KISS: Tidal Heating Workshop

Future missions to tidally heated worlds

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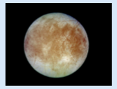
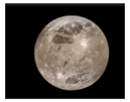
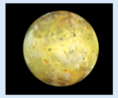
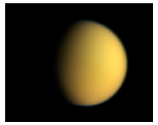
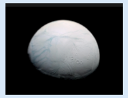
Tidally Heated Worlds

- Jupiter System
  - Io
  - Europa
  - Ganymede
- Saturn system
  - Titan
  - Enceladus
  - Others likely or possible
- Neptune
  - Possibly Triton
- Uranus
  - Possibly Ariel
- Exoplanets and ExoMoons

From top to bottom, Moons (to scale) of Jupiter, Saturn, Uranus, and Neptune.

Missions on the horizon

To Tidally Heated Worlds

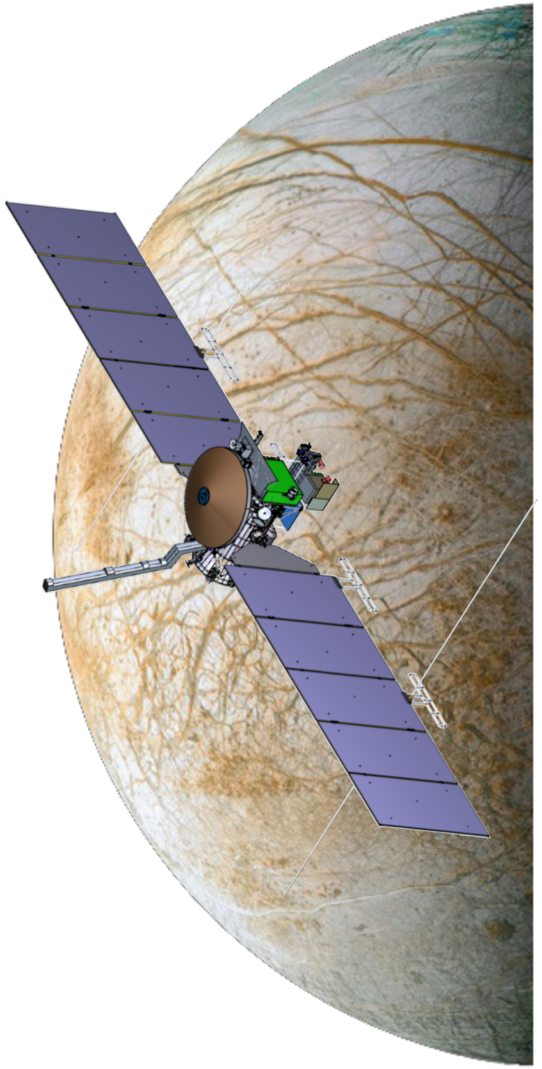
Tidally heated worlds	Mission concepts	Status
Europa 	**Europa Clipper** **Europa Lander**	NASA project, arrival 2025-2030 Pre-phase A study
Ganymede 	**JUICE**	ESA project, arrival 2030
Io 	Io Volcanic Observer Io Observer	Discovery Proposal New Frontiers 5 candidate
Titan 	**Dragonfly** Titan Orbiter/TMME/Titan Explorer TiME	Finalist New Frontiers 4 Study concepts Finalist Discovery 12
Enceladus 	ELF Life Elsah	Proposed Discovery and NF4 Proposed Discovery 14 Proposed NF4, **Tech Dev Efun**
Neptune and Uranus	Ice Giant missions	2017 NASA study
Exoplanets	**TESS, JWST, WFIRST, PLATO**	NASA, ESA missions

Bold items are currently funded projects

Source: Clipper PDR 8-2018

Europa Clipper

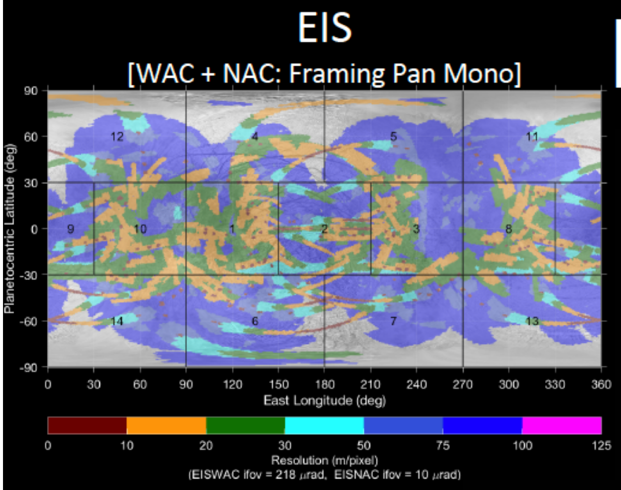
- Europa mission concepts have been studied by NASA for nearly two decades
- The 2011 NRC Decadal Survey stated that the $4.7B Jupiter Europa Orbiter mission concept had *extremely high science value* but was *unaffordable,* and requested a de-scoped option
- Subsequent studies by a joint JPL-APL team resulted in a multiple-flyby concept (referred to as Europa Clipper) that retains high science value at significantly reduced cost
- In June 2015 NASA selected the Europa multiple-flyby mission as its next outer planet flagship mission. PDR held in August 2018.
    - Use flyby concept to buildup global regional coverage
    - Solar powered spacecraft

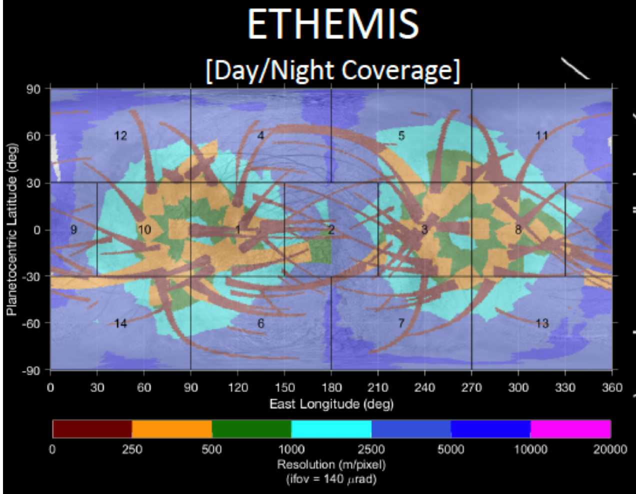


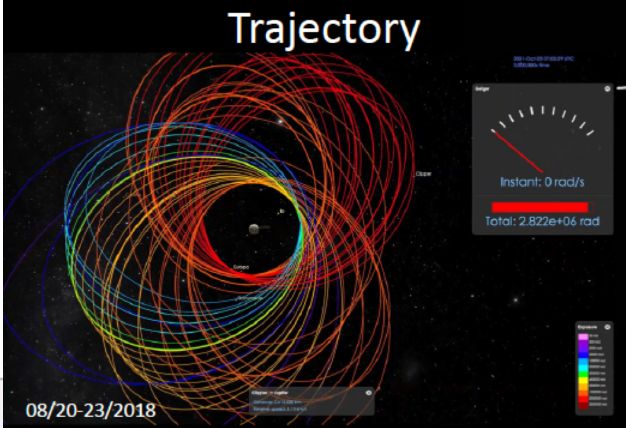
"Because of this ocean's potential suitability for life, Europa is one of the most important targets in all of planetary science."

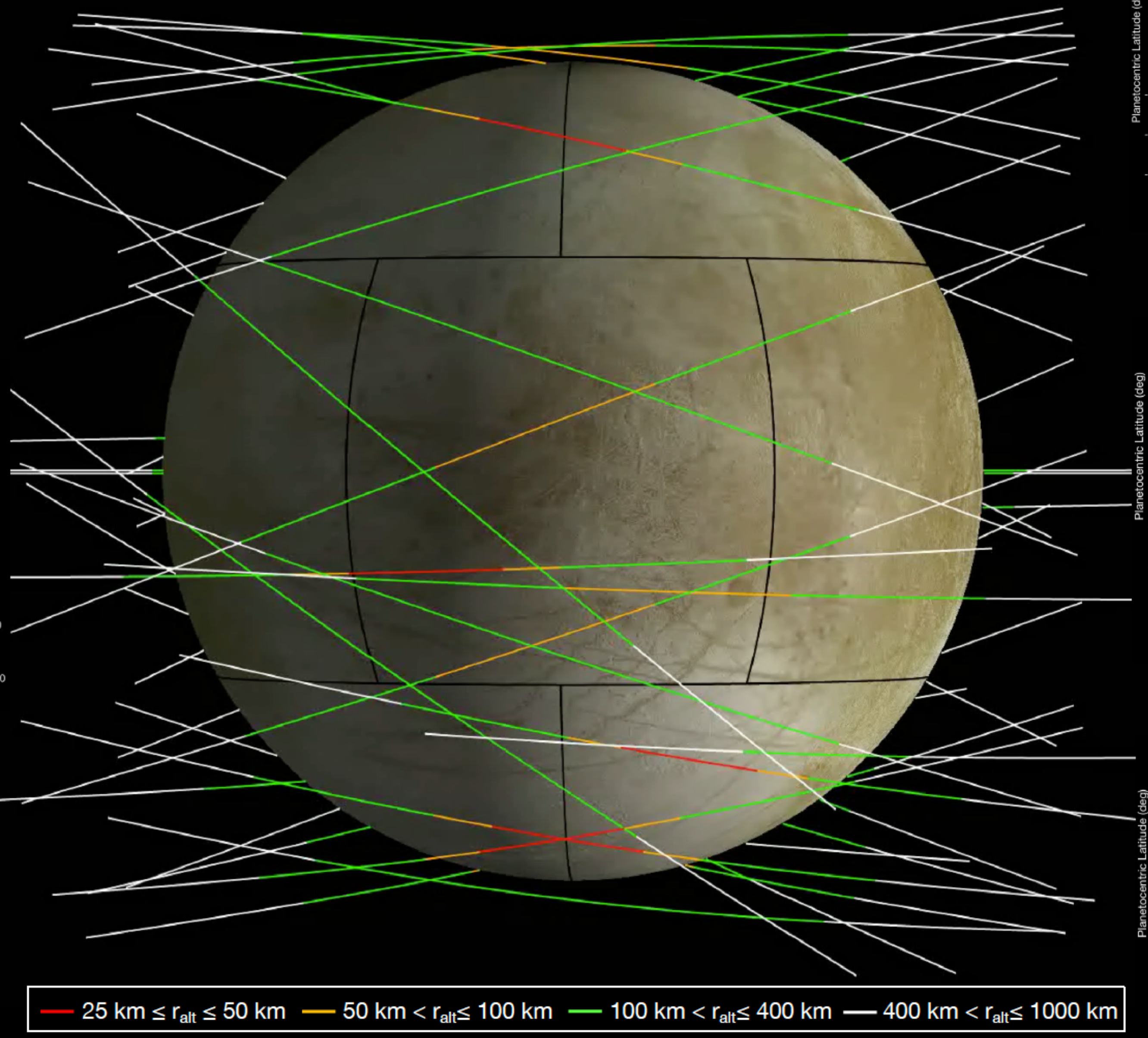
–2011 Planetary Decadal Survey

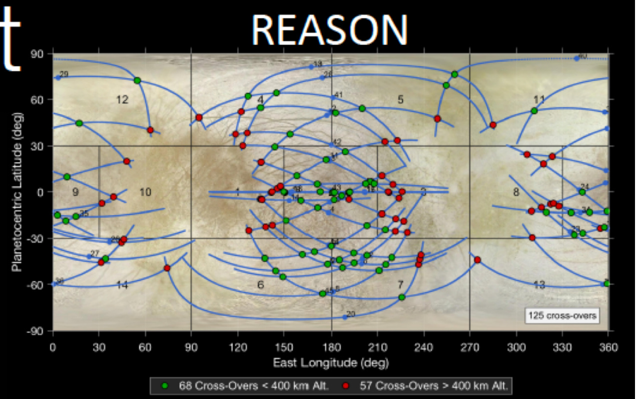
Europa Clipper Mission Concept

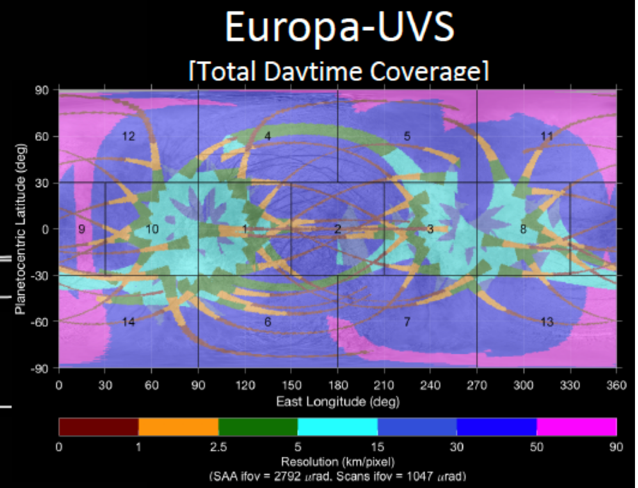


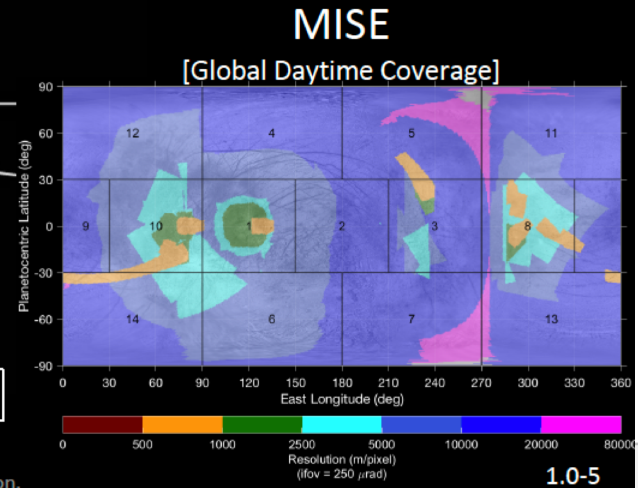


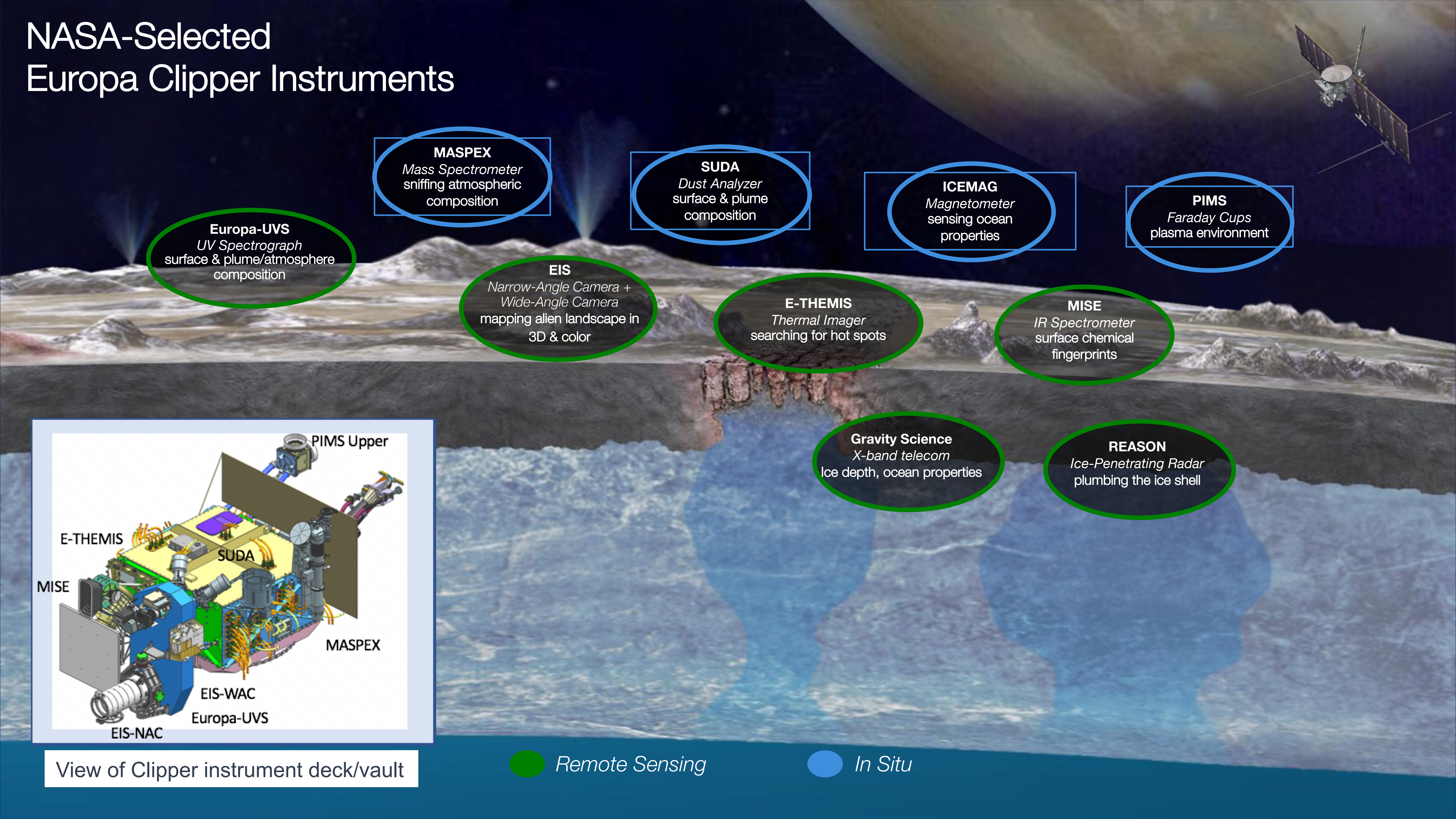






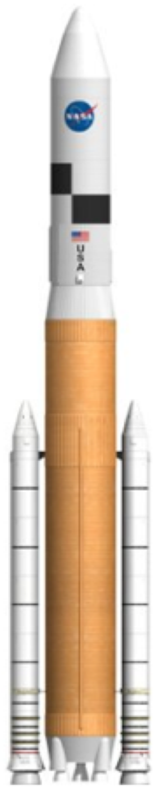


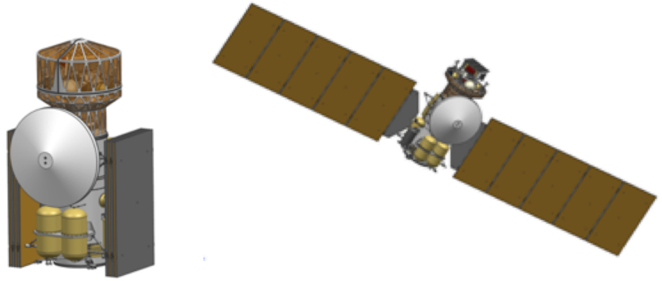


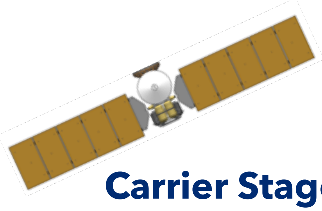

NASA-Selected
Europa Clipper Instruments
MASPEX
Mass Spectrometer
sniffing atmospheric composition
SUDA
Dust Analyzer
surface & plume composition
ICEMAG
Magnetometer
sensing ocean properties
PIMS
Faraday Cups
plasma environment
Europa-UVS
UV Spectrograph
surface & plume/atmosphere composition
EIS
Narrow-Angle Camera + Wide-Angle Camera
mapping alien landscape in 3D & color
E-THEMIS
Thermal Imager
searching for hot spots
MISE
IR Spectrometer
surface chemical fingerprints
Gravity Science
X-band telecom
Ice depth, ocean properties
REASON
Ice-Penetrating Radar
plumbing the ice shell
PIMS Upper
E-THEMIS
SUDA
MISE
MASPEX
EIS-WAC
Europa-UVS
EIS-NAC
View of Clipper instrument deck/vault
Remote Sensing
In Situ

Europa Lander Mission Concept

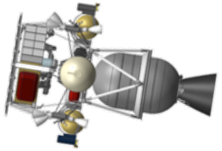
Source: Lander DMCR 2018

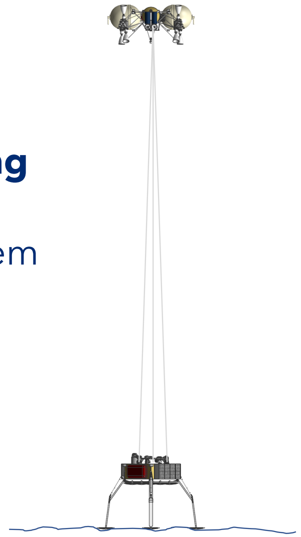






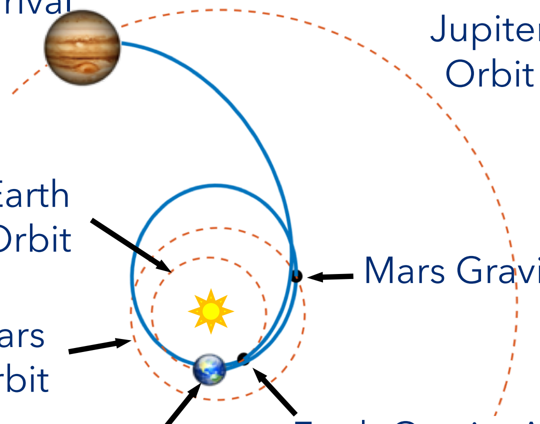
Carrier Stage
- 1.5 Mrad radiation exposure
- Elliptical disposal orbit



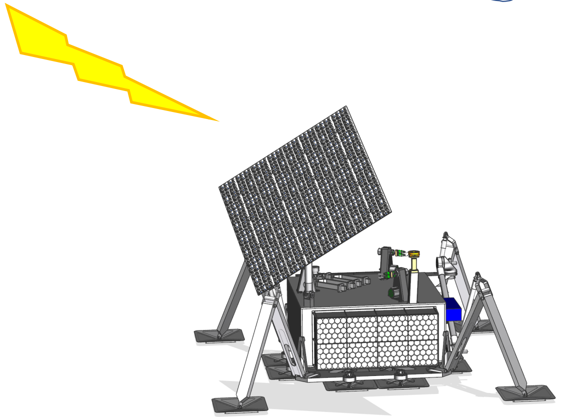


Deorbit, Descent, Landing
- Guided deorbit burn
- Sky Crane landing system
- 100-m accuracy
- DTE tones only

Cruise/Jovian Tour
- Jupiter Orbit Insertion: June 2031
- Europa Landing: 2033



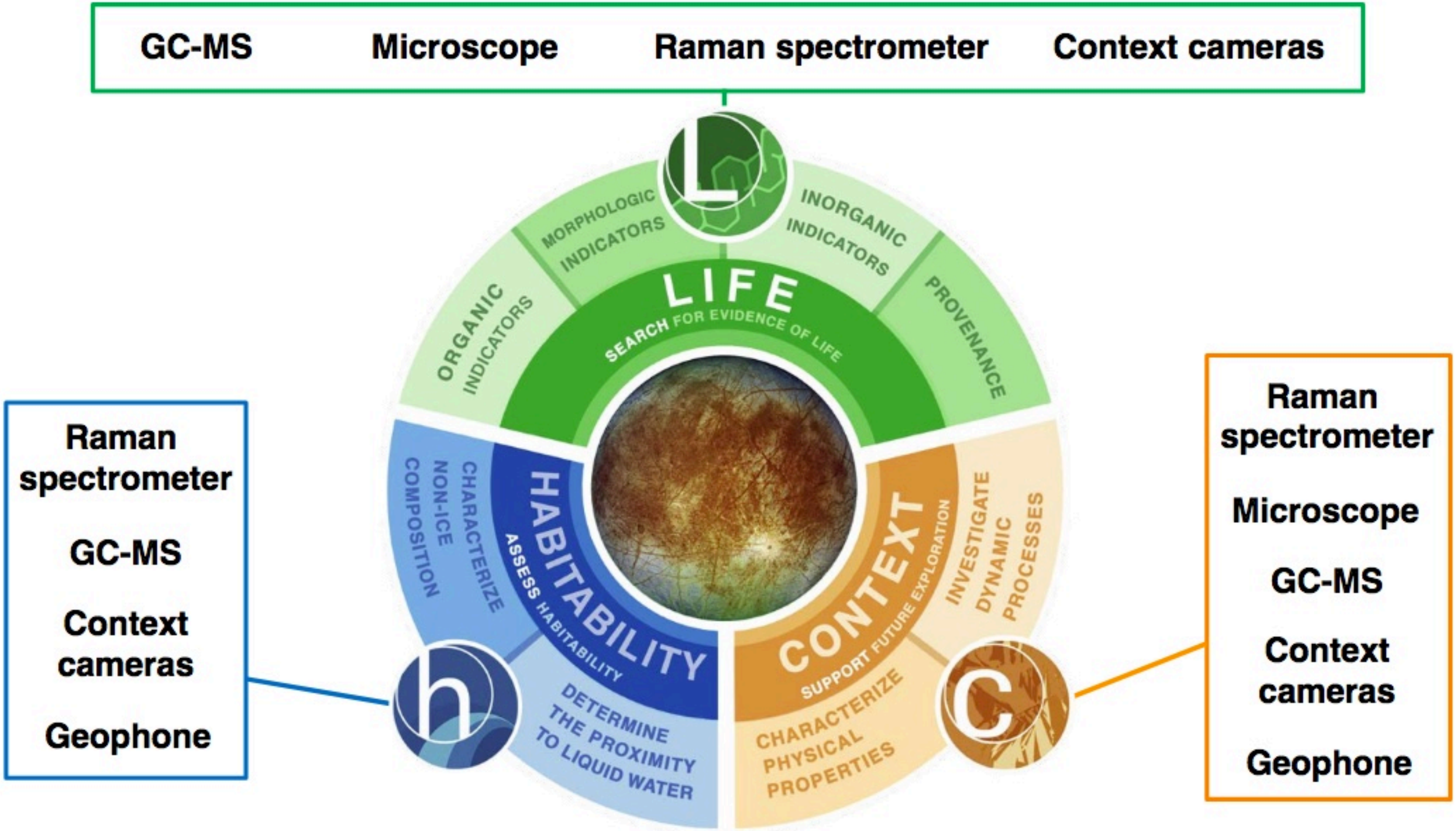
Surface Mission
- Biosignature Science
- 20+ days
- 3 samples from 1 trench
- Direct to Earth Comm or Clipper (backup)
- 1.5 Gbit data return
- 50 kWh battery
- 2.0 Mrad radiation exposure



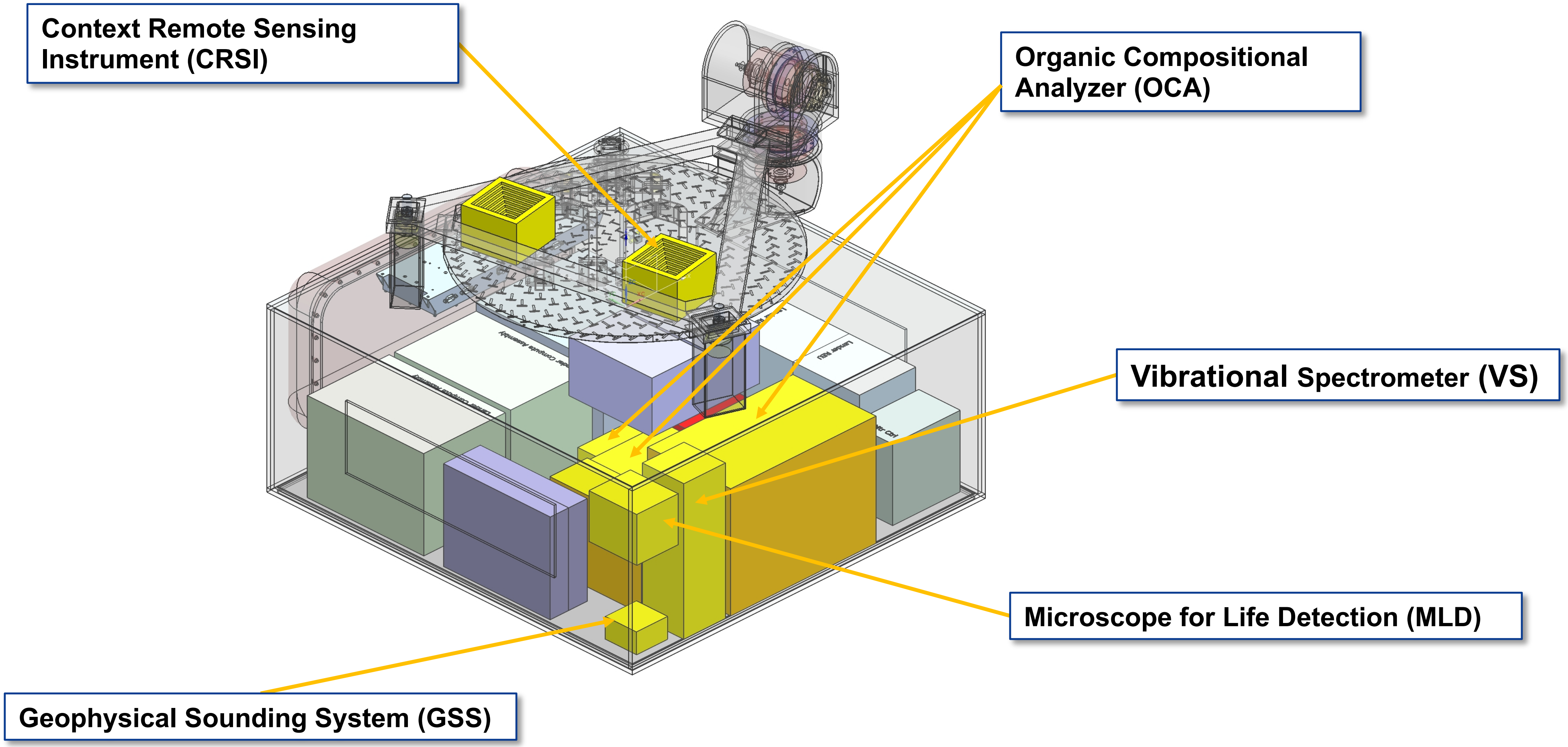
Launch
- SLS Block 1B
- Nov 2026

Leverage past flight experience and high-TRL tech development to reduce mission risk

Europa Lander Science Experiments

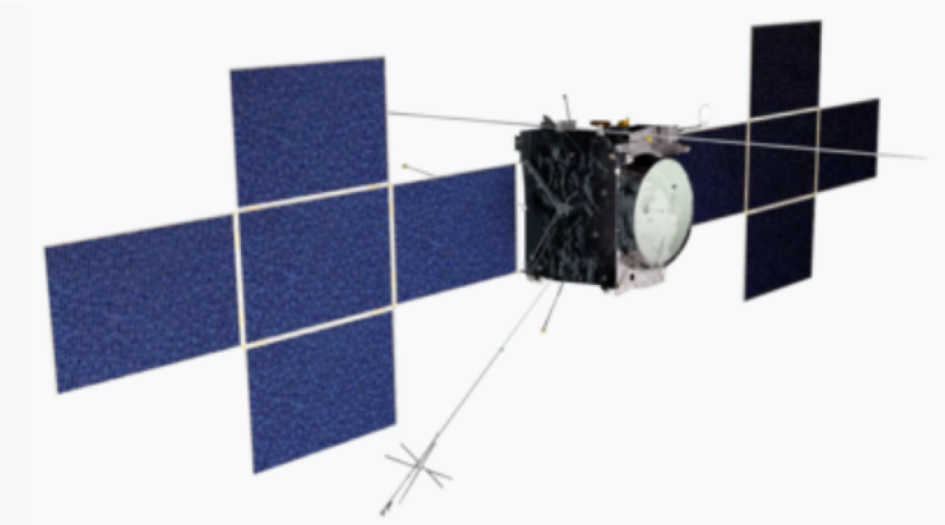


Science Definition Team (SDT) Sample Payload Accommodation



Juice: Jupiter Icy Moons Explorer

Source: Wikipedia



- ESA mission to Jupiter system
  - Launch in 2022
  - Jupiter orbit insertion 2030
  - 3.5 years in Jovian system
  - Ganymede orbit insertion 2033
- Solar powered spacecraft
  - ~100 m^2 solar arrays with 820W EOM
- Science Objectives
  - Ganymede
    - Characterization of the ocean layers and detection of putative subsurface water reservoirs;
    - Topographical, geological and compositional mapping of the surface;
    - Study of the physical properties of the icy crust;
    - Characterization of the internal mass distribution, dynamics and evolution of the interior;
    - Investigation of Ganymede's tenuous atmosphere;
    - Study of Ganymede's intrinsic magnetic field and its interactions with the Jovian magnetosphere
  - Two Europa flybys
  - Io distant monitoring

Source: Clipper-Juice workshop 2018

Europa Clipper – Juice instrument comparison 1 of 2

Plasma Investigation

Europa Clipper

PIMS: Key Instrument Parameters	
Ion Energy Range	0.1 – 50 eV/q, 0.02 – 7 keV/q
Electron Energy range	0.1 – 50 eV, 0.01 – 2 keV
Energy Resolution	<15%
Sensitivity	0.5 – 10^5 pA/cm^2
Time Resolution	1 – 4 s

JUICE – Key Instrument Parameters

PEP-JEI		PEP-JoEE		PEP-JDC		PEP-JENI		PEP-JNA	
Ion Energy Range		Ion Energy Range		Ion Energy Range	1 eV – 41 keV	Ion Energy Range	500 eV – 5 MeV	Ion Energy Range	
Electron Energy Range	1 eV - 55 keV	Electron Energy Range	25 keV – 1 MeV	Electron Energy Range		Electron Energy Range		Electron Energy Range	
Neutral Energy Range		Neutral Energy Range		Neutral Energy Range		Neutral Energy Range	500 eV – 300 keV (ENA)	Neutral Energy Range	10 eV – 3.3 keV (ENA)
Energy Resolution	8%	Energy Resolution	20%	Energy Resolution	12%	Energy Resolution	<14%	Energy Resolution	100%
Time resolution	2D per 512 ms / 3D per 4.1 s	Time resolution	1 s	Time resolution	2D per 250 ms / 3D per 8 s	Time resolution	≤10 s (ions) ≤5 min (ENA)	Time resolution	15 s nominal

Magnetometer

ICEMAG: Key Instrument Parameters	
Vector magnetic field accuracy	< 0.8 nT
Range	± 1500 nT
Precision	0.01 nT
Baseline stability	< 0.1 nT over > 3 yr
Spacecraft magnetic field knowledge	< 0.5 nT
Sampling rate	16 samples / sec

J-MAG: Key Instrument Parameters	
Absolute Accuracy	0.1 nT
Range	± 8000, ± 50000 (MAGOBS), ±16000(MAGIBS), 0-50000 (SCALAR)
Resolution	3 pT (scalar)/15pT(fluxgate, in ±8000nT range)
Baseline stability	0.2 nT (long term), 0.1 nT (short term)
Sampling rate	32-128 vectors/sec

Radio and Plasma Waves

RPWI: Key Instrument Parameters	
Electrons and ions	Number densities: 10-4 to 105/cm3 (with 20% accuracy) Electron temperature: 0.01 to 100 eV (with 20% accuracy) Bulk ion drift speed: 0.1 to 200 km/s (with 20% accuracy) Ion temperature: 0.02 to 20 eV
Plasma waves	Electric field variations: up to 1.6 MHz Magnetic field variations: 0.1 Hz-20 kHz. Spectral sensitivity (f>500Hz): 2 uV/m/sqrt(Hz) Angular and phase accuracy: 3 deg Amplitude accuracy: 3 dB
Radio waves	Frequencies: up to 45 MHz Accuracy of polarization: 10% Absolute flux calibration accuracy: 3dB Accuracy on direction of arrival: 1 degrees
DC electric fields	Electric field: DC <1 Hz range Amplitude accuracy: 0.1 mV/m
Spacecraft potential	±100 V (with 10% accuracy)

Overview Comparison

Type	Europa Clipper Instrument	JUICE Instrument
UV Spectrograph	Europa UVS	UVS
Camera System	EIS	JANUS
NIR Spectrometer	MISE	MAJIS
Ice Penetrating Radar	REASON	RIME
Magnetometer	ICEMAG	J-MAG
Plasma Instrument	PIMS	PEP
Radio Emission		RPWI
Thermal Emission	E-THEMIS	
Mass Spectrometer	MASPEX	
Dust Analyzer	SUDA	
Radio Science	Gravity	3GM
Radio Science		PRIDE
Sub Millimeter Wave		SWI
Laser Altimeter		GALA

Source: Clipper-Juice workshop 2018

Europa Clipper – Juice instrument comparison 2 of 2

UV Spectrograph

Europa Clipper — Europa-UVS: Key Instrument Parameters

Wavelength Range	55 – 210 nm
Field of View	0.1° x 7.3°
Spatial Resolution	0.16° (low res); 0.06° (high res) Nyquist sampled
Spectral Resolution	λ/Δλ = 220; <0.6 nm FWHM (point source)
Spectral Cube Size	2048 (spectral) x 512 (spatial)

JUICE — JUICE-UVS: Key Instrument Parameters

Wavelength Range	55 – 210 nm
Field of View	0.1° x 7.3°
Spatial Resolution	up to 175 m/px at Ganymede and up to 234 km (typically 374 to 657 km) at Jupiter.
Spectral Resolution	<0.6 nm FWHM (point source) and <1.2 nm (extended sources)
Spectral Cube Size	2048 (spectral) x 512 (spatial)

Camera System

Europa Clipper — EIS: Key Instrument Parameters

	NAC	WAC
Detector	4096 × 2048 rad-hard CMOS	
Wavelength Range	Panchromatic plus 6 filters	
	(350 – 1050 nm)	(370 – 1050 nm)
Instantaneous Field of View	10 μrad (0.5 m/pixel at 50 km)	218 μrad (11 m/pixel at 50 km)
Field of View	2.347° × 1.173°	48° × 24°

JUICE — JANUS: Key Instrument Parameters

	NAC
Detector	1504 x 2000 rad-hard CMOS
Wavelength range	Panchromatic plus 13 filters (340 – 1080 nm)
Instantaneous Field of View	15 μrad up to 7.5 m/px at Ganymede and up to 10 km (typically 16 to 28 km) at Jupiter.
Field of View	1.72° x 1.29°

Near-Infrared Spectrometer

Europa Clipper — MISE: Key Instrument Parameters

Wavelength Range	0.8 to 5.0 μm (800 – 5000 nm)
Instantaneous Field of View	250 μrad
Field of Regard	4.3° across-track x slit width (0.01° = IFOV); along-track up to 60°
Spatial Resolution	10km/pixel full-disk images at 40,000 km range; 25 m/pixel at 100 km range
Average spectral Sampling	10 nm/band
Spectral Cube Size	300 lines x 80 to 300 samples x 451 spectral channels
Cubes Collected	Up to 8 per flyby
Signal-to-noise Ratio	>100:1 from 0.8–2.6 μm, 10:1 between 2.6 and 3.2 μm, >25 from >3.2 μm

JUICE — MAJIS: Key Instrument Parameters

Wavelength Range	0.5 to 5.54 μm (500 – 5540 nm)
Instantaneous Field of View	150 μrad
Field of View	3.44° x 3.44°
Spatial Resolution	up to 75 m/px at Ganymede and up to 101 km (typically 161 to 282 km) at Jupiter.
Average spectral sampling	3.64 nm/band (0.5-2.35 μm), 6.48 nm/band (2.25-5.54 μm)
Spectral Cube Size	Up to 400 samples x up to 508 spectral channels x *N* lines (as needed).

Thermal Emission

Europa Clipper — E-THEMIS: Key instrument Parameters

Filters	7–14, 14–28, 28–70 μm
Resolution	9 - 15 m at 25 km range
Image width	5.7° cross-track (720 pixels)
Radiometric Precision	~2K
Radiometric accuracy	2%

JUICE — SWI: Key Instrument Parameters

Frequency	1080-1275 GHz and 530-601 GHz
Spectral Resolving Power	$\sim 10^7$
Spectral resolution	10^5 Hz
Spatial resolution	1000km/2000km (1200/600GHz) at 15 Rj. 500/1000m (1200/600GHz) at 500km for Ganymede

Ice-Penetrating Radar

Europa Clipper — REASON: Key Instrument Parameters

Dual Frequencies	60 MHz (λ =5 m) Very High Frequency (VHF) globally, and 9 MHz (λ = 33.3 m) High Frequency (HF) anti-Jovian
Vertical Resolution	Shallow sounding: VHF with <30 m resolution from depths down to 3 km; Full-depth sounding: VHF (coarser) or HF with <300 m resolution and VHF (finer) with < 30 m resolution from 3 to 30 km depths; Altimetry: VHF with <15m resolution
Antenna	2 deployable HF and 4 VHF dipole antennas mounted on solar array
Radiated Power	10 - 30 W

JUICE — RIME: Key Instrument Parameters

Central Frequency	9 MHz (1 and 3 MHz bandwidth)
Vertical Resolution	9 km depth with vertical resolution of up to 50-140 m in ice.
Antenna	1 deployable HF

Gravity / Occultations

Europa Clipper — Gravity Science: Key Parameters

Wavelength	X band
Fanbeam & LGA FOV	±15° by ±50°; 0 to 80° half angle
System Doppler Accuracy	0.07 mm s^{-1} (60 s integration time)
Received Signal Strength	4 - 10 dB-Hz min @D/L

JUICE — 3GM: Key Parameters

Wavelength	Ka +X band
Resolution	0.01 mm s^{-1} (60 s integration time)
Range accuracy	<20 cm

Mass Spectrometer

Europa Clipper — MASPEX: Key instrument Parameters

Mass Range	2 – 500 u
Mass Resolution	m/△m ≥ 16,988
Min. Density	$10^6/m^3$
Dynamic range	1.00E+11

JUICE — PEP-NIM: Key Instrument Parameters

Mass range	1-1000 u
Mass resolution	m/△m > 1100
Min. Density	$10^6/m^3$

Radiation Monitor

Europa Clipper — RADMON: Key Instrument Parameters

Energy Range	0.3 MeV - 40 MeV (Monitor Stack) > ~1 MeV (Dosimeters)
Total Dosimeters	12
Time Resolution	seconds (mode dependent)

JUICE — RADEM: Key Instrument Parameters

Electron Energy range	0.3 to 40 MeV
Protons Energy range	5 MeV to 250 MeV
Time resolution	1min (by default, can be reprogrammed)

Dust Analyzer

Europa Clipper — SUDA: Key Instrument Parameters

Mass Resolution	m/Δm ≤ 1 u (FWHM) for m ≤ 200 u
Dust Grain Properties	Impact Speed Range: 4-7 km/s (Δ ≤ 1%) Charge Sensitivity ≥ 0.25 fC (Δ ≤ 10%) Grain Size Range: 0.1 – 2 μm (Δ ≤ 25%)
Surface Resolution	Better than spacecraft altitude
Detection Limits	40 ejecta per second

Laser Altimetry

JUICE — GALA: Key Instrument Parameters

Spot Size	50 m
Vertical Resolution	< 5m
Frequency	up to 50 Hz

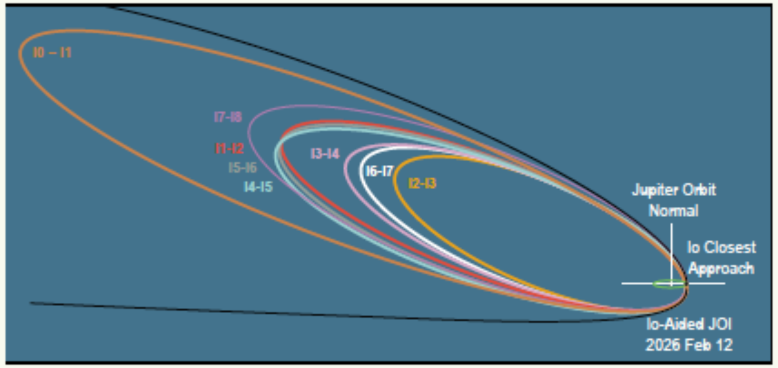
Io Volcanic Observer

Background:
Discovery 2014
U Arizona/APL

- Io multiple flyby mission
- Suite of five instruments
- Solar powered spacecraft

Mission Overview:

- Launch May 29, 2021
- ΔV-EGA (Earth gravity assist) trajectory, asteroid flyby opportunities
- Jupiter orbit insertion (JOI) in February 2026 with 500 km Io encounter (I0) and capture into orbit inclined 42° relative to Jupiter's equator
- Eight additional Io encounters over 22 months with high-resolution views of active volcanism in daylight and darkness
- Four of the encounters are designed for optimal measurement of induced magnetic signature from mantle melt
- Mission design minimizes total ionizing radiation dose (372 krad at 100 mil Al, design margin of 2), <10% of that experienced by *Galileo*
- Collect 20 Gb science data per encounter: 100 times the Io data from the 8-year *Galileo* tour; playback near apoapsis
- Encounters last ~1 week, including global monitoring and four Io eclipses
- Nearly polar approach to and departure from Io is ideal for study of polar regions, key to testing tidal heating models



Io Encounter Number	I0	I1	I2	I3	I4	I5	I6	I7	I8
Days since last encounter	0.0	180.4	81.4	49.5	61.9	81.4	81.4	58.4	92.0
Closest approach altitude (km)	510	500	500	500	500	500	500	400	200

IVO's inclined orbit is optimal for key science objectives and results in a much lower Total Ionizing Dose than other Jupiter orbiters.

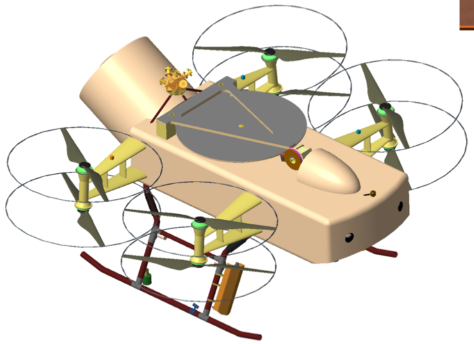
Objectives (Gain Understanding of)	Key Measurements
A1. Io's active volcanism	High-resolution repeat imaging at UV to thermal-IR wavelengths.
A2. State of Io's interior & implications for tidal heating	Measure peak lava temperature for mantle temperature & electromagnetic induction signal from mantle melt. Map/monitor global heat flow.
B1. Nature of Io's lithosphere & unique tectonics	Image & measure topography of key tectonic structures.
B2. Connections between Io's volcanism & its surface & atmosphere	Measure mass spectra & temporal & spatial variability of neutral species, & map spectral variations of surface.
B3. Io's mass loss & magnetospheric interactions	Acquire in situ & remote observations of Io's exosphere, sodium cloud, & plasma torus.
B4. Limits to active volcanism on Europa	Distant repeat imaging to search for plumes or surface changes.
C1. Jupiter system science	Observe Jupiter, rings, moons, & magnetosphere.

Dragonfly

Source: JHUAPL website

Background:
New Frontiers 2017 finalist
APL/Penn State/Langley/Ames/GSFC/JPL

- Launch in 2025
- Two years sampling surface of Titan
- Multiple flights provide access to diverse locations on surface
- Nuclear powered quadcopter rotorcraft
- Could be first seismometer experiment on an ocean world
- CRYOSADS sample system

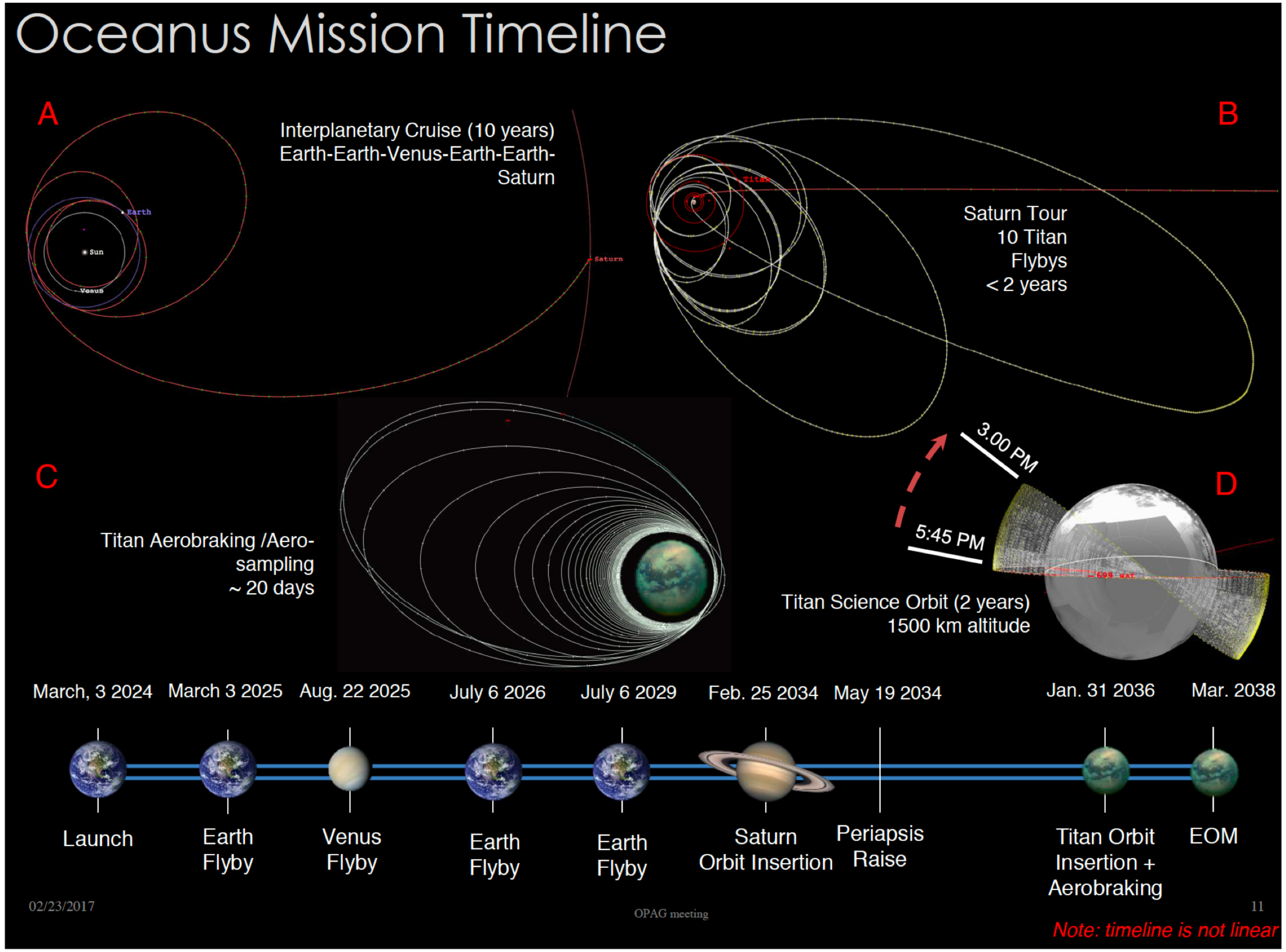


Oceanus

Source: OPAG 2-2017: Sotin

History:
New Frontiers 2017
JPL/??

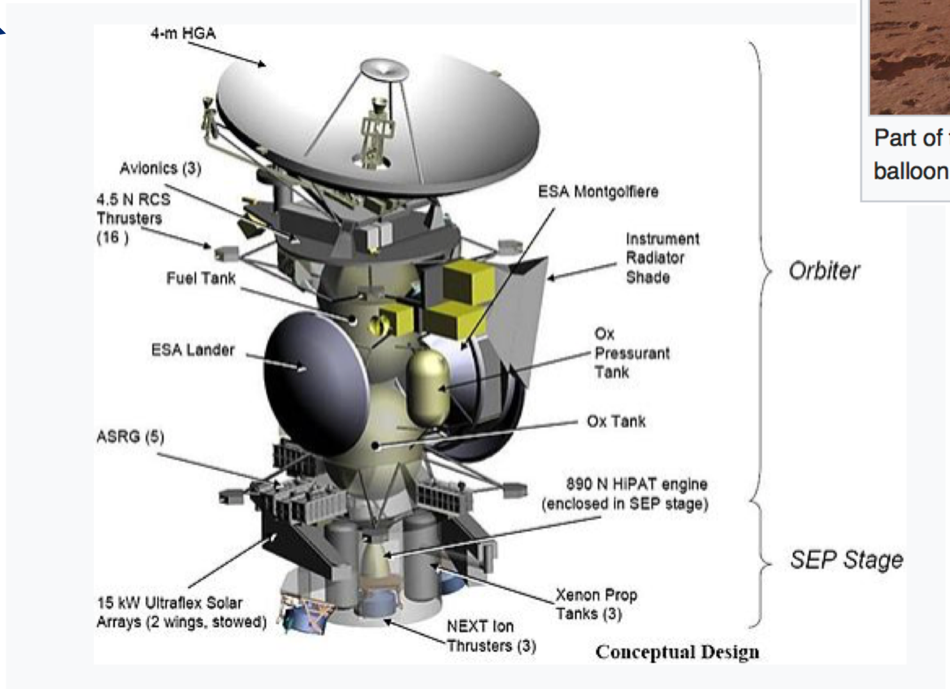
- Titan flyby and orbiter mission
- Imaging and radar of Titan surface from orbit; mass spectrometer
- Gravity science
- Solar powered spacecraft



Source: Wikipeda

Titan Orbiter mission concepts

- Titan Explorer - 2007 NASA flagship mission study
  - Lander and Balloon
- TSSM –NASA-ESA study concept
  - Joint mission to combine Titan Explorer with ESA Enceladus mission
  - Orbiter, lander and balloon
- Titan Mare Explorer
  - Titan Lander proposed NASA mission



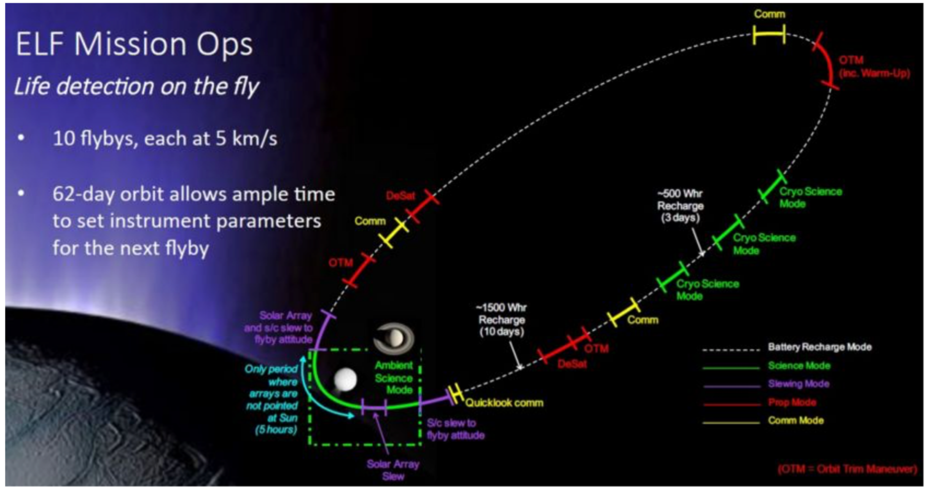
Part of the mission proposal is a balloon planned to circumnavigate Titan.

Enceladus Life Finder ELF

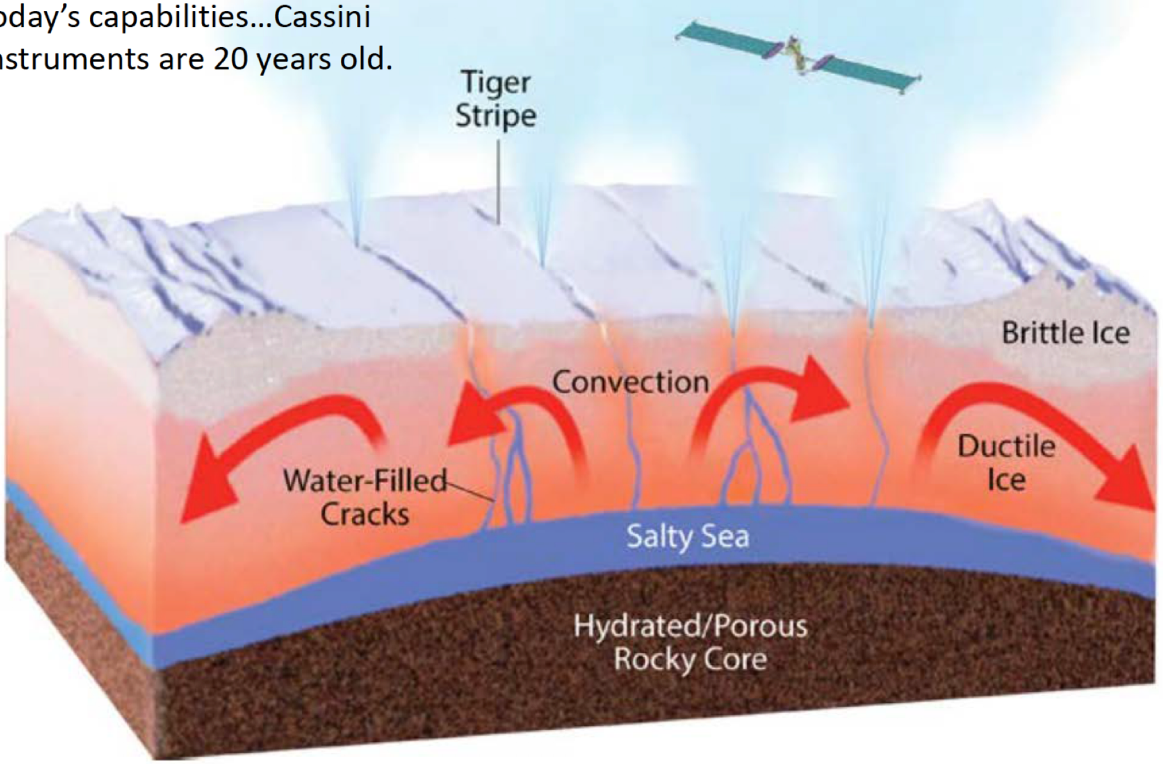
Source: OPAG 2-2015: Cable, Lunine

History:
New Frontiers 2017
Cornell/JPL/SwRI/Univ of Stuttgart

- Fly through Enceladus Plumes (Jets)
- 10 orbits of Saturn
- 2 mass spectrometers
- Solar powered spacecraft



- Fly through the Enceladus plume just like Cassini did….
- But do it with instruments of today's capabilities…Cassini instruments are 20 years old.



Enceladus Life sample return mission

Source: OPAG 2-2015: Tsou

History:
Discovery 2014
JPL/Ball/JAXA

Trajectory

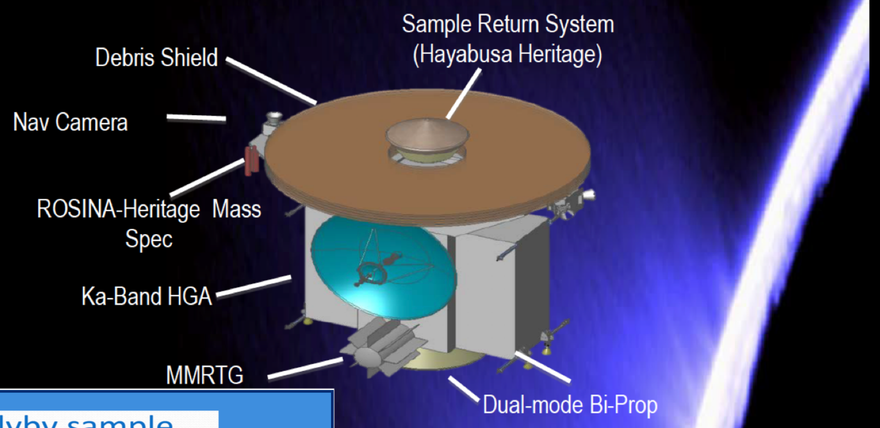
- Saturn Orbit Insertion Pump down to Enceladus via Titan
- 13.5 year mission duration
- Encounter speeds 2-4 km/s
- Multiple flybys

Spacecraft

- Nuclear powered
- 2 instruments

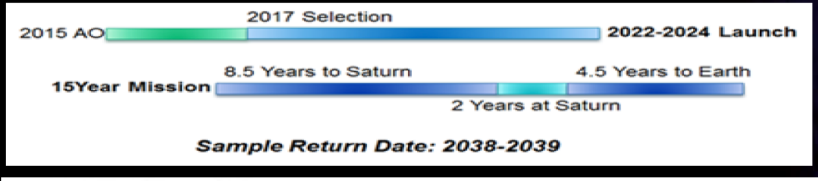
LIFE Fact Sheet

Parameter	Value	Margin
Dry Mass	667 kg	17%
Wet Mass	1682 kg	36%
Power (EOL)	220 W	62-34%
Falcon 9 V1.1	2290 kg	36%
Ka Band 75W	42 kb/s	3.9 dB



A Plume allows low-cost flyby sample return

- Fresh samples
- Locating samples unnecessary
- No landing required
- Proven flyby sample return technology: Stardust and Hayabusa I



Elsah

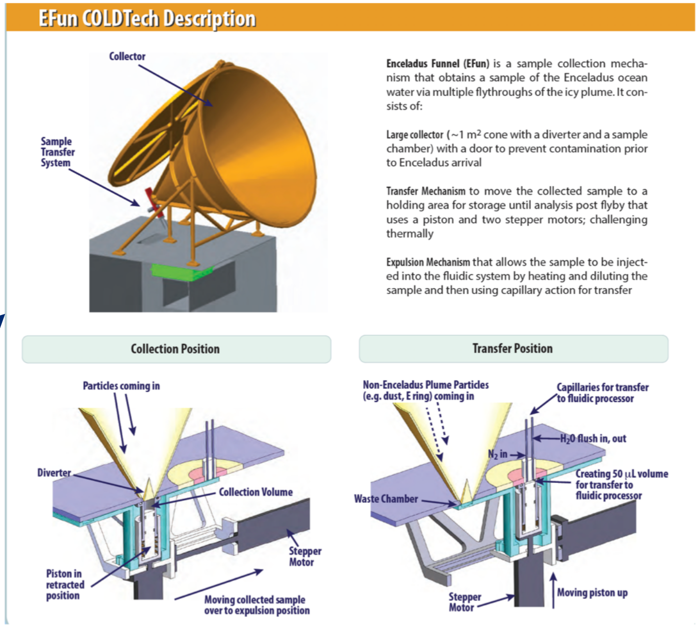
Enceladus life signatures and habitability

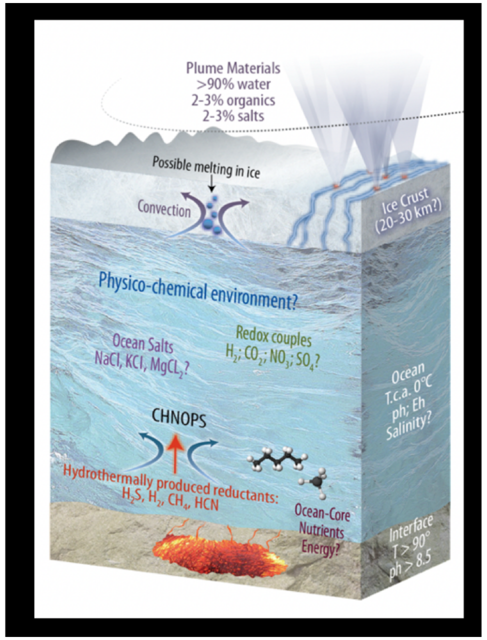
Source: OPAG 2-2018 Hurford and Cospar 2018 Adams

History:

New Frontiers 2017
Ames/GSFC/APL

- Habitability mission
  - Search for life
  - Fly through plumes
  - Plume sample collection system
  - 2 Cameras and Mass Spec
- Enceladus Funnel sample system
  - Technology development COLDTech grant to develop cost-effective techniques that enable life detection measurements on cost-capped missions
  - Ice particle capture and retention



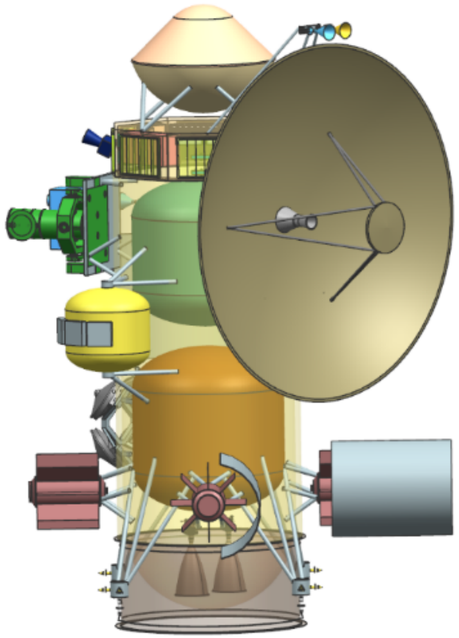


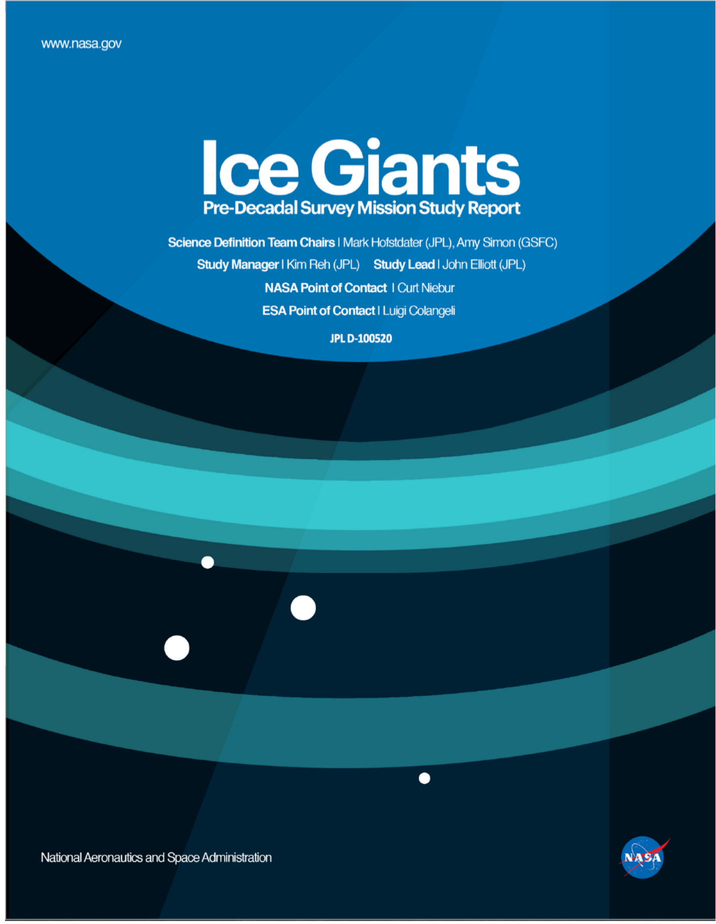
ELSAH Payload

Visible & IR Camera Suite	Imagning of plume and its source regions
GCMS	Life Detection & Habitability
Plume Chemistry Lab	Life Detection & Habitability

Ice Giants Missions

- NASA study report in 2017
- Uranus and Neptune systems seen as equally important in this study
  - However, Roadmaps of Ocean Worlds (ROW) study prioritized Neptune, due to Triton
  - Both worlds should be explored
  - Optimal launch dates 2029-2033
- Highest Priority Science
  - Interior structure of the planet
  - Bulk composition of the planet (including isotopes and noble gases)
- Internal structure of satellites also included
  - Tilted magnetospheres enable magnetic sounding for conductive layers
- 2018 decadal mid-term review recommended a new study

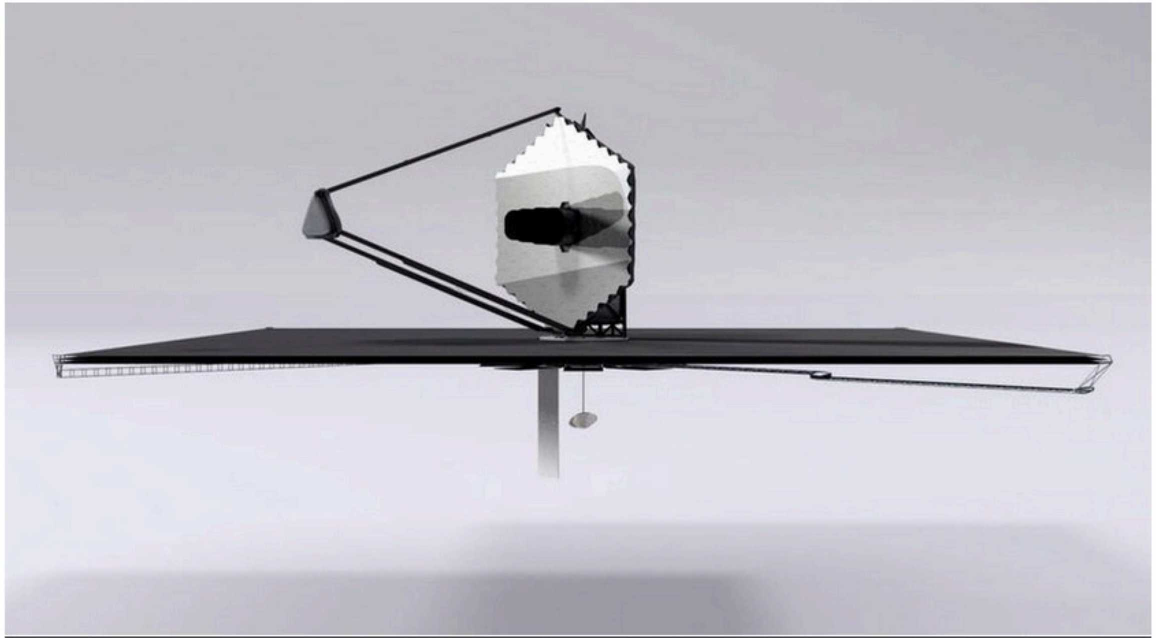




Telescopic Observations of Exoplanets

- Spacecraft: JWST, TESS, WFIRST, PLATO
- Ground-based extremely large telescopes
- 2018 National Academies report recommends direct imaging mission that can measure the reflected light spectra of Earth-sized planets orbiting in the habitable zones of sun-like stars.
  - HabEx or LUVOIR

Orbital resonances are common in exoplanet systems, leading to tidal heating. This increases importance of understanding tidal heating in our system.



LUVOIR is one mission under study that could carry out the direct imaging mission recommended by a new National Academies report, but the committee that prepared the report declined to endorse a specific mission concept. Credit: NASA

Mission architecture trades

- Mission architecture
  - Flyby
  - Orbiter
  - Lander
  - Balloon
- Power
  - Solar
  - Nuclear
  - Batteries (primary or rechargeable)
  - Fuel cells (primary or regenerative)*
- Propulsion
  - Chemical
  - Solar electric propulsion
  - Solar sails*

*Developmental

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