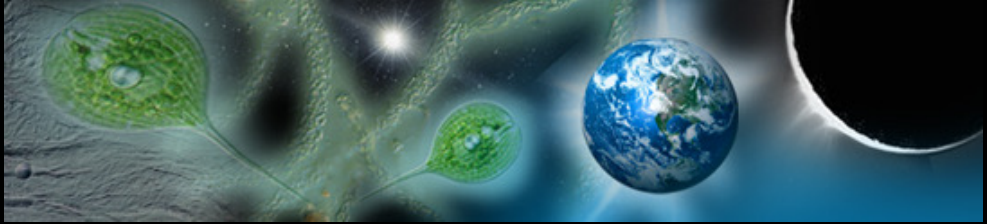
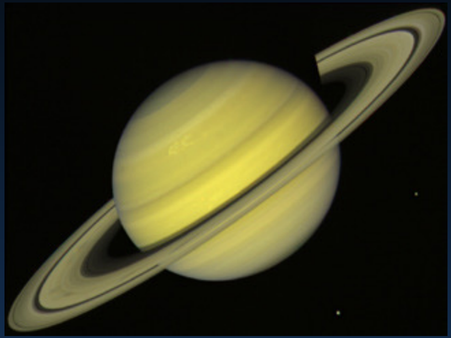


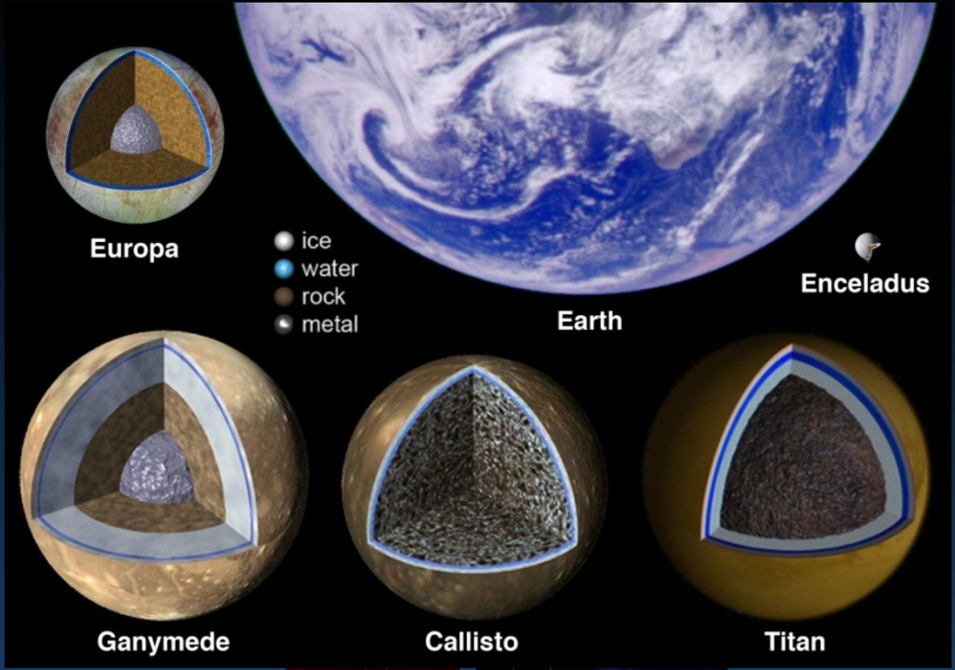
Future atmospheric research objectives of missions to the Jovian and the Kronian systems

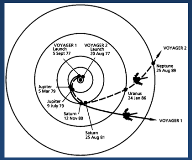
Athena Coustenis[1], Conor A Nixon[2], Therese Encrenaz[1], Panayotis Lavvas[3], Olivier Witasse[4]

[1]LESIA, Paris Observatory, CNRS, UPMC Univ. Paris 06, Univ. Paris-Diderot, Meudon, France, [2]NASA Goddard Space Flight Center, Greenbelt, MD, United States, [3]Universite de Reims, Reims, France, [4]ESA/ESTEC, Noordwijk, Netherlands

Gas giant planets and their satellites

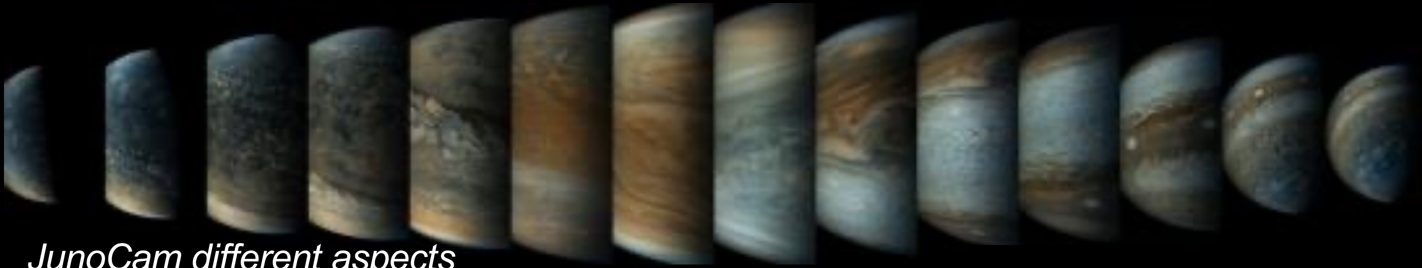






Around JUPITER

Juno images of Jupiter
(NASA/JPL/SWRI)



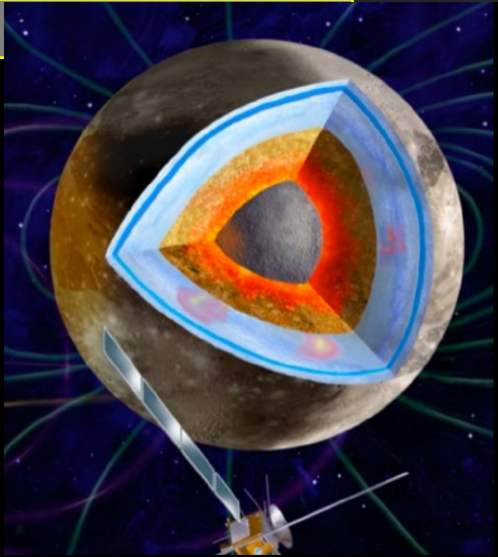
JunoCam different aspects of Jupiter

Southern storms

Ganymede as seen by Juno: Caltech/SwRI/MSSS/Kalleheikki Kannisto

Tenuous atmospheres around jovian icy moons

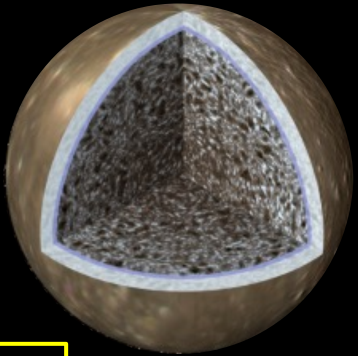
Three large icy moons to explore for habitable conditions



Ganymede - class IV

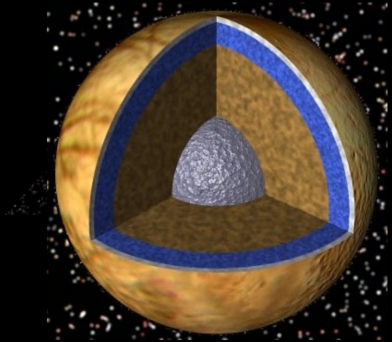
- Largest satellite in the solar system
- A deep ocean
- Internal dynamo and an induced magnetic field – unique
- Richest crater morphologies

- Best example of liquid environment trapped between icy layers



Callisto - class IV

- Best place to study the impactor history
- Differentiation – still an enigma
- Only known example of non active but ocean-bearing world
- The witness of early ages



Europa - class III

- A deep ocean
- An active world?

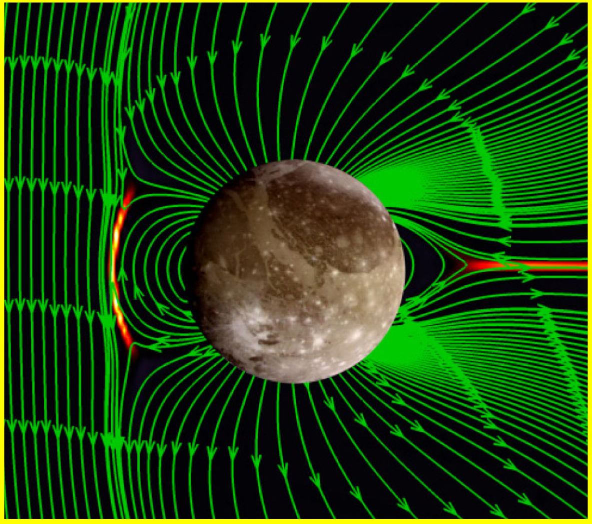
- Best example of liquid environment in contact with silicates

GANYMEDE : atmosphere, ionosphere & magnetosphere

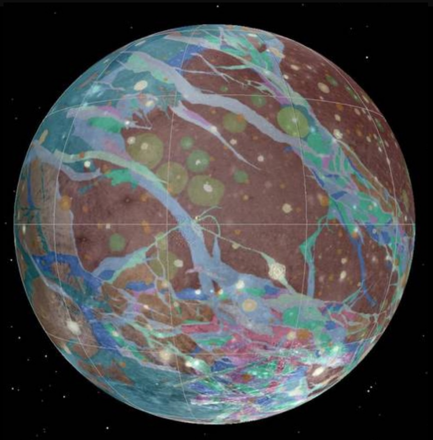
Galileo evidences

- **Induced magnetic field** from interaction of jovian magneto with conducting layer (ocean?)

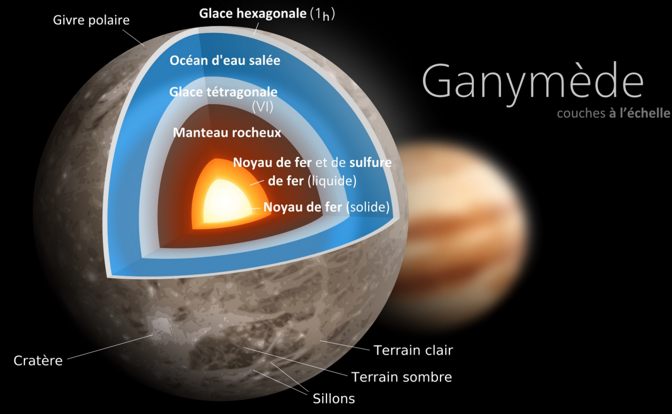
Observed but not characterised

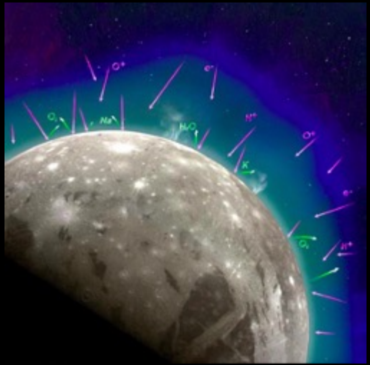


- Own internally-driven dipole magnetic field
- Interaction of Ganymede's mini-magnetosphere with Jupiter's

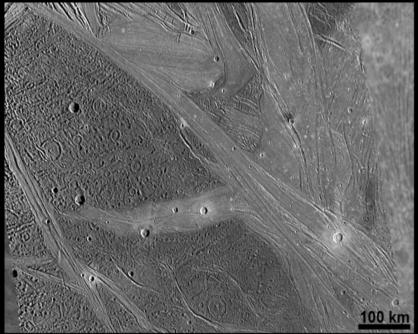


USGS Astrogeology Science Center/Wheaton/NASA/JPL-Caltech



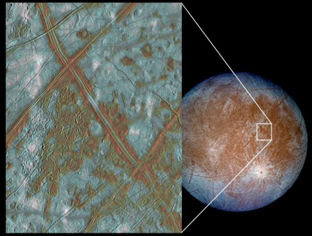


Atmospheric composition : O_2, H_2O, CH_4, NH_3, CO, CO_2, SO_2 and their constituent atoms O, H, C, and S.

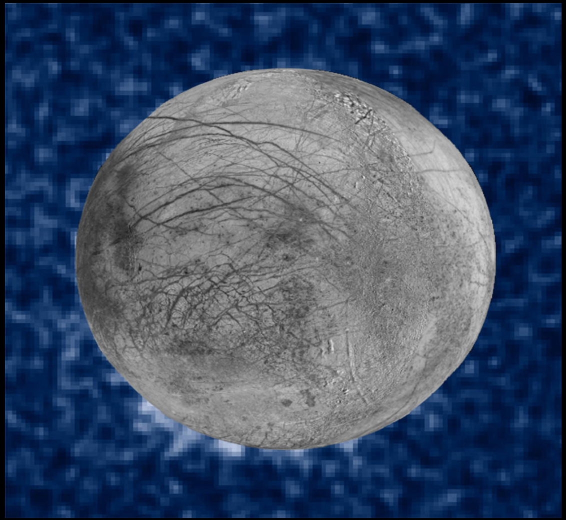


Indications for young surface from water flooding

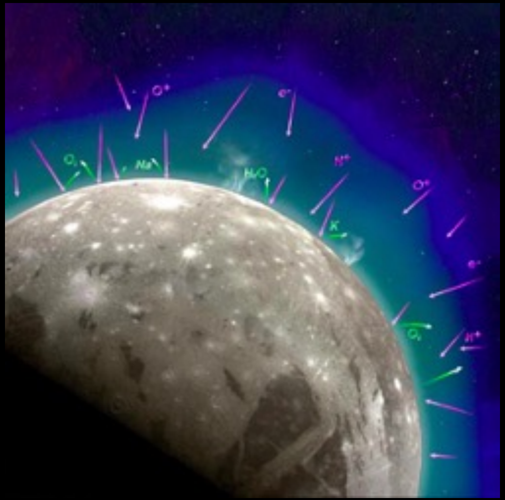
Europa : atmosphere-surface interactions



Tenuous atmosphere & plumes?



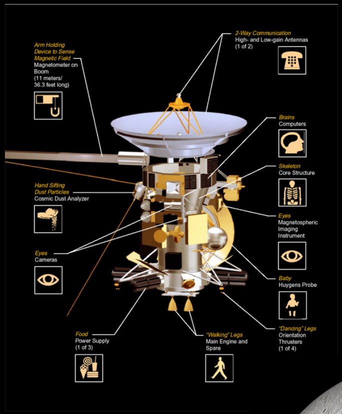
HST image Credits: NASA/ESA/W. Sparks (STScI)/USGS Astrogeology Science Center



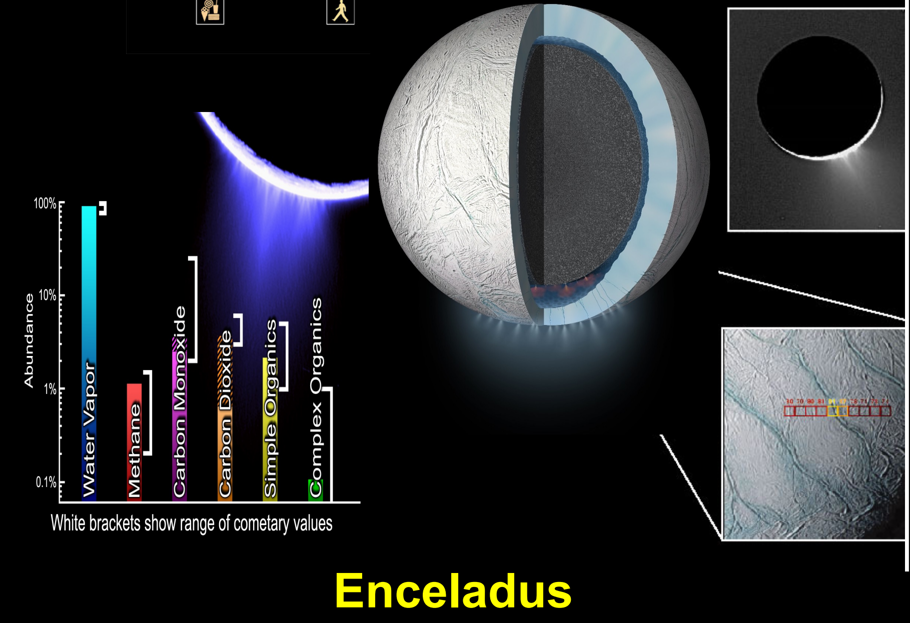
From Galileo : this image covers a surface of 30 x 70 km, and shows what looks like pieces of ice floating on a frozen sea which could have been liquid in the past. Pointing to a liquid water ocean underneath Europa's surface

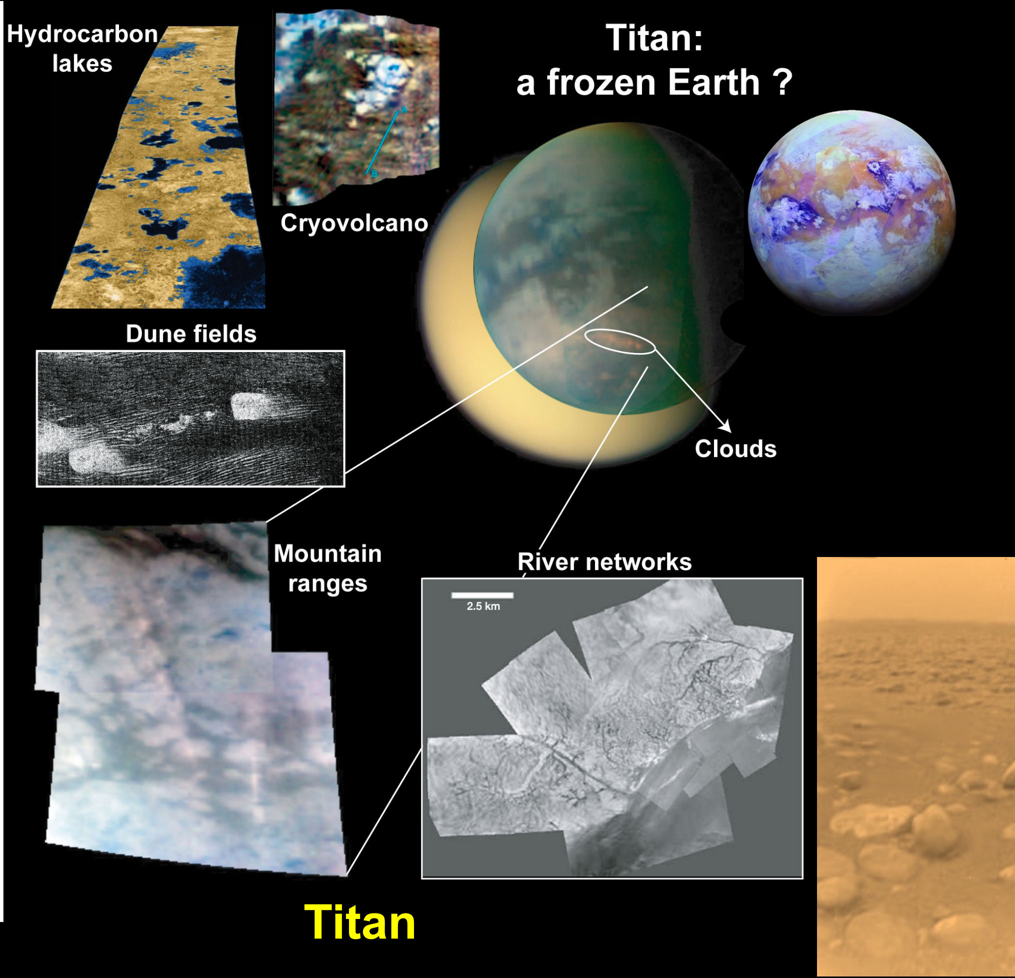
Composition : O_2, H_2O, CH_4, CO_2 etc+ ions resulting from endogenous & exogenous processes & alteration

Around SATURN: Cassini-Huygens mission

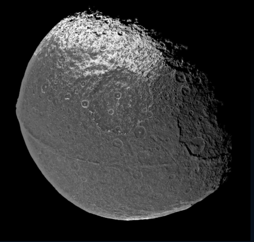


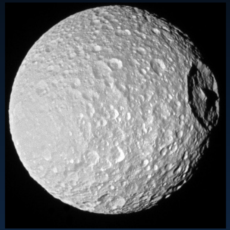
Cassini-Huygens
2004-2017

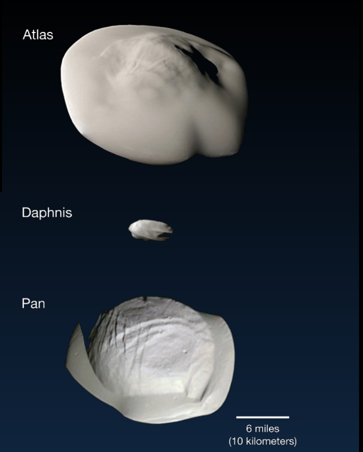


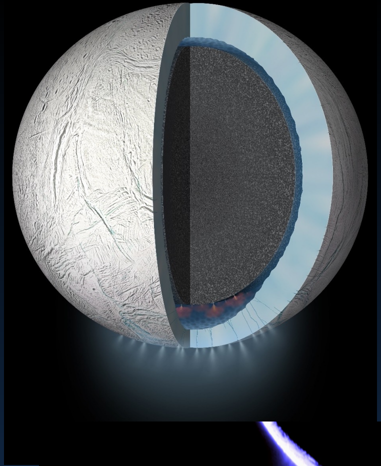


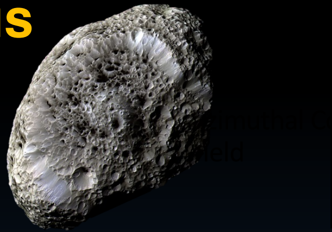
Icy Satellites Science Highlights: Enceladus

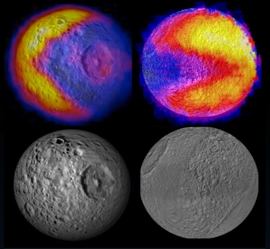


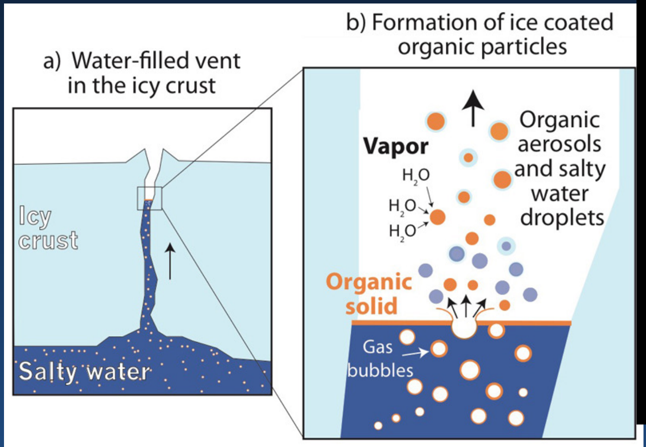


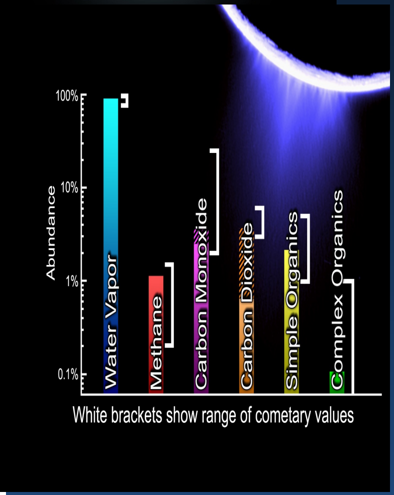












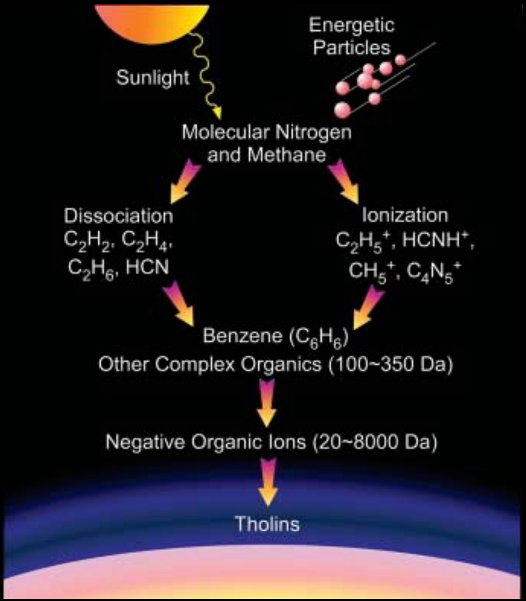
- Discovery of active, icy plumes on Enceladus
- Detection of global oceans beneath Enceladus' and possibly Dione's and Mimas's icy crusts
- Enceladus emitted ice grains contain concentrated, complex, macromolecular organic material with molecular masses above 200μ. The data is suggestive of a thin organic-rich film on top of the oceanic water table

Detection of plume composition: water (vapor and micron-sized grains), salt, organics, nanograin dust, hydrogen, and ammonia

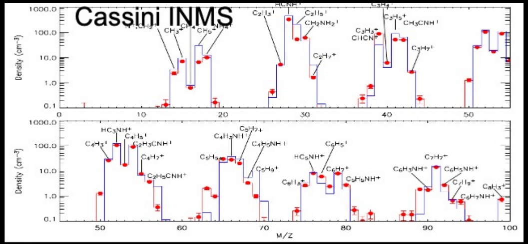
Evidence of hydrothermal chemistry and discovery of a strong thermal anomaly on Enceladus

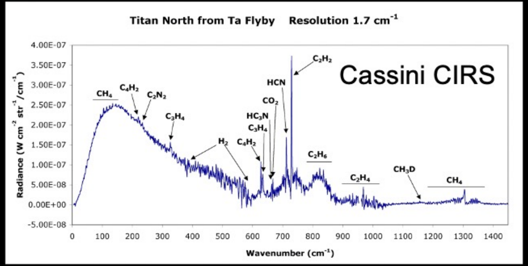
Titan Science atmosphere highlights

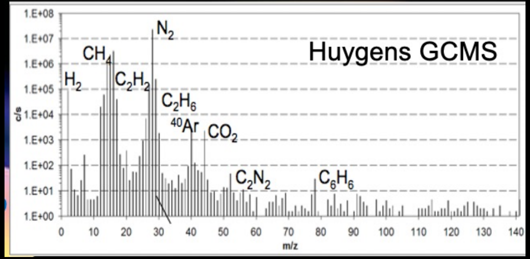
- Titan revealed as Earth-like world with rain, rivers, lakes and seas
- Discovery of variety of weather patterns, including rainstorms, and documented seasonal changes
- Discovery of prebiotic chemistry in a dinitrogen-methane atmosphere on Titan
- Discovery of dense, salty global ocean of liquid water below a thick crust and a relatively low density core

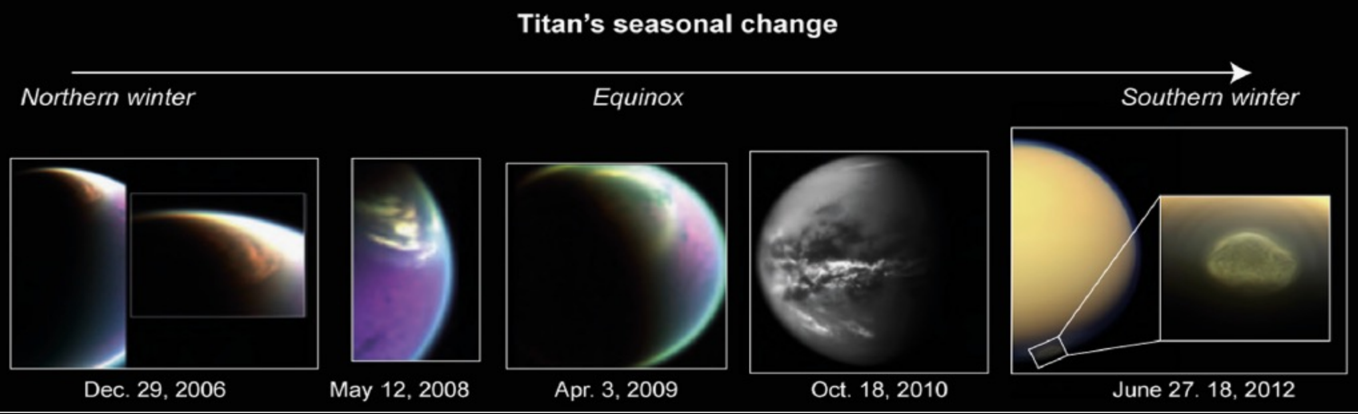


Results from Cassini-Huygens instruments on atmospheric composition





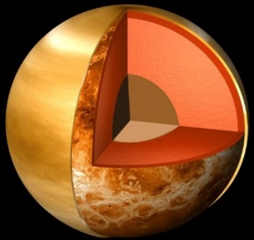


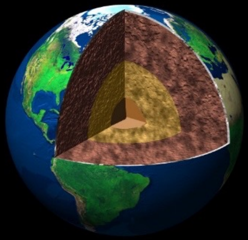


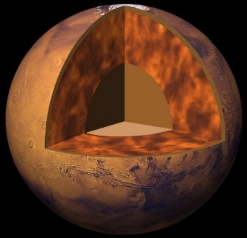
What is the real degree of complexity of the chemistry ?

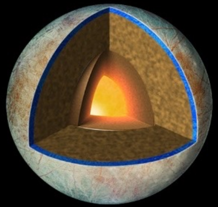
ICY MOONS CONNECTIONS

atmospheric density at the surface



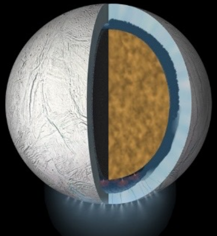






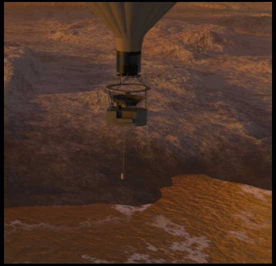
Icy moons offer insights on the terrestrial worlds with atmospheres and the ocean worlds of the Outer Solar System and beyond

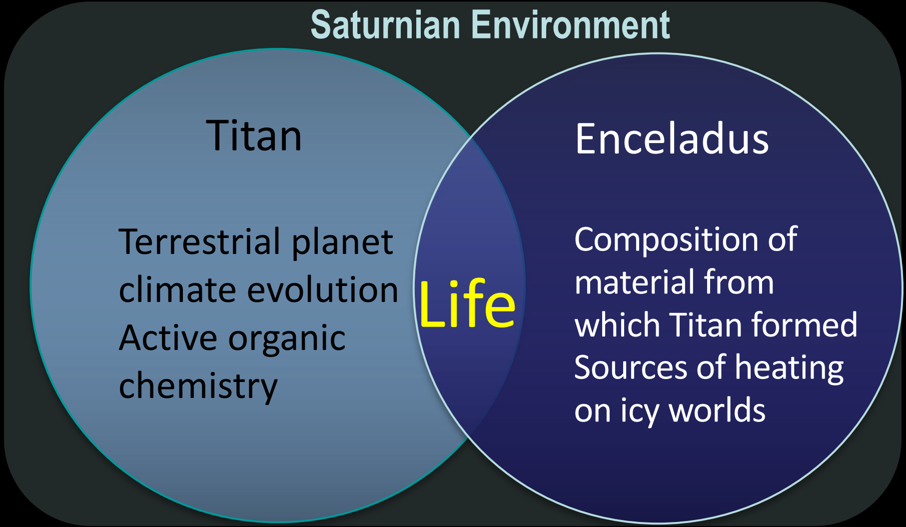
ocean/rock exchange



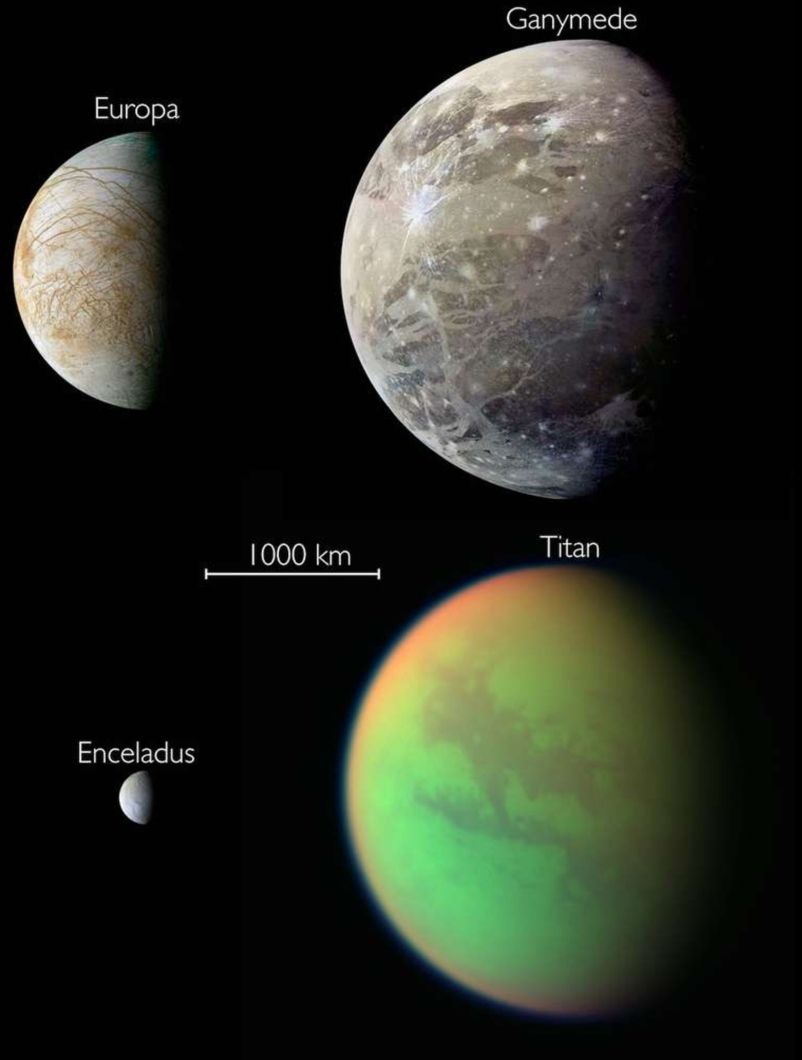
Morgan Cable, Alex Hayes, and Jason Soderblom

The exploration of the Saturnian system : habitats





- The Saturnian system is rich in worlds that could bring insights on important aspects of Earth's
  - *climate,*
  - *organic chemistry and*
  - *emergence of life*.

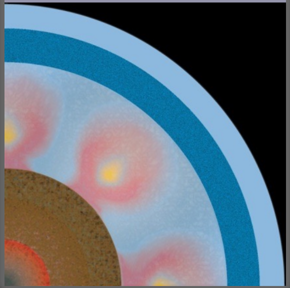


Two categories of icy moons as possible habitats : oceans in contact with the silicate core or not.

Beg for further exploration in the future in multiple ways

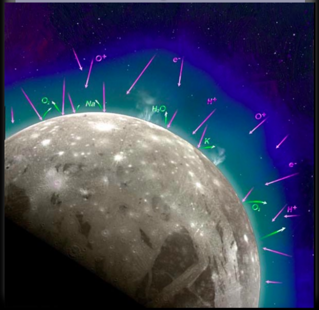
Main scientific objectives for a Ganymede/Titan-like object

Ice shell, ocean, deeper interiors

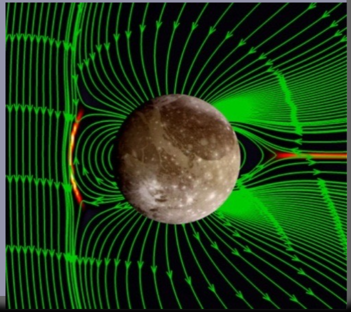


Geology, surface composition

Atmosphere, ionosphere



Magnetosphere, plasma environment

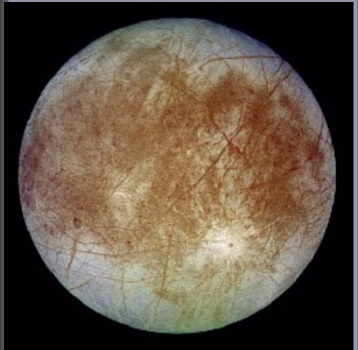


ATMOSPHERIC/ENVIRONMENTAL OBSERVATIONS

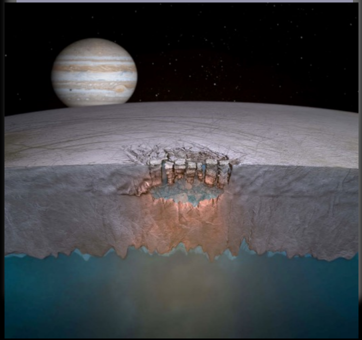
Spectroscopy, occultations, limb observations etc will explore the outer layers from the surface up to about 400 km : O_2, H_2O, CH_4, NH_3, CO, CO_2, SO_2 and their constituent atoms O, H, C, and S.

Main scientific objectives for a Europa/Enceladus-like object

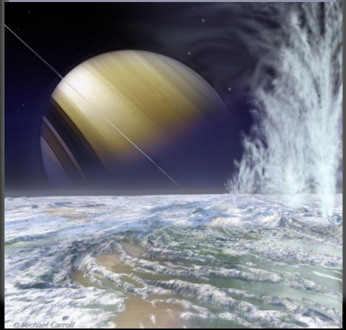
Composition of non-ice material



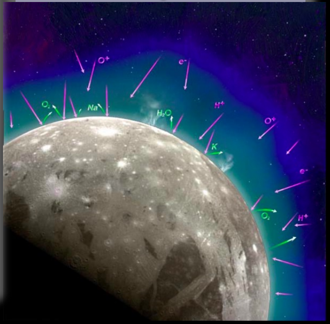
Liquid sub-surface water



Active processes



Atmosphere, ionosphere

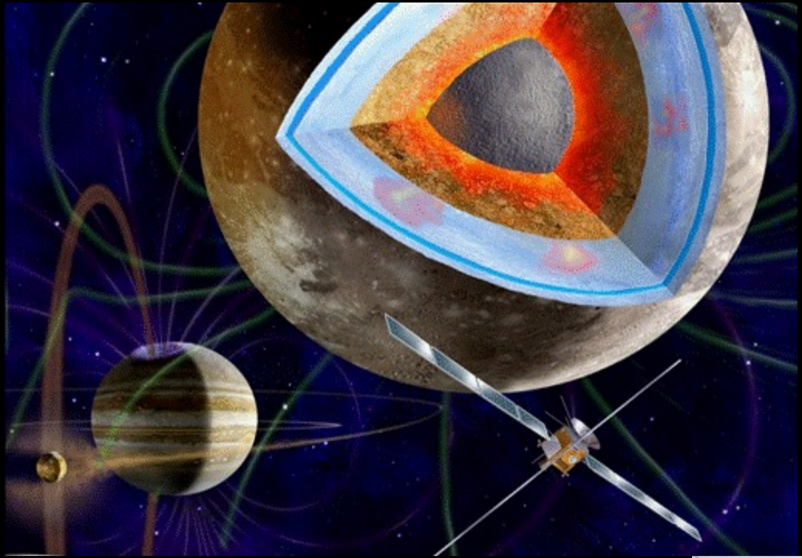


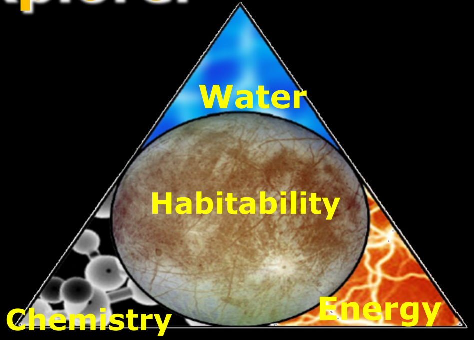
In situ particle experiments will provide key information at low altitudes with the ability to resolve species and isotopic composition

Images Credit : NASA

Future missions at Jupiter

ESA's JUICE: JUpiter Icy moons Explorer





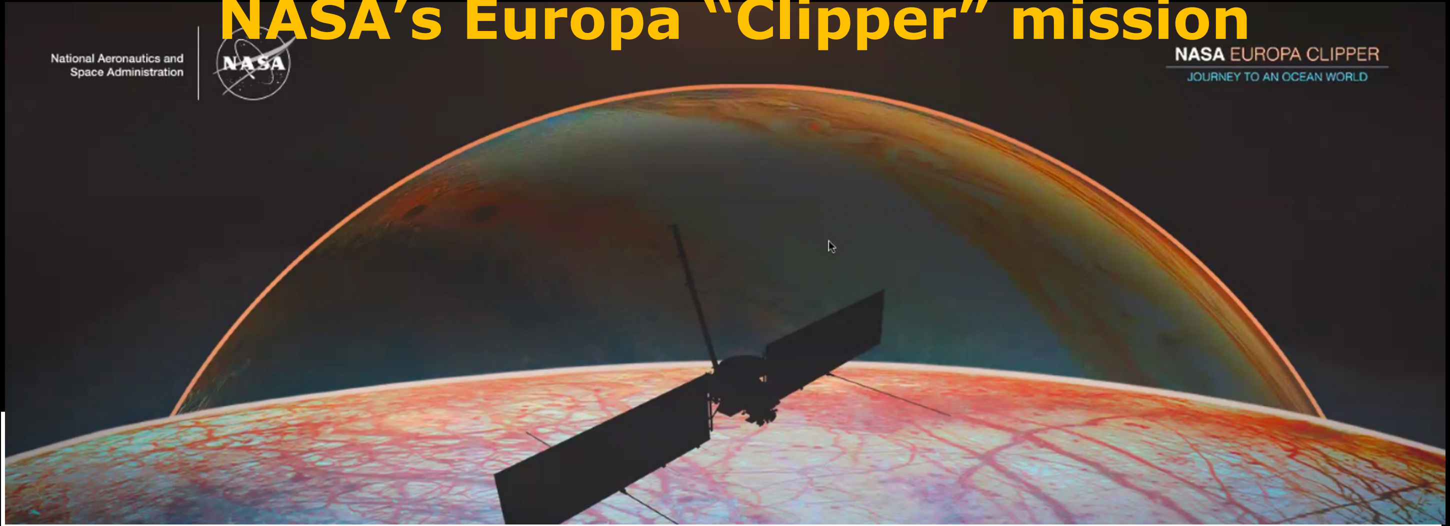
JUICE Science Goals

- *Emergence of habitable worlds around gas giants*
- *Jupiter system as an archetype for gas giants*

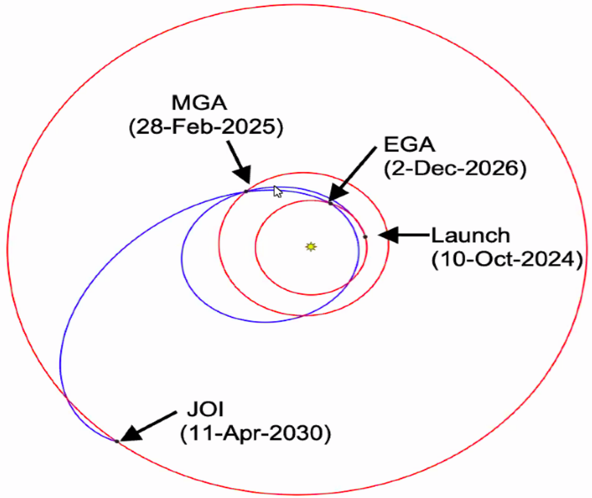
JUICE Payload

- Narrow-angle camera
- Vis-near-IR imaging spectrometer
- UV spectrograph
- Sub-mm wave instrument
- Laser altimeter
- Ice-penetrating Radar
- Radio science experiment
- Very Long Base Interferometry
- Plasma environmental package
- Radio & Plasma Wave instrument
- Magnetometer

NASA's Europa "Clipper" mission



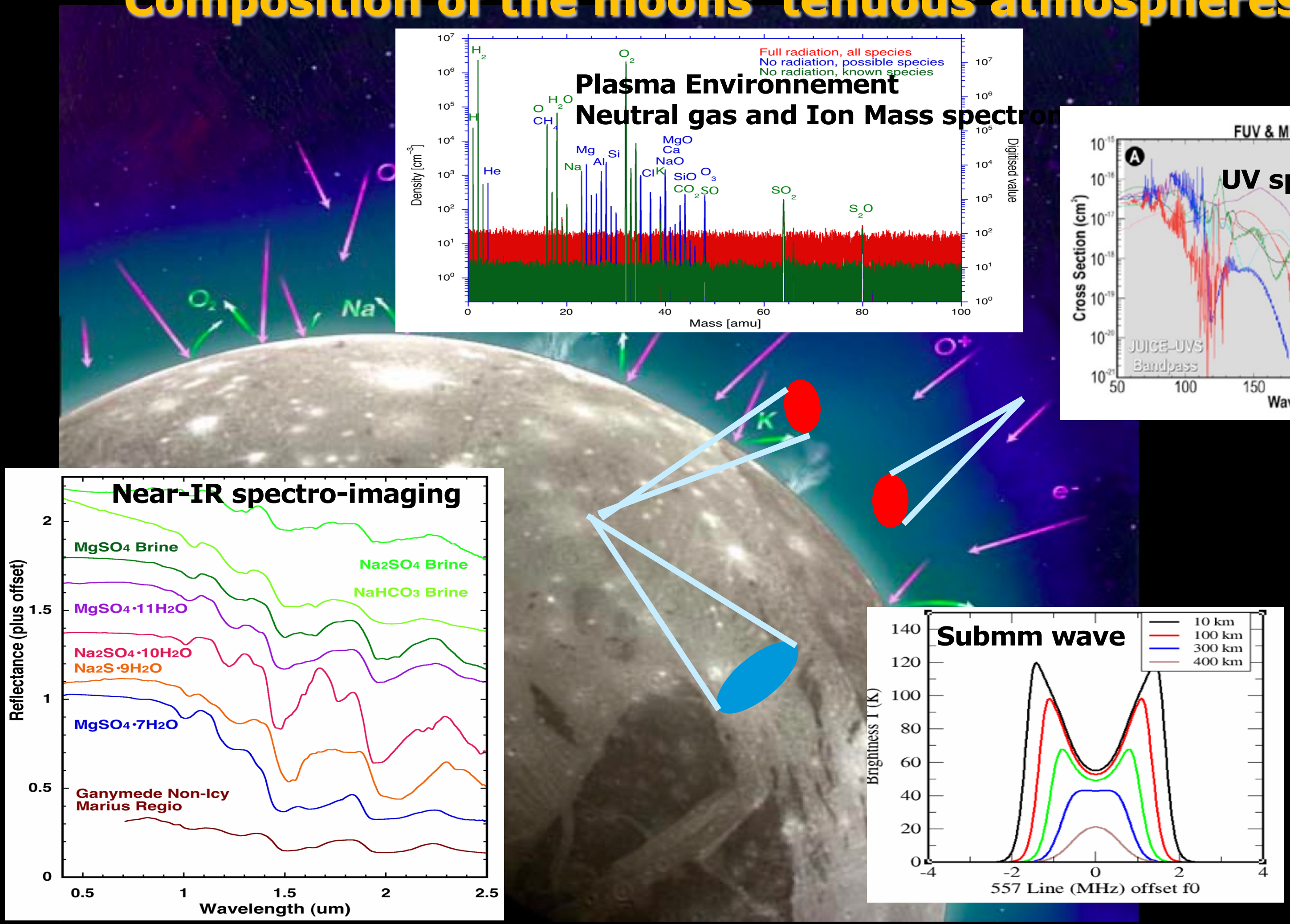
Interplanetary Trajectory: Mars-Earth Gravity Assist (MEGA)

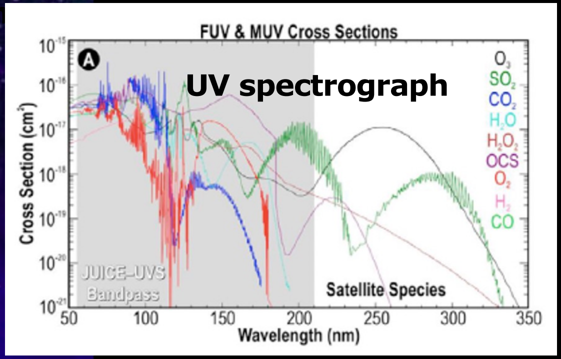


- Minimum solar distance is 0.82 AU
- No Venus flyby – provides Flight System simplifications
- 5.5 year time-of-flight
- 2025 EMEGA and 2026 MEGA available as backup launch opportunities

Instrument	Institution
EIS Europa Imaging System	APL
E-THEMIS Europa Thermal Emission Imaging System	ASU
Europa-UVS Europa Ultraviolet Spectrograph	SwRI
MISE Mapping Imaging Spectrometer for Europa	JPL
REASON Radar for Europa Assessment & Sounding: Ocean to Near-surface	UTIG/JPL

Composition of the moons' tenuous atmospheres/exospheres

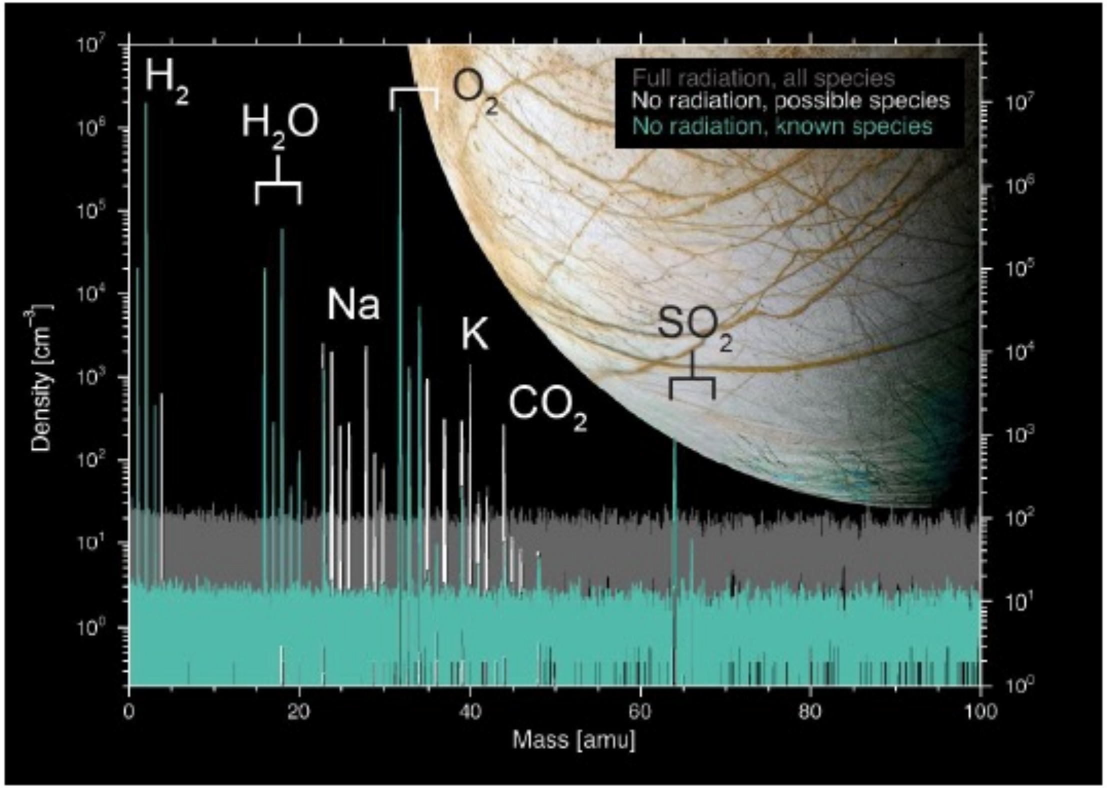




Future missions (like JUICE and Europa Clipper) will monitor directly the tenuous atmospheres/exospheres structure (Sub-mm, UVS), composition (Plasma, UV, IR, sub-mm), dust content, and the surface sputtering process of energetic neutrals

INSTRUMENTS

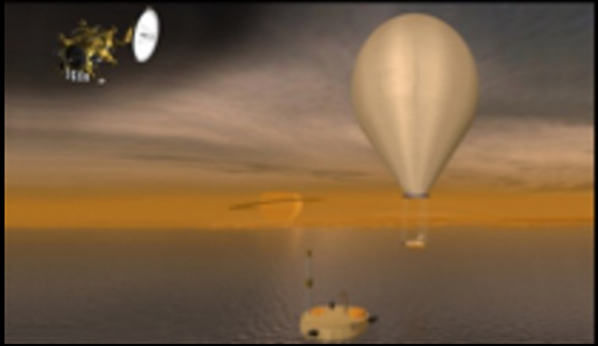
Measurements expected by a Neutral gas and Ion Mass spectrometer: Thermal neutrals and ions (< 5 eV) ; Mass range: 1-1000 amu ;M/ΔM=1100 ; Sensitivity: 2 cm-3 (~10^{-16} mbar)



Future missions at Saturn

Some of the proposed Titan exploration

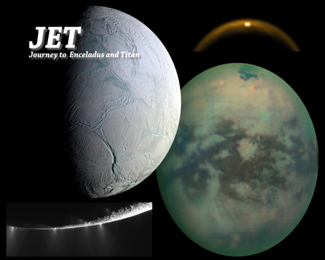
Titan Explorer
(Lorenz et al. 2007)



TSSM: Balloon, lander & orbiter
(Coustenis et al. 2009)

AVIATR /plane
(Barnes et al. 2010)

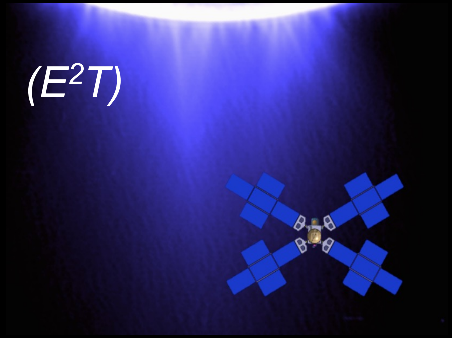
TandEM
(Coustenis et al. 2007)



Journey to Enceladus & Titan
(Sotin et al., 2011)

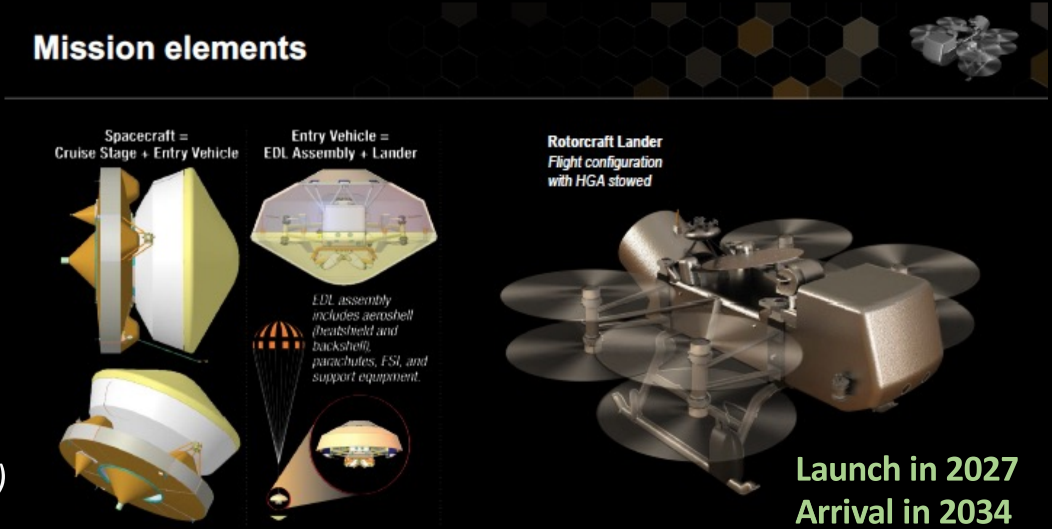
Titan Aerial Explorer
(Lunine et al., 2011)

TIME: Lake lander
(Stofan et al. 2013)



Explorer of Enceladus and Titan
(Mitri et al. 2017)

Dragonfly



- *High mass and prebiotic molecules*
- *Proportion of C,H,N,O atoms*
- *Atmospheric p,T, wind and meteorolgogy*
- *Ground properties (porosity, humidity, dielectric)*
- *Images*

Launch in 2027
Arrival in 2034

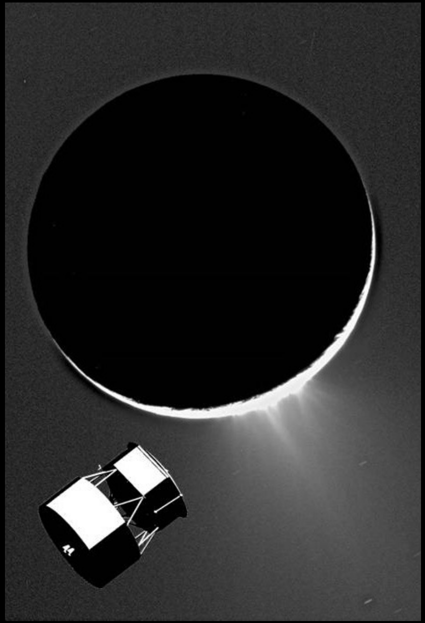
Titan after *Cassini* & *Dragonfly* science objectives

Missing insights on :

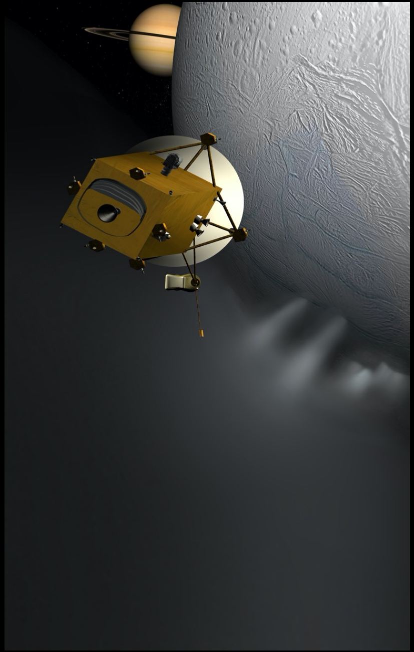
- global-scale geological history
- origin and evolution of the polar seas
- atmospheric seasonal cycle and chemical processes
- long-term atmospheric evolution and stability (in particular at the poles)
  - What are the dominant escape processes at Titan’s exobase, how do they vary with Titan’s magnetospheric environment, and what is the fate of escaping molecules?
  - What is the nature of the Saturn magnetosphere-Titan ionosphere interaction and which plasma processes contribute to atmospheric escape?
  - Is the atmosphere in a steady-state, with on-going methane replenishment, or will it suffer long-term changes or collapse after methane depletion?
  - What chemical pathways synthesize complex organic molecules in Titan’s atmosphere?
  - What chemistry and microphysics produce organic aerosols and clouds in the atmosphere?
  - How fast do erosive processes act to obliterate surfaces features, including impact craters?
  - How symmetric are the physical and chemical responses to Titan’s seasons, and do liquids eventually migrate between hemispheres on long timescales leaving a climate record?
  - What is the variability of composition between the lakes and seas, as well as surface terrains?
  - Is there a vast, subsurface network of ‘alkanofers’ connecting the seas, acting as a reservoir for atmospheric methane?
  - Does Titan have any internal geophysical activity (tectonic, seismic, cryovolcanic)?
  - Do organic compounds from the atmosphere enter the subsurface ocean, producing a potentially habitable environment?

Nixon et al., 2020

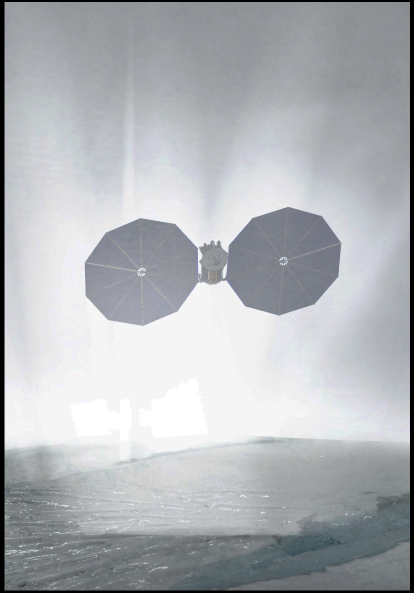
Future mission concepts to Enceladus



Enceladus Plume Sample Return



Enceladus Orbiter



Saturn Orbiter/Multiple Enceladus Flybys

Moons of the Giant Planets. Exploring the issues of habitability of ocean worlds, searching for biosignatures, and studying the connection of moon interiors, near-surface environments, and the implications for the exchange of mass and energy into the overall moon-planet system. This theme follows the science from Cassini-Huygens and expected scientific return from JUICE.

Origins, Worlds, and Life
A Decadal Strategy for Planetary Science and Astrobiology 2023-2032

Chapter 13
QUESTION 10: DYNAMIC HABITABILITY (extract)

- Determine whether there are modern habitable environments in atmospheres by characterizing chemistry, including organic molecules, in the atmospheres

- Determine the complexity attained by organic chemistry in Titan's atmosphere, its sources and sinks, and its role in producing a potentially habitable environment by entering the subsurface ocean, through in situ and remote spectral imaging and mass spectrometry investigations.

- **Enceladus orbilander**
  Orbilander will analyze fresh plume material from orbit and during a 2-year landed mission. Its main science objectives are: (1) to search for evidence of life; and (2) to obtain geochemical and geophysical context for life detection experiments.