions to Enceladus can make major contributions to answering fundamental science questions, 2) the expansion of the target list for New Frontiers class missions to include Enceladus and 3) the recommendation that studies be conducted to identify the range of possible missions that can be flown under the New Frontiers line of missions.

1. Introduction

Cassini observations of Enceladus by multiple instruments provided an amazing surprise; a small moon (500 km in diameter) ejecting plumes of water ice and vapor into the Saturnian system. This confirmed, as suspected, that Enceladus is the source of the tenuous E-ring, but generated many questions about how such a small moon could maintain this activity for so long. These initial results led to many follow-up observations with Cassini's suite of remote-sensing and fields and particles instruments, as well as the development of a multitude of interior models that attempted to recreate the plumes' composition, temperature and visible surface structure.

However, Cassini's instruments are not optimized to study the unexpected plumes, the cold surface and the possibly complex organic chemistry of Enceladus; they were intended to study all of the objects in the Saturnian system, spanning a vast range of size, temperature and composition. So, while observations will continue to provide tantalizing previews, ultimately they will be unable to answer many of the scientific puzzles of Enceladus. However, Enceladus would clearly classify as an exceptionally intriguing science target that can address many of the major science themes for planetary exploration (see *The Case for Enceladus Science* white paper).

Currently, Europa and the Jupiter system has been selected for the next flagship mission to the outer solar system. Moreover the next highest priority target for an outer solar system flagship mission is the Saturnian system but with a heavy focus on Titan science. Thus it is unlikely that a flagship mission devoted to Enceladus will occur in the next few decades but Enceladus remains a compelling science target for a future mission. A limited, well-focused New Frontiers class mission to Enceladus can make major contributions to answering some of the fundamental questions we have about the solar system, its formation and evolution and the likelihood that other habitable environmental niches occur outside the Earth's biosphere.

In this white paper, we will summarize one possible mission concept to explore Enceladus within a New Frontiers-level mission: to stay below the cost cap of \$650M (FY09 dollars) and within the launch capability of the Atlas V 551. We imagine that there are other possible mission scenarios, which would also be valid as a New Frontiers mission to Enceladus.

2. Overall Science Goal

The goals of this mission concept can contribute to three major themes in NASA's 2006 *Solar System Exploration Roadmap*: 1) How did the Sun's family of planets and minor bodies originate? 2) How did the Solar System evolve to its current diverse state? and 3) What are the characteristics of the Solar System that led to the origin of life and has life evolved elsewhere in the Solar System. All the science objectives (Table 1) address these major themes and focus on areas where additional well-defined measurements would have the highest scientific return.

2.1. Science Objectives (Priority Order)

A. **Understand the Satellite's Evolution.** Knowledge of interior structure and evolution are vital for understanding the size of the core, the thickness of the lithosphere, the degree of internal heterogeneity, and the source of the surface activity. While water ice and vapor have been detected, is liquid water present? If so, is it present as a global subsurface ocean, or as localized pockets of water? What roles do convection, polar wander and rotation rate have on the

extensive tectonic activity and why does geologic activity vary so widely across the surface?

Measurement Objectives:

- A1. Determine core size
- A2. Refine global shape estimates
- A3. Determine crustal ice thickness and distribution of sub-surface liquid

B. Determine Composition, Mechanisms and Evolution of the Plume. These data are required to understand the sources and mechanisms driving the plumes. What is the nature of the plume source, are liquids involved, and, if so, how close to the surface are they? Is the source pressurized ice? What are the mass escape and resurfacing rates and how do they vary spatially and temporally? What are the temperatures in and around the vent regions and over what spatial scales? What can this tell us about subsurface conditions?

Measurement Objectives:

- B1. Measure plume composition
- B2. Measure plume density, particle size distribution, source locations and variability

C. Infer Subsurface Composition and Potential for Habitability. This is required to understand the chemical processes occurring at and below the surface. Are clathrates, ammonia or ammonia hydrates important in modifying the temperatures required for geyser formation? What are the ratios of [D/H], and other important isotopes, in the plume and on the surface? What chemical processes are occurring at and below the surface? Are organics, particularly those associated with prebiotic chemistry or even life, present? What heat/energy sources might be available for life, and is there evidence for extant or extinct life?

Measurement Objectives:

- C1. Measure plume composition
- C2. Determine the distribution of sub-surface liquid
- C3. Determine surface and near surface temperatures

D. Assess Internal Energy Sources and Quantify Heat Flow. This estimate is necessary for understanding the processes driving the surface activity and how energy is supplied to the plumes. To what extent is tidal heating an energy source for the active plume features? What is the contribution of other sources including photolytic and/or radiolytic processes? What is the spatial distribution and temporal variability of the processes and what are the dissipation mechanisms?

Measurement Objectives:

- D1. Determine the tidal stresses' spatial distribution, variability and dissipation mechanism

Table 1. Science Traceability Matrix

Science Objective	Measurement Objective	Level 1 Measurement Requirement	Mission Requirement
A. Understand the Satellite's Evolution	A1. Determine core size	Gravity measurements to degree 4	12 flybys, range <100 km, variable flyby latitudes; at least two near-polar (70° N and S) and one near-equatorial pass
	A2. Refine global shape estimates	Optical imaging at 50 m/pixel, over > 50% of the globe	Pointing accuracy 2 mrad, range <500 km
	A3. Determine crustal ice thickness and distribution of sub-surface liquid	Sounding depth 10 km, accuracy 300 m, spatial resolution <50 km at several latitudes, emphasizing polar vents	Pointing accuracy 5 km, range <200 km. Total of 12 flybys targeting multiple latitudes
B. Determine Composition, Mechanisms and Evolution of the Plumes	B1. Measure plume composition	Plume chemical identification to 300 a.m.u, isotope ratios, with m/Dm of 500	25-200-km altitude, including several targeted plume passes, E-ring and neutral torus sampling
	B2. Measure plume density, particle size distribution, locations and variability	Broad-band thermal mapping of surface at 70-250 K, $NE\Delta T \leq 1$ K at 100K. Resolution of 10-m at south pole (70° S) with 100% coverage, 50 to 100-m elsewhere	Pointing accuracy 2 mrad, range ≤ 200 km for spatial resolution at pole
		High-phase (> 165°) plume imaging an at least two occasions	Multiple high phase views of south pole
C. Infer Subsurface Composition and Potential Habitability	C1. Measure plume composition	Same as B1 composition sampling	
	C2. Determine the distribution of sub-surface liquid	Same as A3 sounding	
	C3. Determine surface and near surface temperatures	Same as B2 thermal mapping	
D. Assess Internal Energy Sources and Quantify	D1. Determine the tidal stress' spatial distribution, variability and dissipation mechanism	Same as B2 thermal mapping	
		Same as A3 sounding	

Heat Flow		Optical imaging of limb at 20 to 50 m/pixel	Imaging opportunities at perikrone and apokrone
		Visible surface and shadow imaging, 5-m spatial res. at the south pole, 10-50 m/pixel elsewhere with 50% coverage	Pointing accuracy 2 mrad, range <200 km
E. Study Surface Morphology, Geologic Processes, Evolution, and Rate of Surface Modification	E1. Measure plume densities, locations and variability	Same as B2 thermal mapping	
		Same as B2 High phase	
	E2. Study other surface features	Same as B2 thermal mapping	
		Same as D1 surface	
E3. Determine resurfacing rates	Same as B2 High phase		

E. Study Surface Morphology, Geologic Processes, Evolution and Rate of Surface Modification. These data are needed to create a temporal baseline for study of surface changes by comparison with observations from Cassini. Is photolytic and/or radiolytic surface chemistry important? Why is the surface albedo so high? What role does resurfacing from plume particle fallout and sputtering from collisions with E-ring particles play in surface chemistry?

Measurement Objectives:

- E1. Measure plume densities, locations and variability
- E2. Study other surface features

E3. Determine resurfacing rates3. Strawman Instrument Payload

While many different instruments could meet the outlined science objectives, a low power option suitable for a solar powered mission is shown below. This restriction meant that traditional, high-powered instruments were not included in the strawman payload. In addition, the science objectives must be met from Saturn orbit, with potentially fast flybys (~4 km/s), which drives the performance requirements of the chosen instruments. How each instrument maps to the science objectives is shown in Table 2. Other strawman payloads that can address the major science themes are possible and can fit within a New Frontiers class mission.

3.1. Mid-IR Thermal Instrument (MIRTI)

The mid-infrared thermal mapper measures temperatures in the vent region, and can search for other regions on Enceladus that may be warmer than their surrounding areas. Results from Cassini CIRS’ two mid-IR focal planes, with coarser spatial resolution than the thermal source,

indicate an ambiguity between size of the hottest regions and their temperatures. By spanning 8 to 14.5 mm (690 to 1250 cm^{-1}) at high sensitivity ($\text{NEDT} \leq 1\text{K}$ at 100K) and spatial resolution (10 m at 200 km), MIRTl would resolve this temperature vs. size discrepancy. The instrument is well suited to monitoring small temperature changes at the plume sources that may be associated with orbital phase-dependent tidal flexing. The mass of the thermal mapper was estimated to be 10 kg and the peak operating power 7 W. This mass includes a passive radiator, needed to cool the detectors.

3.2. Ice Penetrating Radar (IPR)

An ice penetrating radar system provides the best single measurement to determine Enceladus' sub-surface structure, and unlike direct seismometry, does not involve touching the surface with its implications for planetary protection. This system must be able to detect isolated bodies of liquids, but also be able to penetrate deeply enough to look for ice-water interfaces. The depth of ground penetration for a given frequency will depend on the ice's actual conductivity, but could penetrate many kilometers into the surface. A dual-frequency system also helps to remove ambiguities in the analysis of the return signals.

Pure water ice has a conductivity of less than 10^{-8} S/m. Little is known about the geophysical parameters of likely materials on Enceladus, especially under extreme temperatures and pressures, though 1% of metallic scatterers would result in an order of magnitude increase in conductivity. The conductivity of ice laced with sodium at low temperatures should still behave as near-ideal ice, primarily because the temperature is so low that the sodium is not activated to create any ionization (local electrical layer) in the ice. However, if the sodium is "chunky," like little rocks, there could be increased scattering. Thus, the actual penetration depth will depend on the composition and distribution within the ice.

Spatial resolution is obtained by the Doppler return delay along the track of the spacecraft. Cross-track resolution can also be improved by adding multiple cross-track beams. The nominal design included a 10-m dipole antenna with a 2.6-m Yagi antenna at 50 MHz. Mass was estimated to be 9 kg, peak operating power was 30 W, with an expected warm-up power of 10 W. While this may be optimistically undersized in terms of power, it does not represent a mission driver. SHARAD and MARSIS are good examples of this instrument type.

3.3. Enceladus Mass Spectrometer (EMS)

The mass spectrometer is required to accurately assess the Enceladus plume composition and inventory the organics. While the Cassini INMS is capable of detecting lower mass molecules, it is limited to a mass range of 1-99 Daltons with a mass resolution ($m/\Delta m$) of 100. All but two of the known amino acids (glycine and alanine) have masses above 100 Daltons.

Thus, to study all biologically interesting amino acids, while also studying bulk composition and high-order hydrocarbons, requires a mass range up to a minimum of 300 Daltons, with a mass resolution ($m/\Delta m$) sufficient to resolve molecular isotopes ($m/\Delta m$ of 500). 10 kg and 20 W were held for the mass spectrometer in the strawman payload. Quadrupole mass spectrometers have been flown on many missions and are high heritage.

Table 2. Science goals met by each strawman payload instrument

Instrument Science Objective	ICE	MI RTI	EM S	IPR	US O
A. Investigate Interior Structure and Evolution	X			X	X
B. Determine Plume Composition and Evolution	X	X	X		
C. Infer Subsurface Composition and Potential Habitability		X	X	X	
D. Assess Tidal Stressing and Quantify Heat Flow	X	X		X	
E. Study Surface Morphology, Geologic Processes, Evolution, and Rate of Surface Modification	X	X			

3.4. Imaging camera for Enceladus (ICE)

The imager is a multi-spectral camera, capable of pushbroom imaging and high spatial resolution (5 m) to resolve the polar vents and other surface structures. It must operate at low illumination levels expected at the south pole near equinox and during high-phase plume observations, but would also be useful for imaging other regions of the body. Because of the long shadows expected at the south pole, topography measurements will be possible, as well.

It is expected that these goals could be easily met with an off-the-shelf type camera or one similar to the New Horizons MVIC. A multiple flyby approach is well suited to acquiring high spatial resolution multispectral imaging data. Relatively long intervals between successive observations permit many images to be recovered from every flyby. The camera is expected to have a mass of ~2 kg and a power of 10 Watts while operating.

3.5. Gravity Experiment

While not strictly a science instrument *per se*, it is highly desirable to further refine our knowledge of the Enceladus gravity field by performing multiple gravity passes. Passes at different sub-spacecraft latitudes will help constrain the interior structure. This requires dedicated gravity passes and an Ultra-Stable Oscillator (USO) as part of the communications subsystem. This hardware is standard on most deep space missions, and does not drive the mission pointing, mass or power, though it does affect the mission operations scenario in that during gravity passes, the Enceladus closest approach must be visible with the high gain antenna pointed at Earth. Power permitting, the mass spectrometer or another instrument could also be used on these passes.

4. Trajectory

Trajectories have been identified for launch dates from 2015 to 2018. One mission requirement on the trajectory is the need to view the south pole of Enceladus with at least minimal sunlight. This restricts preferred arrival dates to no earlier than late 2024, as spring equinox is May 2025. The trajectory capable of delivering the most mass requires multiple flybys, and the final trajectory used for this study utilized an all-chemical propulsion V-V-E-E-S trajectory, which includes two Venus (minimum altitude 332 km) and two Earth (minimum altitude 1403 km)

flybys. This trajectory allows sufficient mass to be delivered to the Saturn system for an ~8-month mission, with a 9.4-year flight time to the Saturn system and large propellant margins on all burns and maneuvers. Using the V-V-E-E-S trajectory, an orbit insertion burn of 1.1 km/s is performed at 160,000 km from Saturn, outside the rings, but in the ring plane. SOI is followed by an apoapse maneuver to target Titan to set up the rest of the mission tour.

In this study, a Saturn orbit has been chosen since achieving an actual Enceladus orbit is difficult, risky and time-consuming. Moreover, achieving and maintaining an Enceladus orbit would most likely drive mission costs above the New Frontiers class cost cap.

After SOI, four Titan flybys and a final targeting burn are used to achieve a resonant Saturn orbit. A 5:1 resonant orbit that allows for Enceladus flybys every 6.85 days, but doesn't encounter Titan often, as apoapse is within Titan's orbit. In this orbit, the Enceladus closest approach distances are in the 25 to 200 km range and the flyby velocity is roughly 4 km/s. The sub-spacecraft latitude at closest approach can be varied, as can other aspects of the resonant orbit with small targeting burns. For example, small targeting burns of 10 m/s are included in the propellant plan, and can be used to step the latitude of the closest approach. Larger latitude or longitude changes would require big burns, but the occasional Titan perturbations can also be used to change the orbit. Small correction maneuvers are planned to counter any undesirable gravitational effects from Titan and/or Enceladus.

5. Summary

In summary, a brief design study has shown that a highly capable, small mission to the Saturn system can be achieved with solar power within the New Frontiers cost cap. The mission concept, as described here, fits well within existing Atlas V 500-series launch vehicle capabilities; the spacecraft has a launch mass of 3,261 kg, which fits on all the 500-series Atlas V launch vehicles. However, other viable options for a well-focused New Frontiers-class mission to study Enceladus exist and those mission concepts should also be considered.

Though not discussed in this white paper, Titan science could also be accomplished with a spacecraft studying Enceladus, during many Titan flybys.

6. Recommendations to Consider

We would like to make the following recommendations for the panel to consider:

- Acknowledge that a limited, focused mission to Enceladus can make major contributions to answering some of the fundamental questions we have about the solar system, its formation and evolution and the likelihood that other habitable environmental niches occur outside the Earth's biosphere.
- Recommend the inclusion of Enceladus as a target for the New Frontier class of spacecraft missions.
- Recommend that studies (for are both Solar and RPS-powered missions) be conducted to identify the range of possible missions that can be flown under the New Frontiers program.