Europa and Titan (and Enceladus)

Docente modulo II: R. Orosei, INAF-IRA

https://www.unibo.it/sitoweb/roberto.orosei

Why this lecture

- Outer Solar System bodies have properties that are very different from the Terrestrial planets.

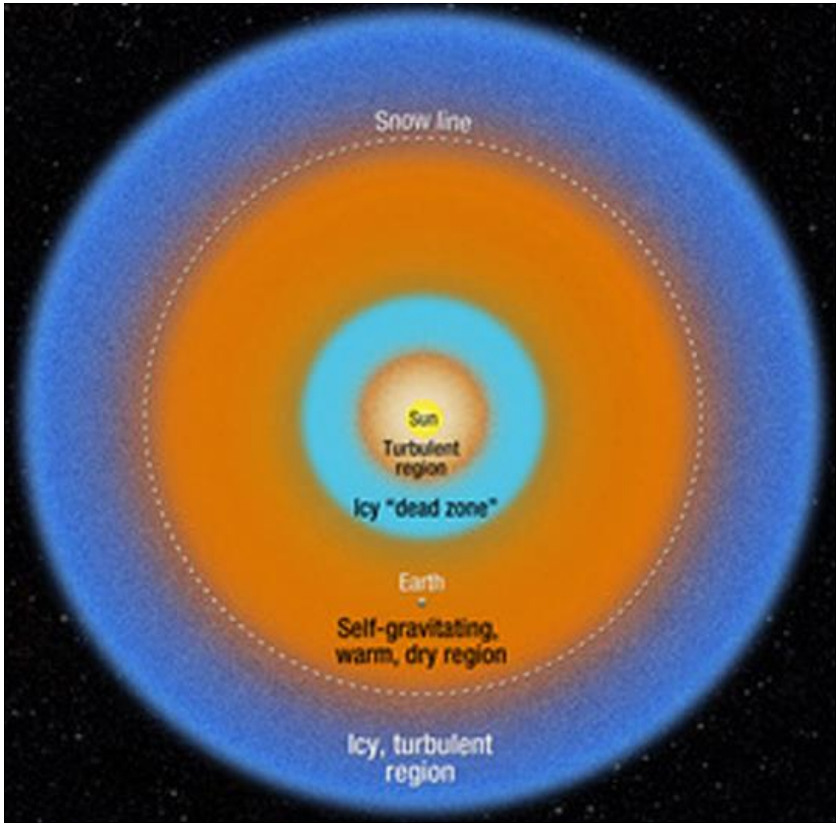
- As the search for planets around other stars progresses, it is found that the most common inhabitable planets may in fact be icy moons of gas giants.

Goals for today

- Learn about the current state of knowledge about Europa and its habitability.
- Learn about the current state of knowledge about Titan and its habitability.
- Review other potential locations for the search of habitats in the outer Solar System.

The outer Solar System

- Defined as the region of the Solar System where water ice is stable, beyond 4 AU from the Sun ("snow line").
- In the course of planetary formation, temperatures within the protoplanetary disk were very high, and the snow line was pushed forward.
- The presence of water ice more than doubled the availability of solid material, faster planetary accretion.
- Many solid bodies exist in this region (moons, minor planets), but only Titan possesses an atmosphere.
- Too far away from the Sun, no liquid water (by definition).

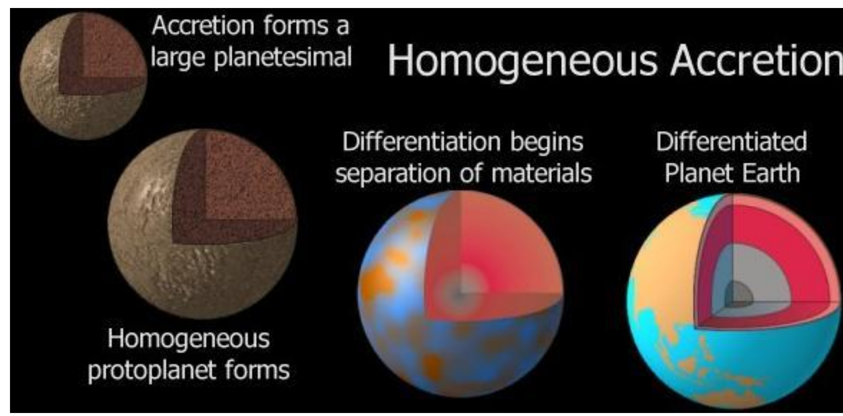


Sources of energy in the outer Solar System (1)

- Accretional heating is the conversion of the kinetic energy of infalling planetesimal into heat.
- Large bodies are more efficient in injecting energy in the interior of the accreting body.
- Accretion stops when the mass of the accreting body accelerates planetesimals so that the energy deposited by the impact is capable of sublimating a quantity of ice equal to the mass of the impactor.

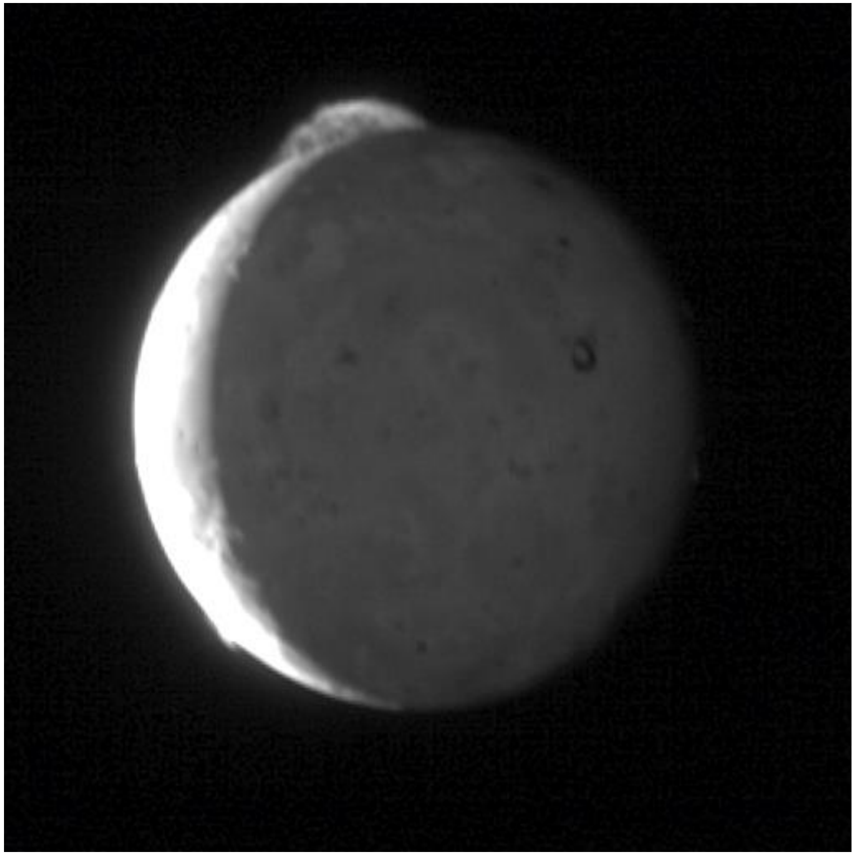
Sources of energy in the outer Solar System (2)

- Decay of radioactive isotopes ^{40}Ar, ^{232}Th, ^{235}U, ^{238}U, which have half-lives ranging from 1 billion to 10 billion years.
- Contrary to accretional heating, radioactive decay releases heat continuously at a slowly-decaying rate.
- The larger the body, the lower the surface-to-volume ratio, the more efficient the heating.
- For a composition similar to carbonaceous chondrites, the heat released would be insufficient to maintain a liquid water ocean on Europa.



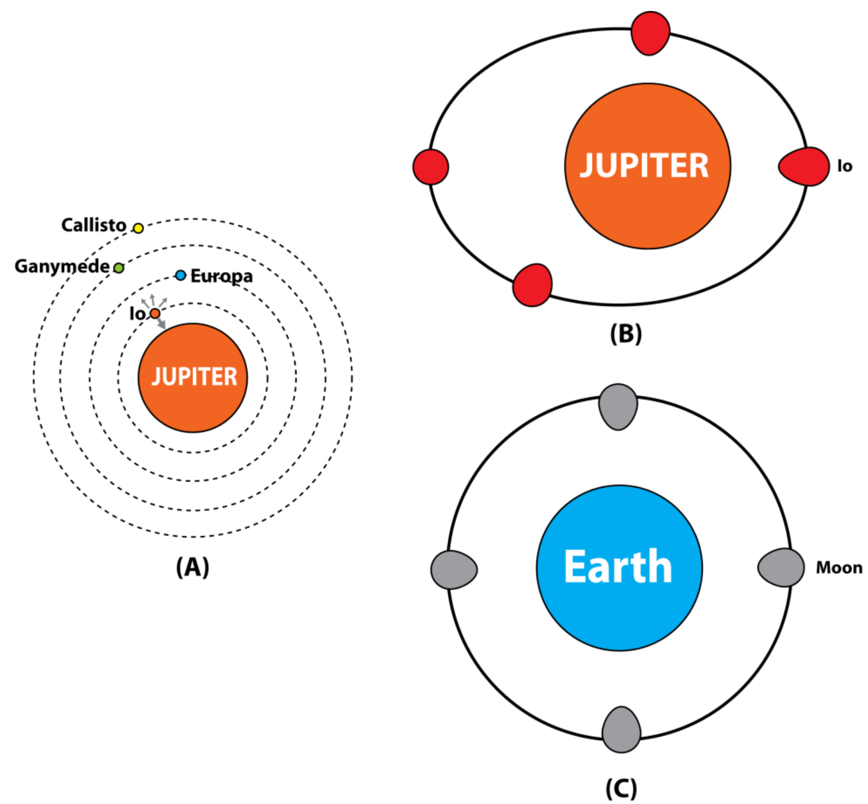
Sources of energy in the outer Solar System (3)

- Tidal heating is produced by the deformation caused by the differential gravitational pull across a body.
- Tidal forces distort the shape of the Earth, especially that of the oceans, causing a bulge that moves in response to Earth's rotation and the Moon's revolution.
- The kinetic energy of this motion is eventually converted by friction to thermal energy.
- Conversion of orbital energy to heat is accompanied by a transfer in angular momentum, slowing Earth's rotation and increasing the Moon's distance (tidal dissipation)



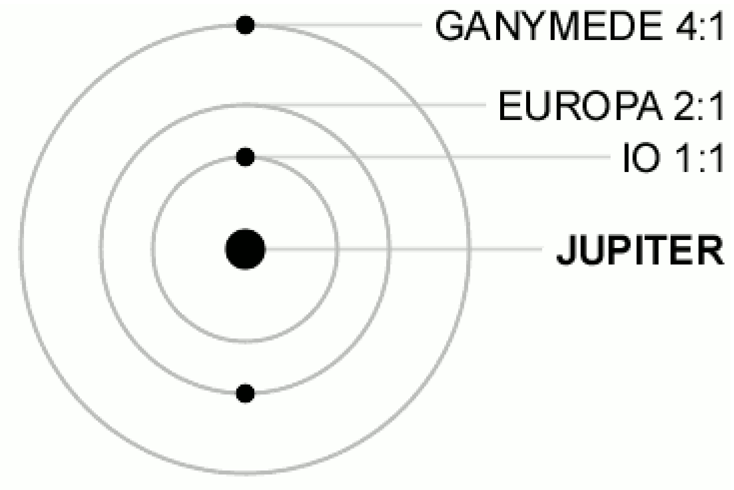
Tidal heating in moons around giant planets (1)

- Tidal dissipation takes place mostly in the interior of moons around giant planets, as these are mostly gaseous.
- Because the orbit is elliptical, the bulge position changes across the surface of the moon, as it tries to remain fixed w.r.t. the line connecting the center of the moon with the center of Jupiter.
- The friction within the solid body creates heat and dissipates the energy of the orbit.
- Tidal dissipation tends to circularize the orbit over time scales that are small compared to the history of the Solar System.



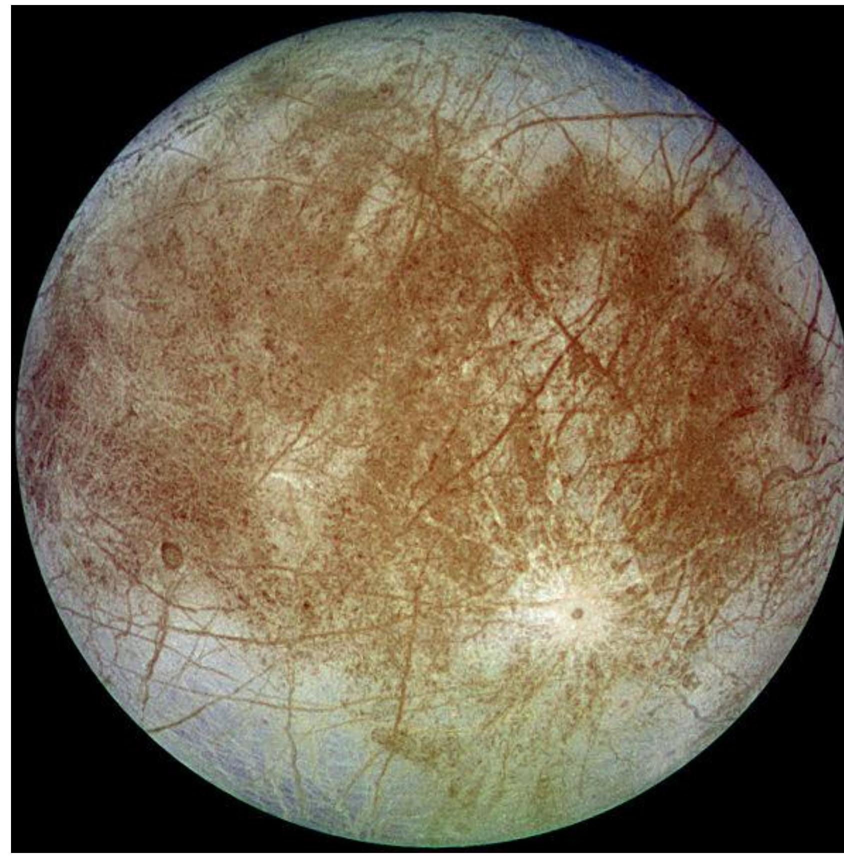
Tidal heating in moons around giant planets (2)

- The small, but non-zero, eccentricity of Titan's orbit sets limits on the amount of tidal heating taking place in its interior.
- For Io, Europa and Ganymede, eccentricity is locked in place by orbital resonance between the moons (rotation periods are in a 1:2:4 ratio).
- The source of energy (Jupiter's gravitational pull) is enormous, tidal dissipation has probably been taking place for billions of years.
- Tidal heating depends on the difference in gravitational pull through a body, and thus its dependence on the main force of gravity diminishes with distance with a power greater than r^{-2}.
- Modelling shows in fact that such dependence is greater than r^{-3}, as shown by the dramatic differences between Io, with its restless volcanoes, Europa, which is suspected of harboring an ocean in its interior, and Ganymede, whose geologic activity seems to have ceased long ago.



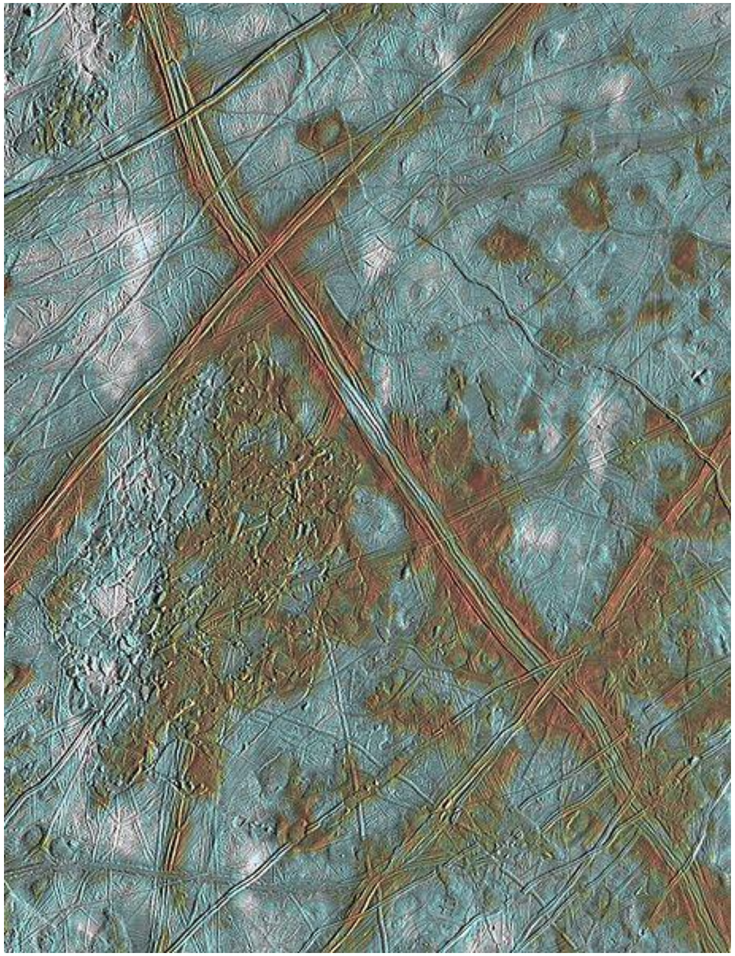
Europa

- It is the sixth-closest moon of the planet Jupiter, and the smallest of its four Galilean satellites.
- Slightly smaller than the Moon, Europa is primarily made of silicate rock and has a water-ice crust and probably an iron-nickel core.
- It has a tenuous atmosphere composed primarily of oxygen.
- Its surface is striated by cracks and streaks, whereas craters are relatively rare.
- It has the smoothest surface of any known solid object in the Solar System.



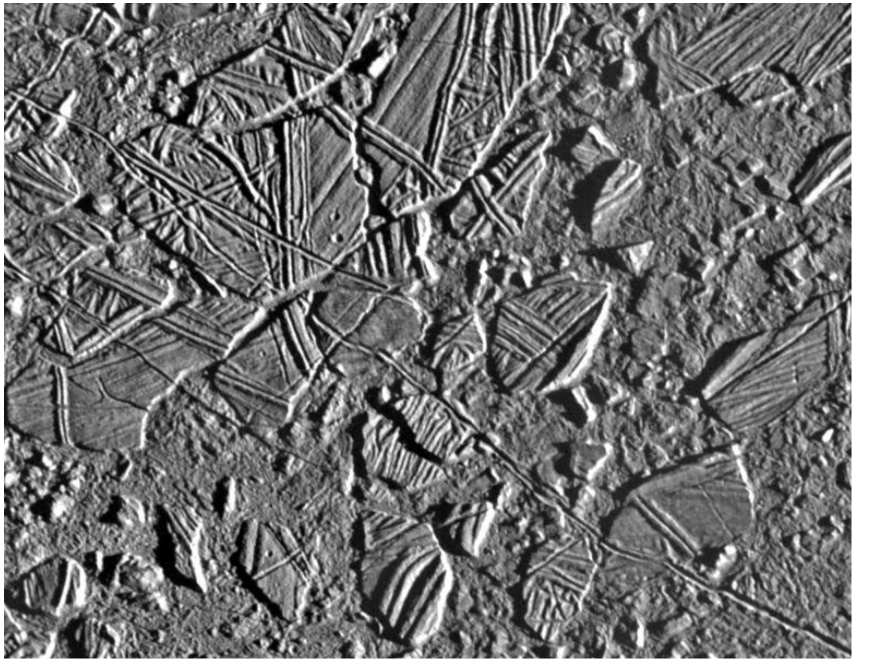
Lineae

- Lineae are fractures, often composed of many ridges and troughs, crisscrossing the entire globe.
- The edges of Europa's crust on either side of the cracks have moved relative to each other.
- The largest lineae are more than 20 km across, often with dark, diffuse outer edges, regular striations, and a central band of lighter material.
- Lineae may have been produced by a series of eruptions of warm ice as the Europan crust spread open to expose warmer layers beneath.
- The effect would have been similar to that seen in Earth's oceanic ridges.



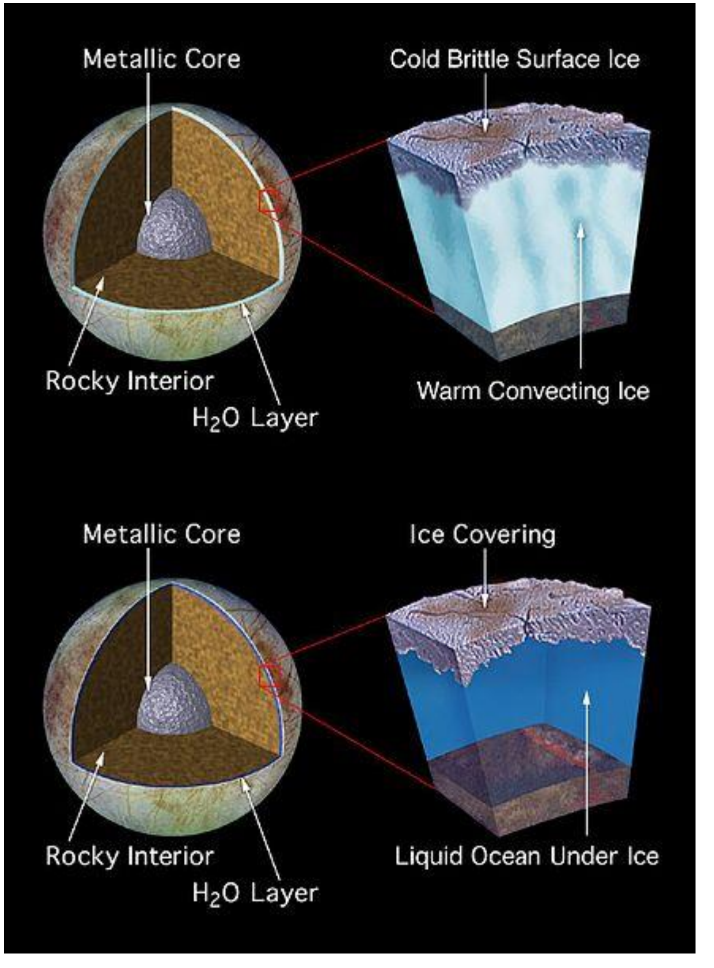
Other surface features

- Cycloidal fractures appear to be a response of a relatively thin crust to the tidal stresses exerted by Jupiter, breaking the crust and then bringing it back together once the stress is released.
- Other areas look like pack ice on Earth, in which individual scattered blocks could be put back together like a jigsaw puzzle.
- Such geology requires that a liquid layer, or a layer of very warm and ductile ice, underlies the solid ice crust of Europa.
- The liquid/soft ice layer must be present today, as the surface is geologically very young (from crater counts).
- Unusual domes and pits hint that cryovolcanism is taking place on Europa.



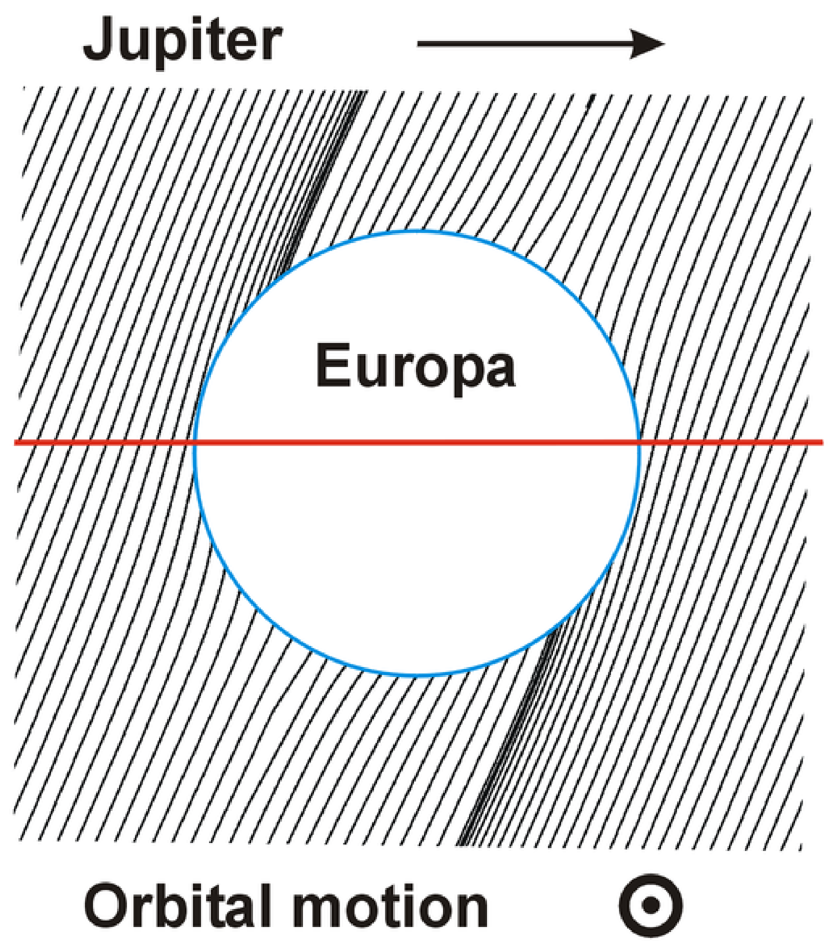
The interior

- Doppler tracking of the Galileo spacecraft allowed the analysis of the gravitational field of Europa.
- Europa appears to be strongly differentiated, with the densest material in the center and the least dense on the surface.
- Europa could thus differentiate into an iron-nickel core, a silicate mantle, and an ice crust.
- This, plus constraints on the bulk composition of Europa (carbonaceous chondrites) and estimates of its density, led to the conclusion that the outer shell of ice is hundreds of kilometers thick.



A subsurface ocean

- The magnetometer on Galileo detected no magnetic intrinsic field at Europa, but rather an induced magnetic field opposing Jupiter's.
- This requires that currents form within Europa, induced by Jupiter's magnetic field.
- Repeated observations by the magnetometer revealed that the conducting region was the outer layer of Europa.
- Solid ice could not reach the required conductivity, a liquid layer containing dissolved salts was necessary to explain observations.

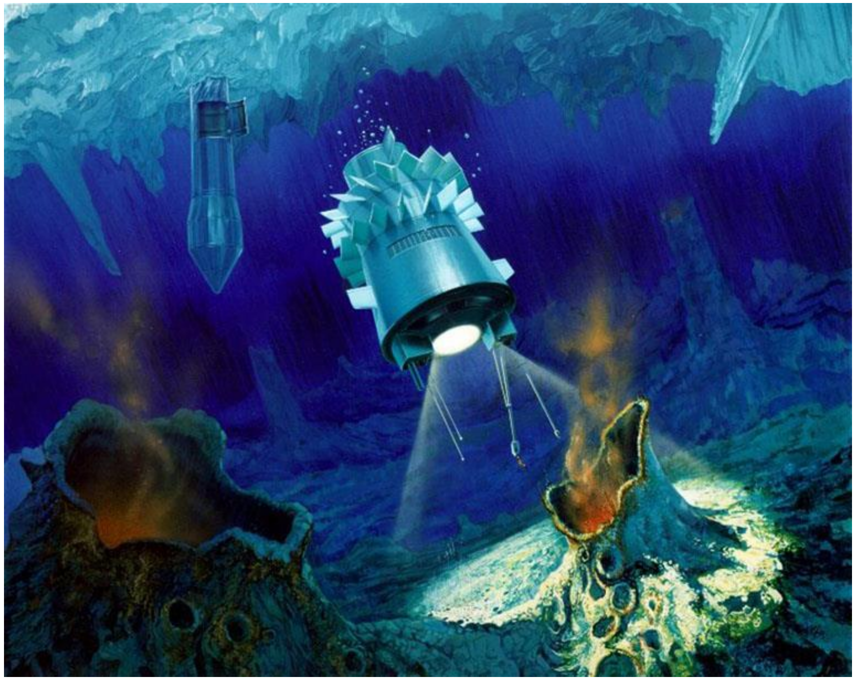


Chemistry of the Europan ocean

- The distortion of water ice bands observed in the infrared is characteristic of the presence of hydrated minerals (such as evaporite salts and clays).
- Ultraviolet spectroscopy revealed that the most geologically active areas of Europa are also the darkest, and that they brighten with age, as it would be typical for sulfur or sulfur dioxide bombarded by Jovian radiation.
- Because of their nature and distribution, these minerals appear to be coming from the interior of Europa, dissolved in the water reaching the surface through cracks caused by tidal stresses.
- Galileo could not detect organic compounds on the surface of Europa, but these compounds are very fragile, as their carbon-hydrogen bonds would be quickly broken by particle radiation and the hydrogen would escape.

Thickness of the ice crust

- Neither magnetic field measurements nor theoretical models of tidal dissipation allow a precise estimate of the ice crust thickness.
- Ice rafts constrain the local thickness of the ice crust, which should be of the order of their size, otherwise they wouldn't be able to break free.
- Pwyll, one of the largest and freshest craters on Europa, could have a central peak only if the ice thickness was of several kilometers.
- Cycloidal features require a very thin ice, of the order of tens of meters.
- The knowledge of ice thickness is critical in determining if a landing spacecraft can reach the ocean below.



Is there life on Europa?

- Stable liquid water is available on Europa, but a source of organics and free energy are required for habitability.
- Photosynthesis would not be possible for an ice more than 10 m thick, but such environment is high in radiation, being close to the surface.
- Tidal dissipation at the water-ice interface would provide a source of heat, but no pre-biotic compounds.
- Radiogenic heating at the base of the ocean, at the top of the silicate mantle, is a better source of energy for biology, and could provide nutrients the chemical elements necessary for life to evolve, through volcanic or hydrothermal activity.
- Estimates of present energy sources allow the production of 10^{21} g/yr of biomass, orders of magnitude below the Earth (one cell per cm^{-3} or less).

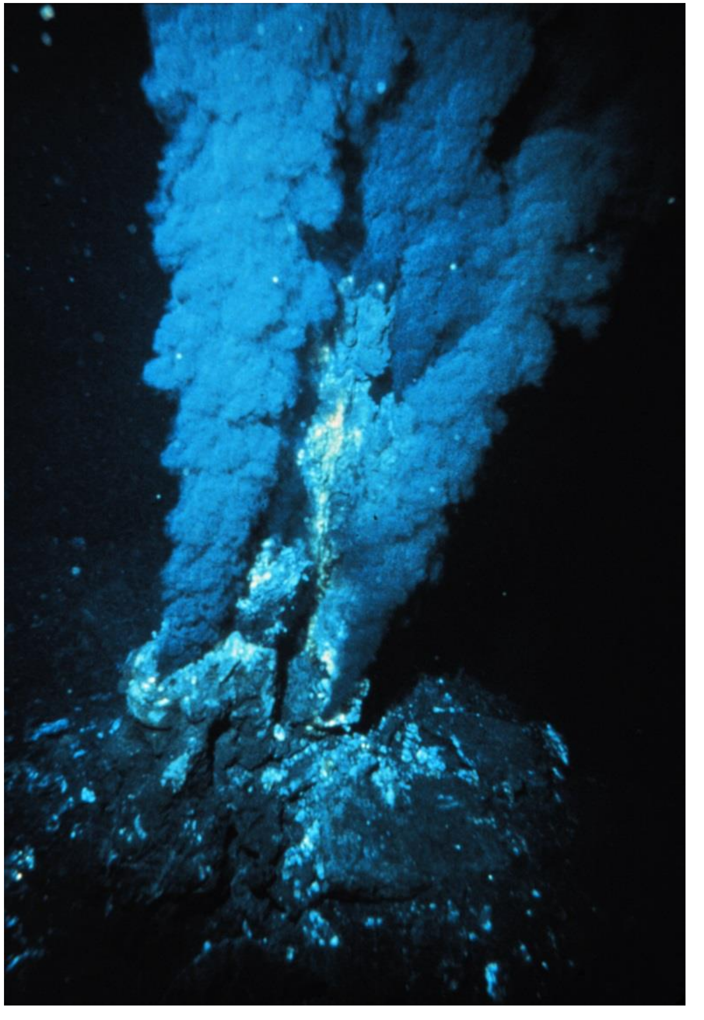
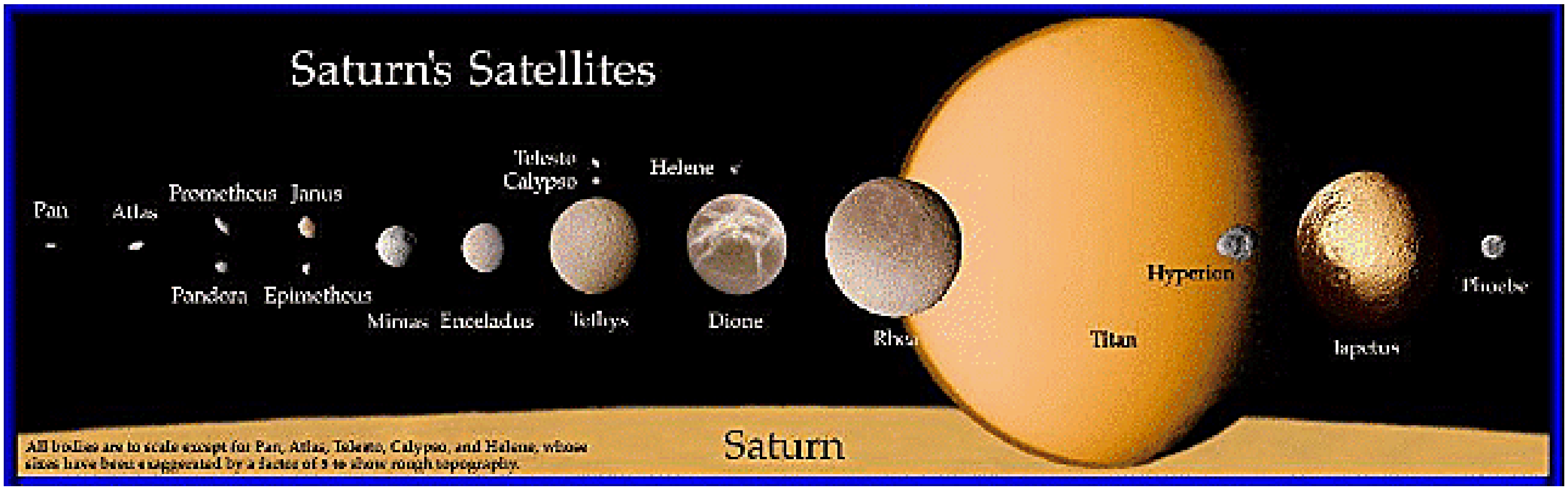


TABLE 3. A PLANETARY HABITABILITY TABLE FOR EUROPA

Requirement			*Comments and references*
Liquid water	Present in subsurface ocean		Khurana *et al.*, 1998
Main elements			
C	CO_2, carbonate, organics		Cooper *et al.*, 2001; organics expected from meteoritic delivery
H	H_2O, H_2SO_4, organics		Carlson *et al.*, 1999; Cooper *et al.*, 2001; organics expected from meteoritic delivery
N	?		NH_3 from primordial inventory possible; other fixed N species from surface?
O	H_2O, O_2 and other oxidants, organics		Johnson *et al.*, 2003
P	?		Unknown source, but source in rocky core possible
S	SO_4^{2-}, other sulfur oxidation states		Carlson *et al.*, 1999; Cooper *et al.*, 2001; McKinnon and Zolensky, 2003; Dalton, 2003; Hansen and McCord, 2008
Other elements	K, Na		Johnson *et al.*, 2002
Energy—full redox couples	***Electron donor***	***Electron acceptor***	
Chemolithotrophy			
Methanogenesis, acetogenesis	H_2	CO_2	H_2 plausible if there is rocky core-water interaction
Sulfate reduction	H_2	SO_4^{2-}	H_2 plausible if there is rocky core-water interaction
Chemoorganotrophy			
Sulfate reduction	Organics	SO_4^{2-}	Organics expected from meteoritic input
Other forms of energy	Photosynthesis unlikely in ocean as ice layer expected to block all light. Fermentation possible if organics entrained in ocean?		

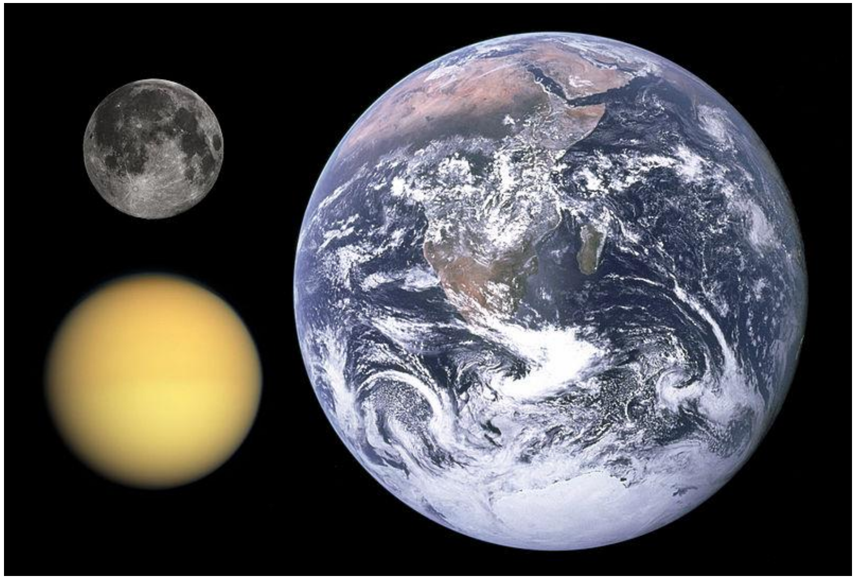
Satellites of Saturn



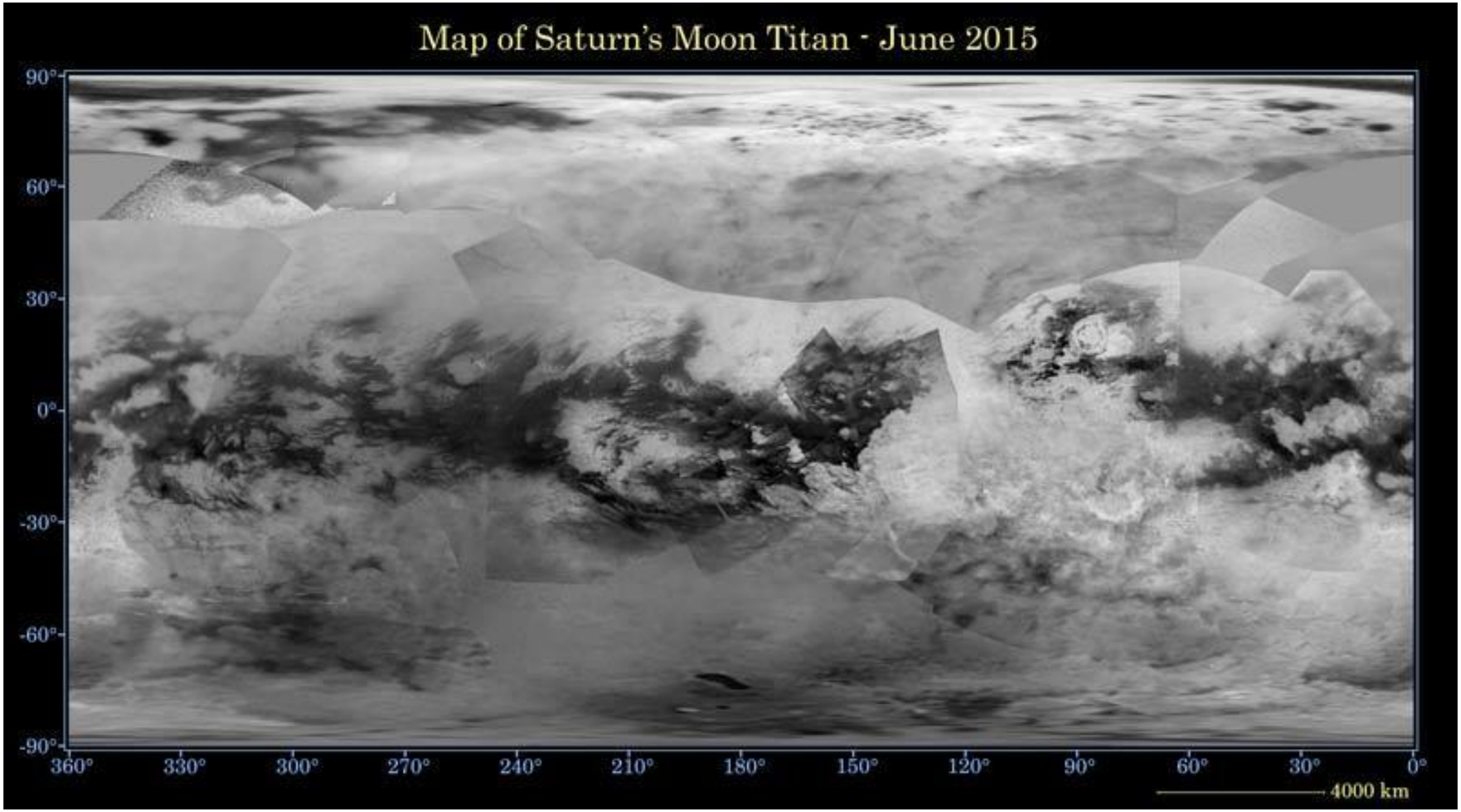
- Saturn has at least 150 moons and moonlets, more than any other planet.
- Only Titan is as large as the Galilean satellites of Jupiter.
- Except for Titan, Saturn's satellites have low densities (1 to 1.5 g/cm^3) and high surface reflectivity, indicating that they are composed of water ice.
- All the satellites, except Enceladus, have old, highly cratered surfaces.

Titan

- Titan is the sixth ellipsoidal moon from Saturn, with a diameter 50% larger than the Moon, being also 80% more massive.
- It is the second-largest moon in the Solar System, after Jupiter's moon Ganymede, and is larger by volume than the smallest planet, Mercury, although only 40% as massive.
- Titan is the most gas-rich moon in the solar system, having an atmospheric mass per unit area much greater than even that of the Earth, and the only object other than Earth where clear evidence of stable bodies of surface liquid has been found.

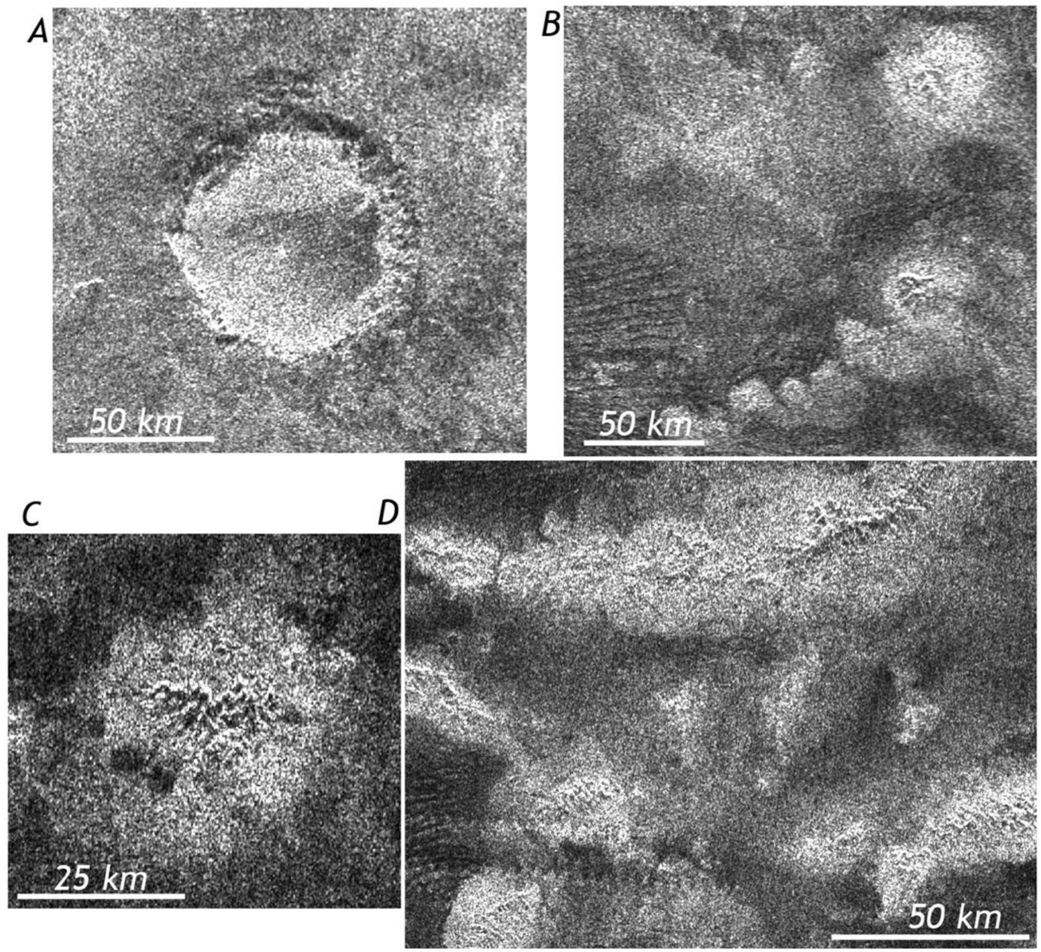


IR map of Titan

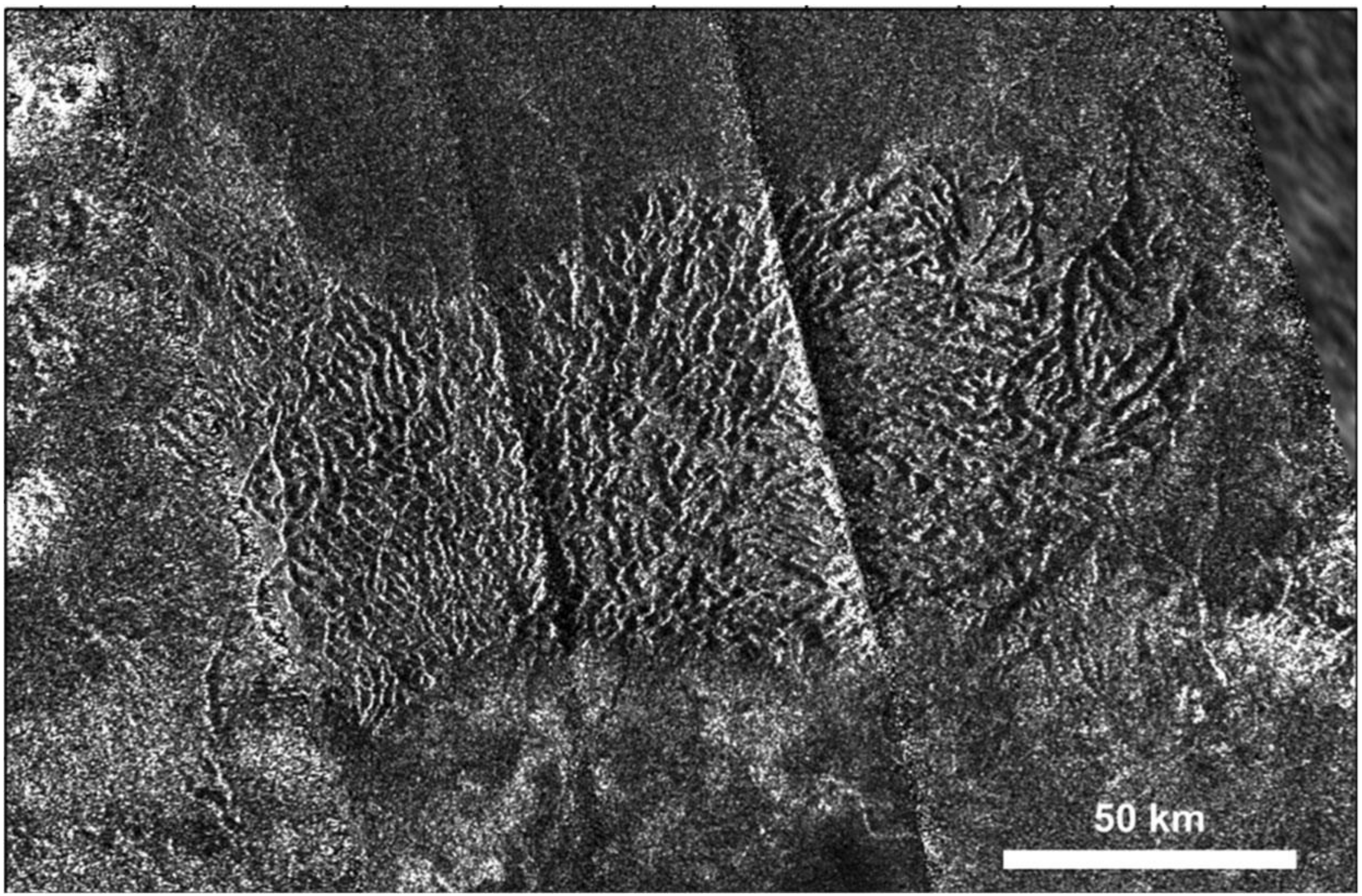


SAR observations

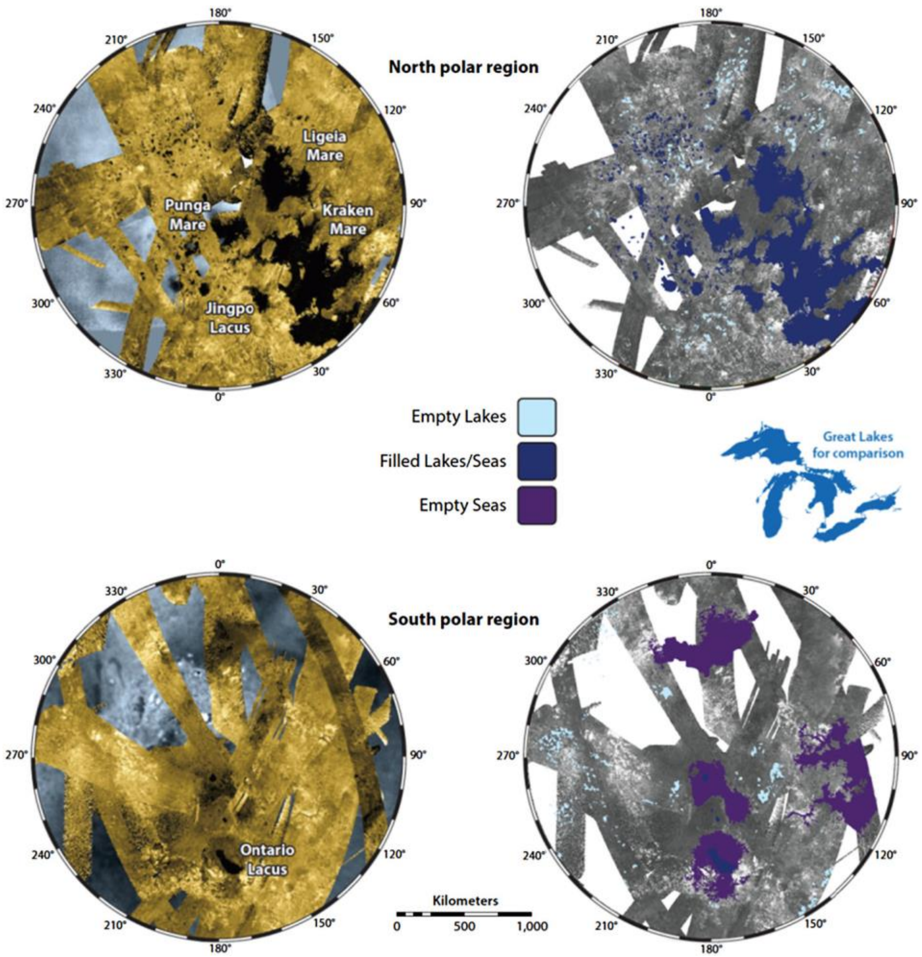
Mountains



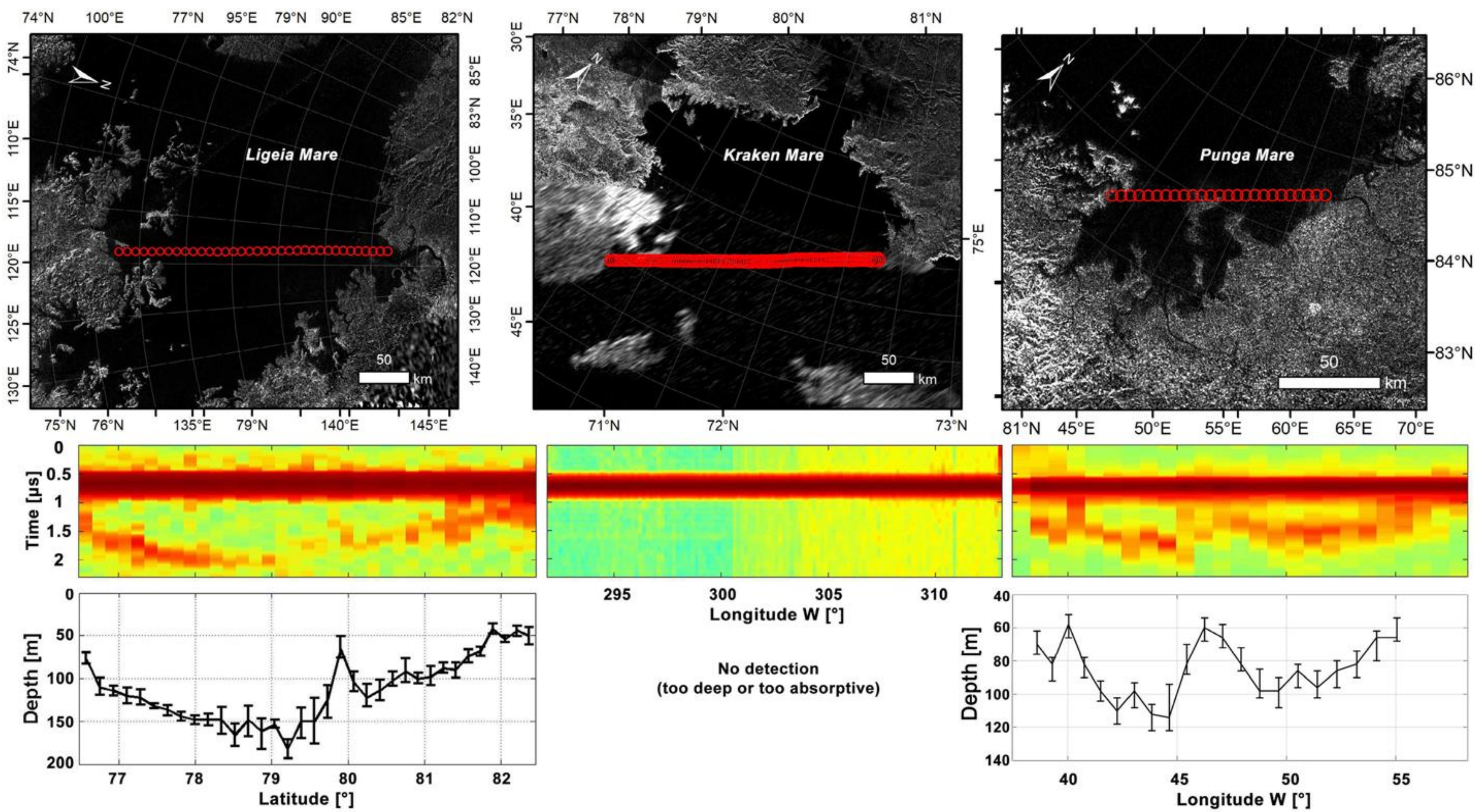
Labyrinths



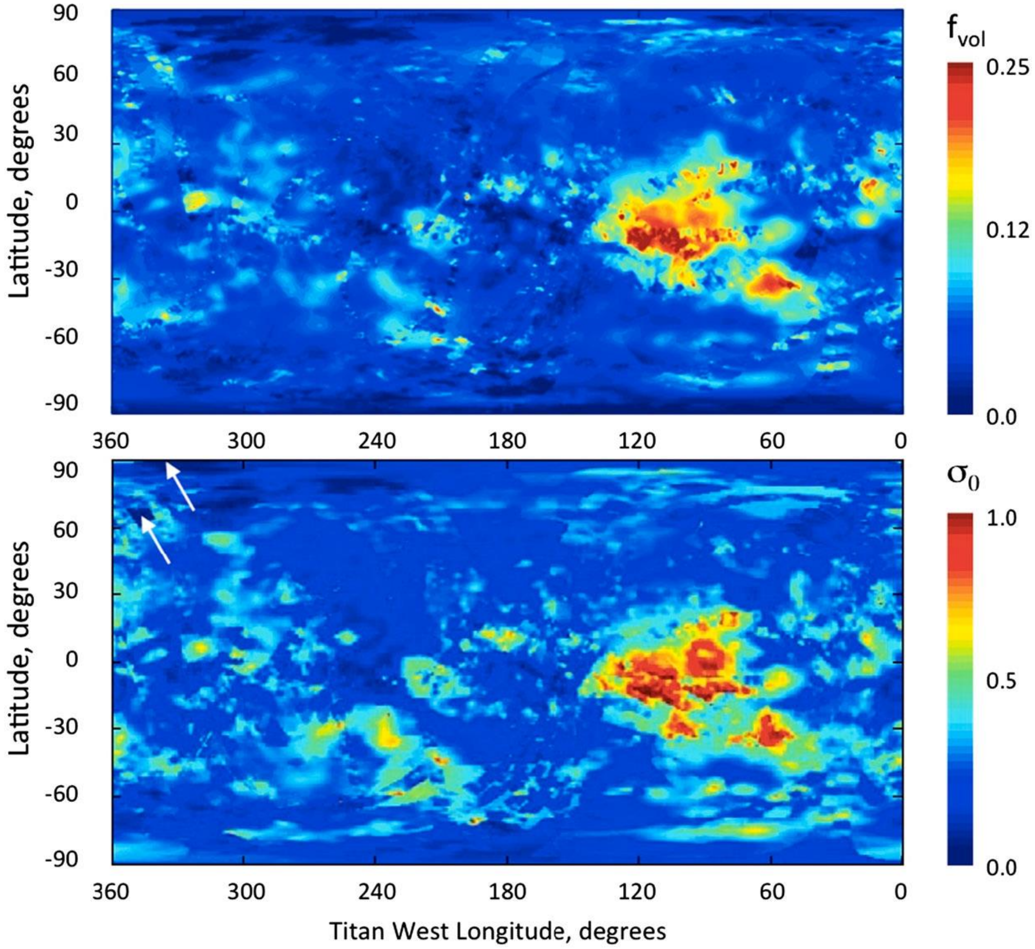
Lakes and seas



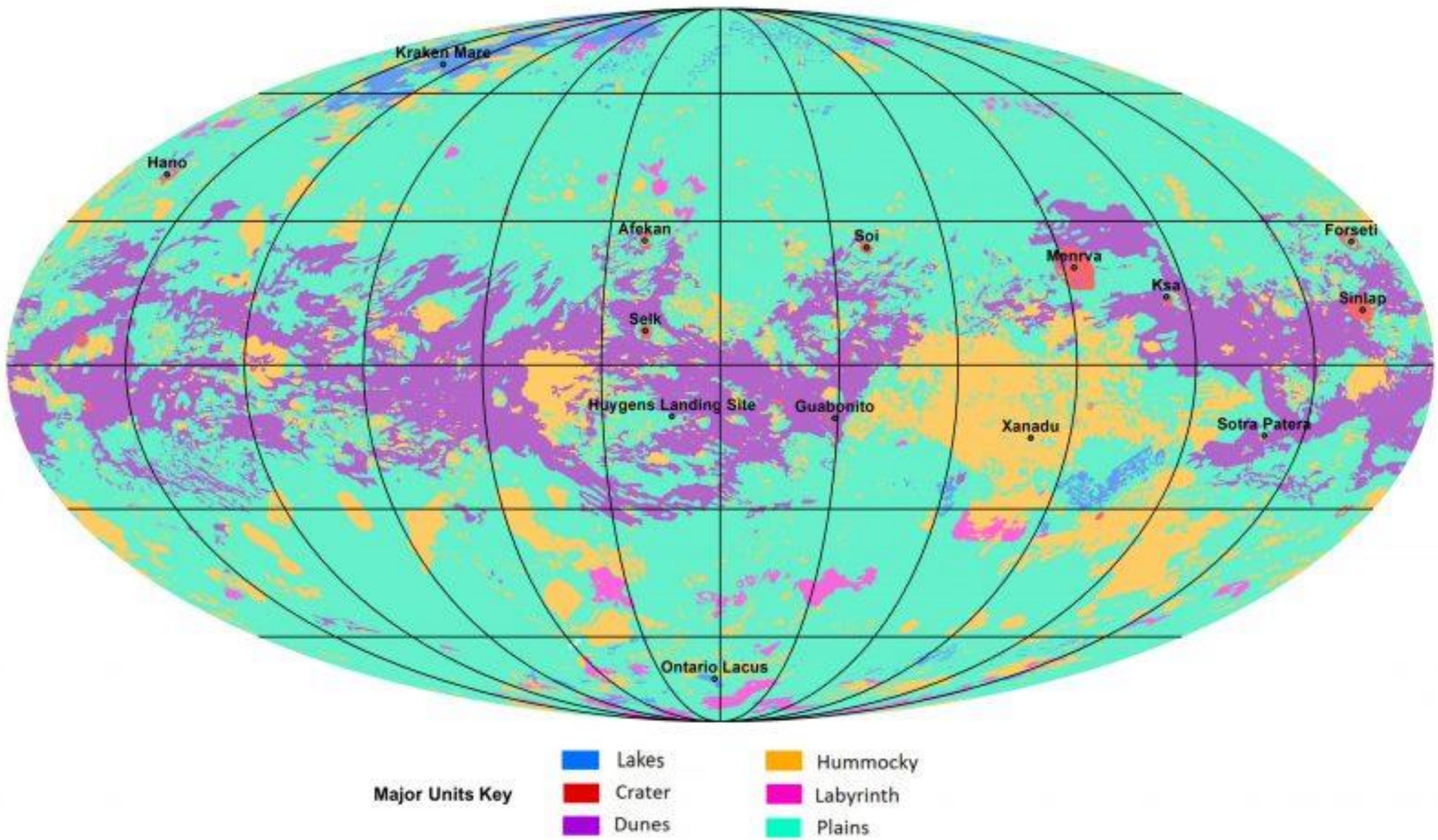
Lake bathymetry



Radar volume scattering



Breaking news: a geologic map of Titan

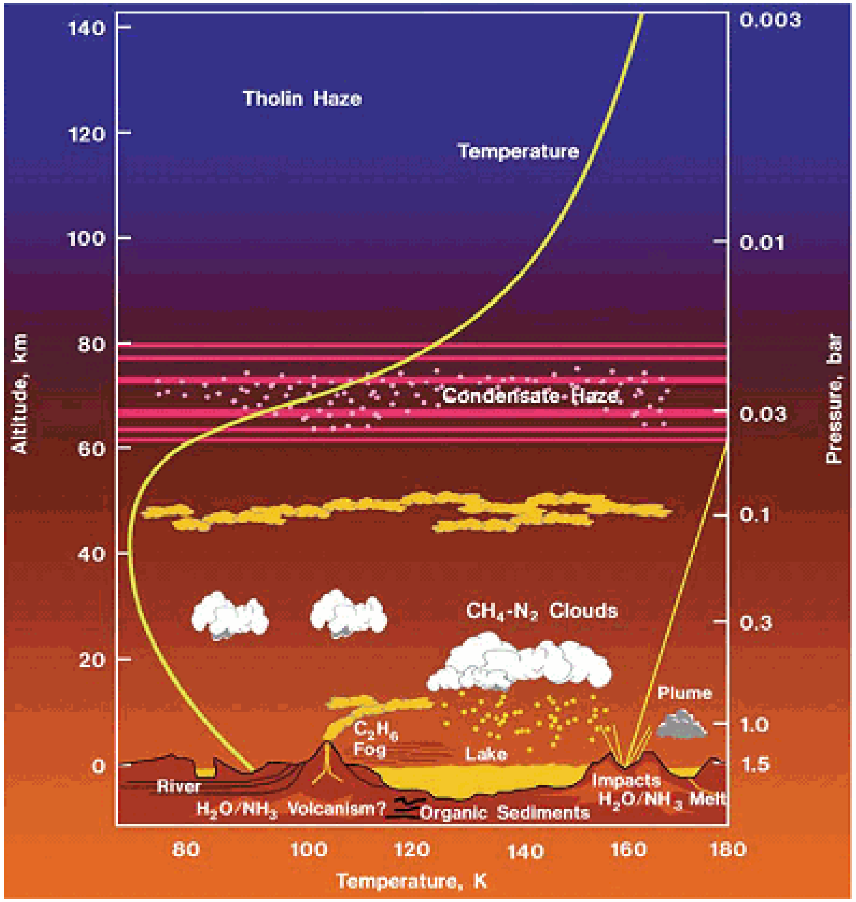


Titan's atmosphere

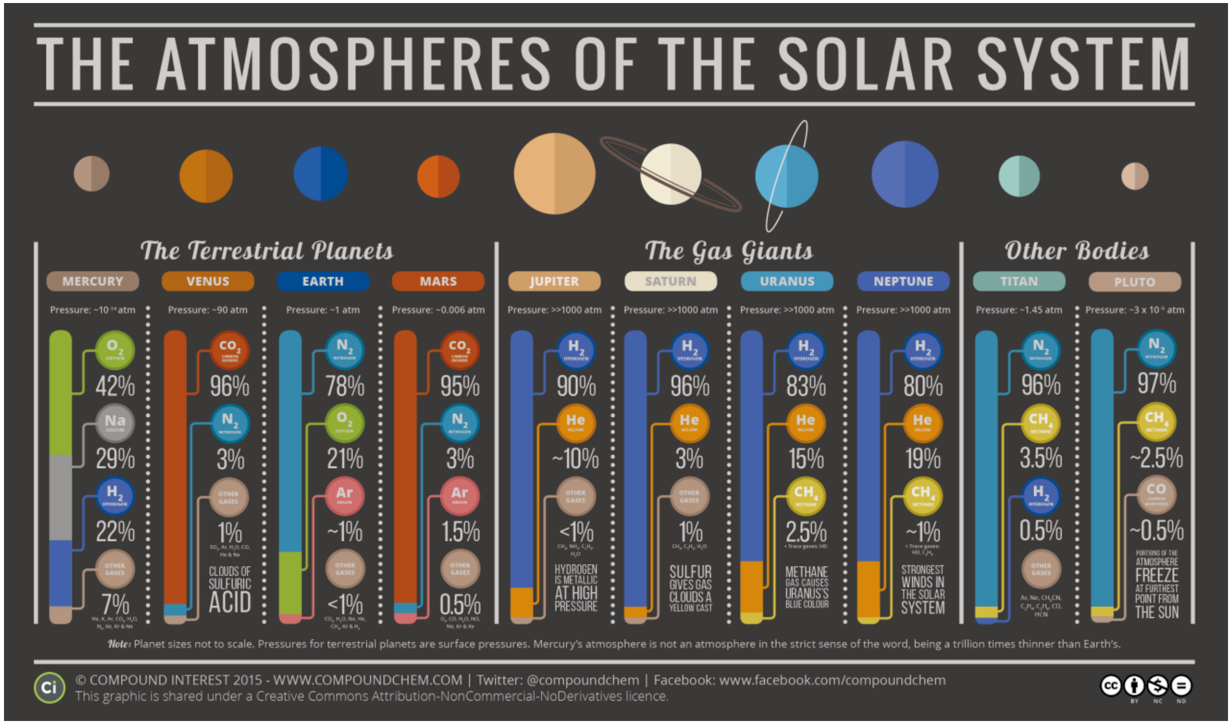
- Spectroscopic observations from Earth in the 1940s revealed the presence of atmospheric gases, but only Voyager 1 could reveal the nature of Titan's atmosphere in 1980.
- Observations from the Voyager space probes have shown that Titan's atmosphere is denser than Earth's, with a surface pressure about 1.45 atm.
- It is also about 1.19 times as massive as Earth's overall, or about 7.3 times more massive on a per surface area basis.
- It supports opaque haze layers that block most visible light from the Sun and obscures Titan's surface features.
- Titan's lower gravity means that its atmosphere is far more extended than Earth's.

How Titan’s atmosphere works

- Titan receives about 1% as much sunlight as Earth.
- Titan's surface temperature is about 94 K (-179.2 °C), thanks to atmospheric methane creating a greenhouse effect.
- Haze in Titan's atmosphere contributes to an anti-greenhouse effect by reflecting sunlight back into space.
- Titan's clouds, probably composed of methane, ethane or other simple organics, are scattered and variable, punctuating the overall haze.
- The findings of the Huygens probe indicate that Titan's atmosphere periodically rains liquid methane and other organic compounds onto its surface.



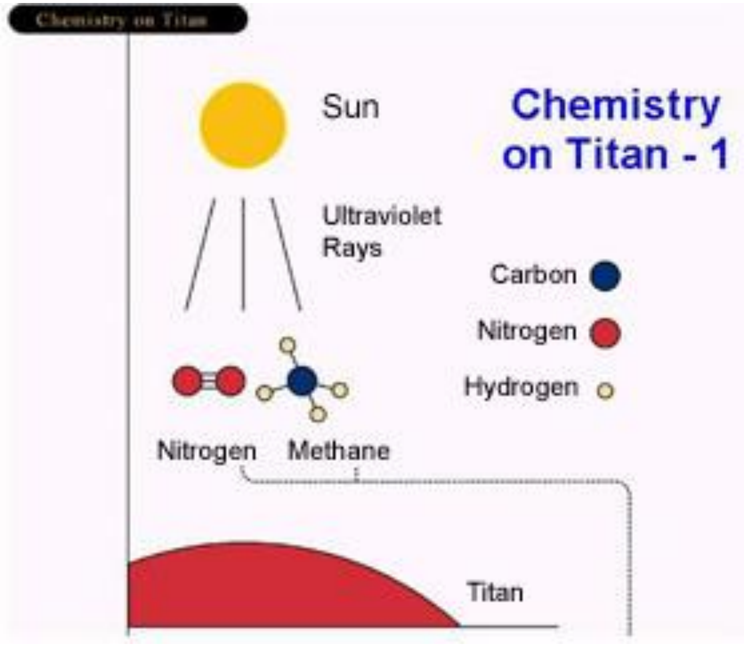
Atmospheric composition



- Titan's atmospheric composition in the stratosphere is 98.4% nitrogen with the remaining 1.6% composed mostly of methane (1.4%) and hydrogen (0.1-0.2%).
- There are trace amounts of other hydrocarbons, such as ethane, diacetylene, methylacetylene, acetylene and propane, and of other gases, such as cyanoacetylene, hydrogen cyanide, carbon dioxide, carbon monoxide, cyanogen, argon and helium.
- The hydrocarbons are thought to form in Titan's upper atmosphere in reactions resulting from the breakup of methane by the Sun's ultraviolet light, producing a thick orange smog.

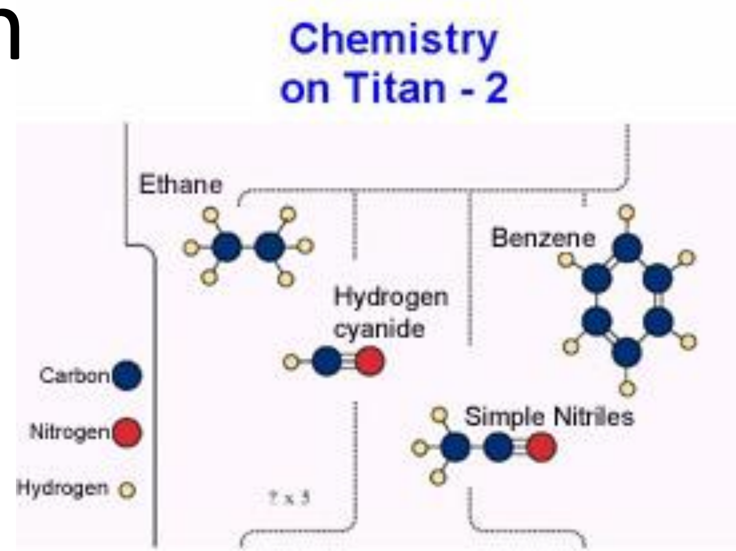
Methane

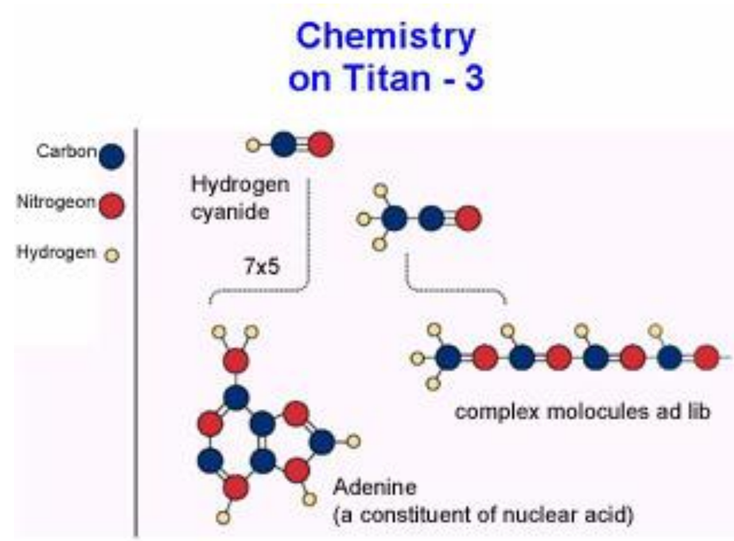
- Energy from the Sun should have converted all traces of methane in Titan's atmosphere into more complex hydrocarbons within 50 million years, a short time compared to the age of the Solar System.
- This suggests that methane must be replenished by a reservoir on or within Titan itself.
- The ultimate origin of the methane in its atmosphere may be its interior, released via eruptions from cryovolcanoes.



The chemistry of methane and UV radiation

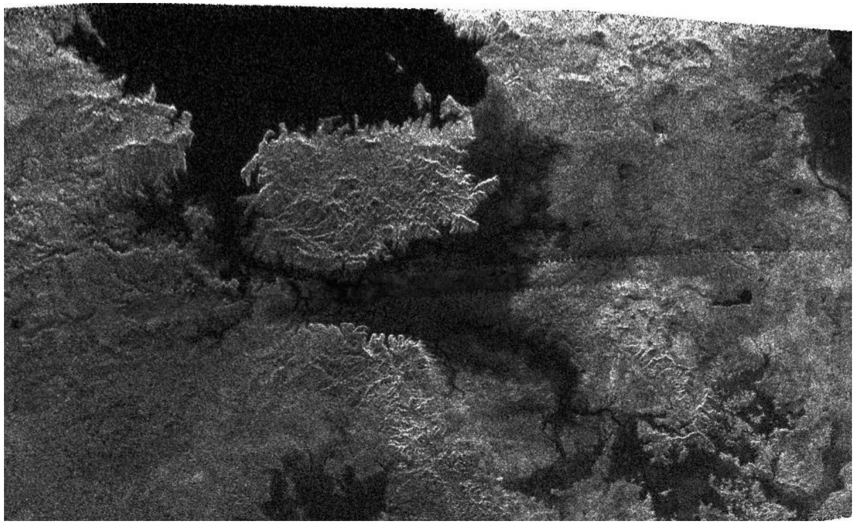
- On June 6, 2013, scientists at the IAA-CSIC reported the detection of polycyclic aromatic hydrocarbons in the upper atmosphere of Titan.
- On September 30, 2013, propene was detected in the atmosphere of Titan by NASA's Cassini spacecraft, using its composite infrared spectrometer (CIRS).
- On October 24, 2014, methane was found in polar clouds on Titan.





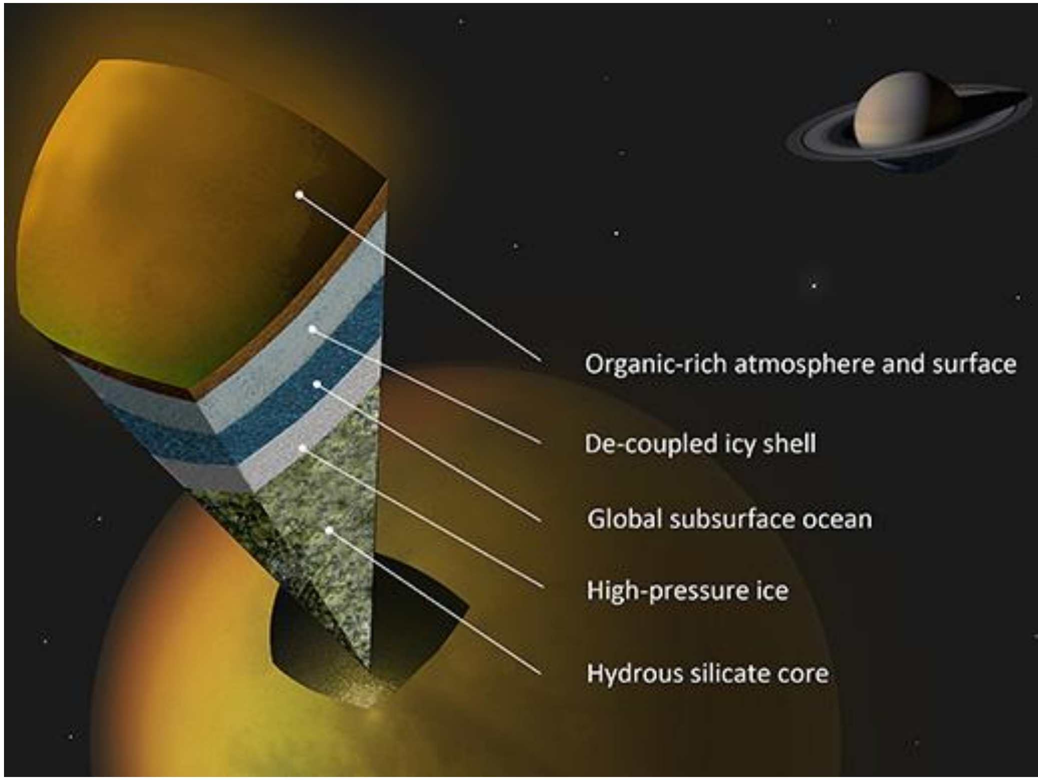
Liquids on the surface of Titan

- The possibility of hydrocarbon seas on Titan was first suggested based on Voyager 1 and 2 data that showed Titan to have a thick atmosphere of approximately the correct temperature and composition to support them.
- Synthetic-aperture radar images of the surface of Titan allowed identification of shorelines around the North pole of Titan.
- In the South, where it is currently Summer, much fewer lakes were found, together with depressions resembling dried lake beds.
- The liquid erosion features appear to be a very recent occurrence: channels in some regions have created surprisingly little erosion, suggesting erosion on Titan is extremely slow, or some other recent phenomena may have wiped out older riverbeds and landforms.
- Overall, the Cassini radar observations have shown that lakes cover only a few percent of the surface, making Titan much drier than Earth.



The interior of Titan

- Measurements by the Cassini spacecraft revealed that Titan is likely differentiated, with a 3,400-kilometre rocky center surrounded by several layers composed of different crystal forms of ice.
- Its interior may still be hot and there may be a liquid layer consisting of a "magma" composed of water and ammonia between the ice Ih crust and deeper ice layers made of high-pressure forms of ice.
- The presence of ammonia allows water to remain liquid even at a temperature as low as 176 K (-97 °C) (for eutectic mixture with water).
- Surface features were observed by the Cassini spacecraft to systematically shift by up to 30 kilometers between October 2005 and May 2007, which suggests that the crust is decoupled from the interior, and provides additional evidence for an interior liquid layer.
- Comparison of the gravity field with the RADAR-based topography observations suggests that the ice shell may be substantially rigid.

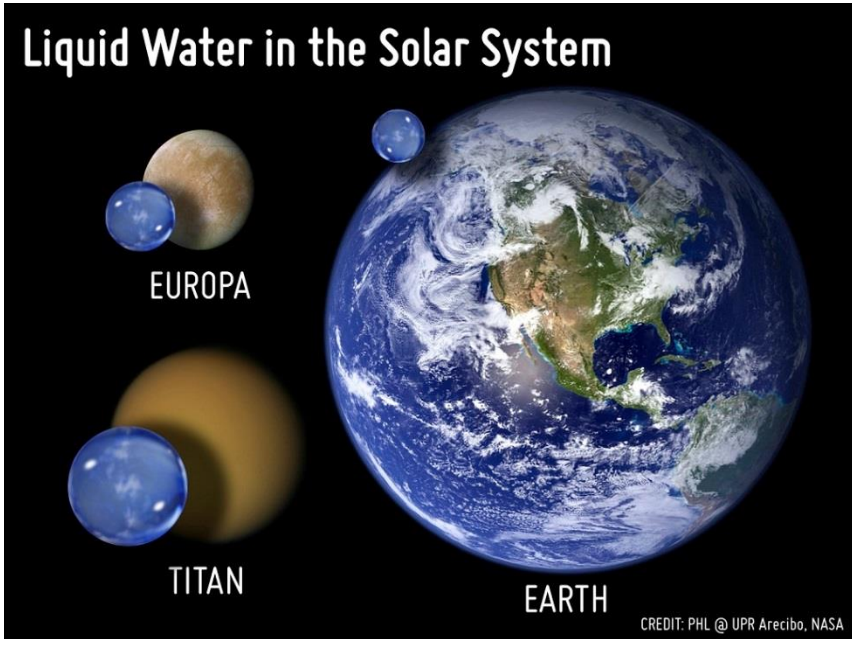


Life on Titan?

- Titan is thought to be a prebiotic environment rich in complex organic chemistry with a possible subsurface liquid ocean serving as a biotic environment.
- Titan's atmosphere is similar in composition to that of the primordial Earth, with the important exception of a lack of water vapor.
- The Miller-Urey experiment has shown that with an atmosphere similar to that of Titan and the addition of UV radiation, complex molecules and polymer substances like tholins can be generated.
- In October 2010, the five nucleotide bases - building blocks of DNA and RNA - and amino acids were found among the many compounds produced when energy was applied to a combination of gases like those in Titan's atmosphere (no water!).

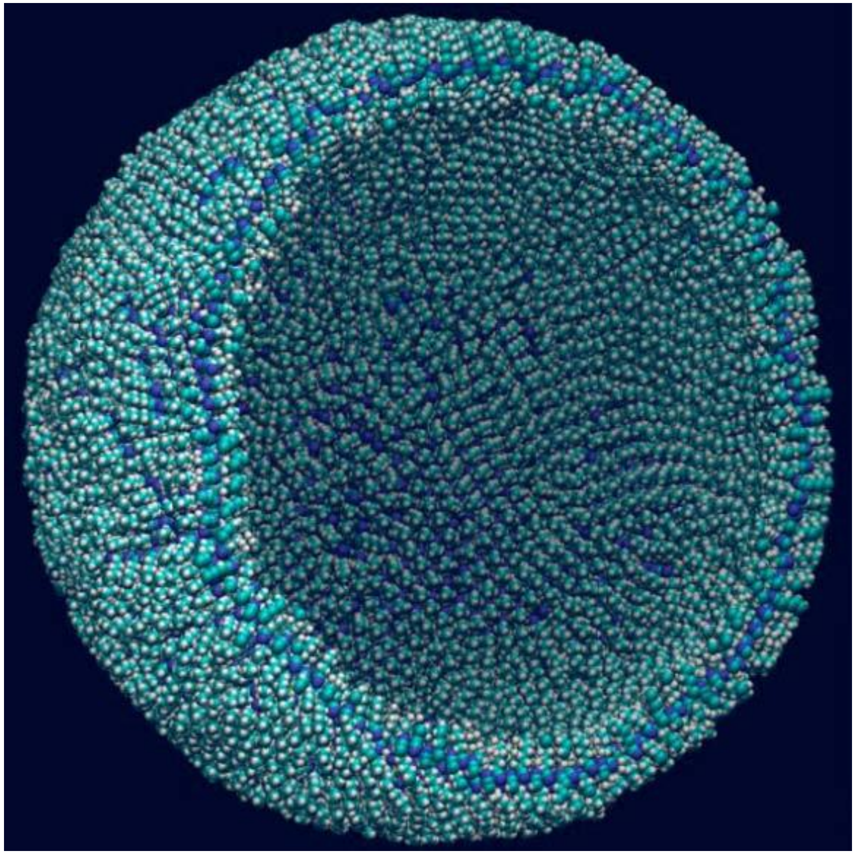
Life on Titan as we know it

- Several theories suggest that liquid water from an impact could be preserved for thousands of years under a frozen isolation layer, providing an environment for the development of life.
- Conditions within the water ocean existing deep beneath the water-ice crust, although extreme by terrestrial standards, are such that life could indeed survive.
- Heat transfer between the interior and upper layers would be critical in sustaining any subsurface oceanic life.



Life on Titan as we don't know it

- It has been suggested that life could exist in the lakes of liquid methane on Titan, just as organisms on Earth live in water.
- Such organism would inhale H_2 in place of O_2, metabolize it with acetylene instead of glucose, and exhale methane instead of carbon dioxide.
- Although all living things on Earth (including methanogens) use liquid water as a solvent, it is speculated that life on Titan might instead use a liquid hydrocarbon, such as methane or ethane.
- In February 2015, a hypothetical cell membrane capable of functioning in liquid methane in Titan conditions was modeled.
- Composed of small molecules containing carbon, hydrogen, and nitrogen, it would have the same stability and flexibility as cell membranes on Earth, which are composed of phospholipids, compounds of carbon, hydrogen, oxygen, and phosphorus.

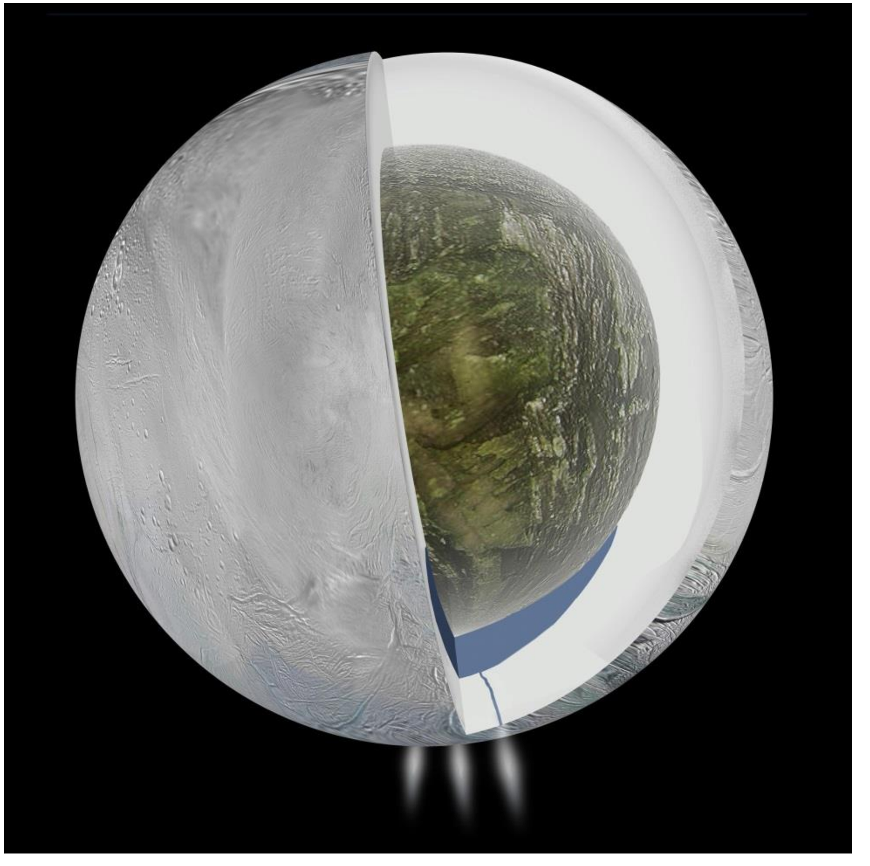


Enceladus

- Enceladus is approximately 500 kilometers in diameter.
- Enceladus is mostly covered by fresh, clean ice, reflecting almost all the sunlight that strikes it, making its surface temperature at noon reach only -198 °C.
- Despite its small size, it has a wide range of surface features, ranging from old, heavily cratered regions to young, tectonically deformed terrains.
- In 2005, the Cassini spacecraft started discovered water-rich plumes venting from the south polar region.
- Cryovolcanoes near the south pole shoot geyser-like jets of water vapor, other volatiles, and solid material, including sodium chloride crystals and ice particles, into space, totaling approximately 200 kilograms per second.
- Some of the water vapor falls back as "snow"; the rest escapes, and supplies most of the material making up Saturn's E ring.

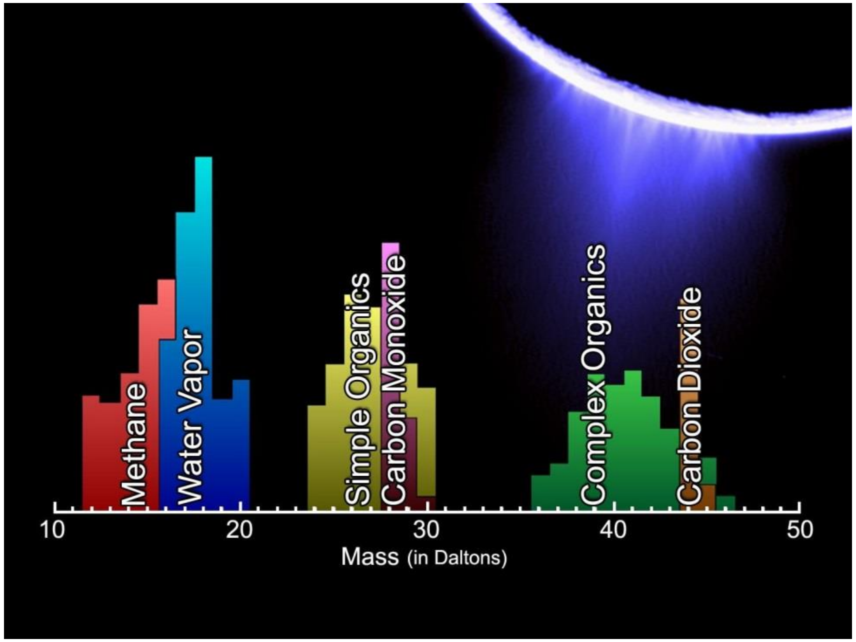
A subsurface ocean

- In 2014, NASA reported that Cassini found evidence for a large south polar subsurface ocean of liquid water.
- These geyser observations, along with the finding of escaping internal heat and very few (if any) impact craters in the south polar region, show that Enceladus is geologically active today.
- Like many other satellites in the extensive systems of the giant planets, Enceladus is trapped in an orbital resonance.
- Its resonance with Dione excites its orbital eccentricity, which is damped by tidal forces, tidally heating its interior, and possibly driving the geological activity.



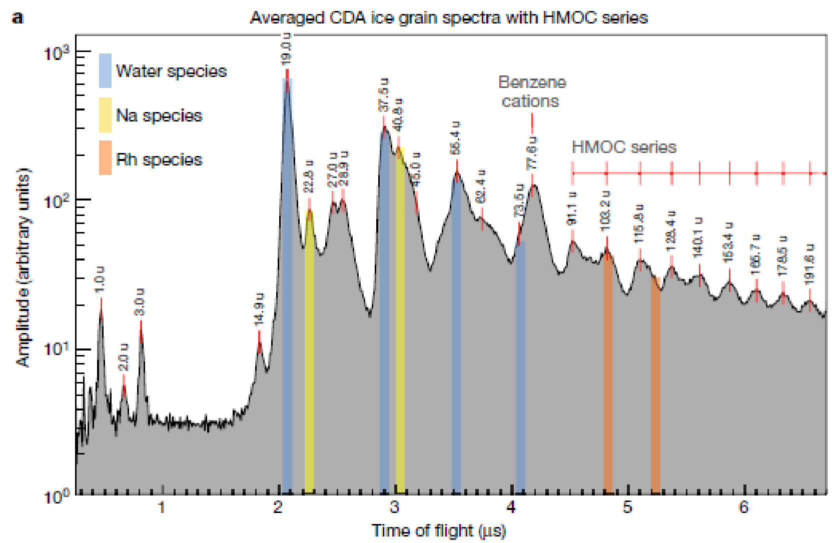
Sampling the plume

- Cassini flew through a water-rich cryovolcanic plume, originating from vents near the south pole, on July 14, 2005.
- This allowed instruments such as the ion and neutral mass spectrometer (INMS) and the cosmic dust analyzer (CDA) to directly sample the plume.
- INMS measured the composition of the gas cloud, detecting mostly water vapor, as well as traces of molecular nitrogen, methane, and carbon dioxide.
- The CDA "detected a large increase in the number of particles near Enceladus", confirming Enceladus as the primary source for the E ring.



Latest news on plume composition

- Cassini observations reveal emitted ice grains containing concentrated and complex macromolecular organic material with molecular masses above 200 atomic mass units.
- The data constrain the macromolecular structure of organics detected in the ice grains and suggest the presence of a thin organic-rich film on top of the oceanic water table.



The interior of Enceladus

- The size and chemical makeup of dust grains detected in the plume indicate that they likely formed as a result of interactions between hot rock and water, that is hydrothermal activity.
- On Earth, chemically similar particles forms at undersea hydrothermal vents, when chemicals dissolved in hot water crystallize as the water is suddenly cooled when it meets the ocean.
- It was found that to produce silica grains of the size and composition found by Cassini, one needs rock that is at least 90°C to be in contact with the cool ocean water.
- If the plumes can be sampled with a future spacecraft, it would be possible to directly determine whether life has evolved on Enceladus, and perhaps even detect it!

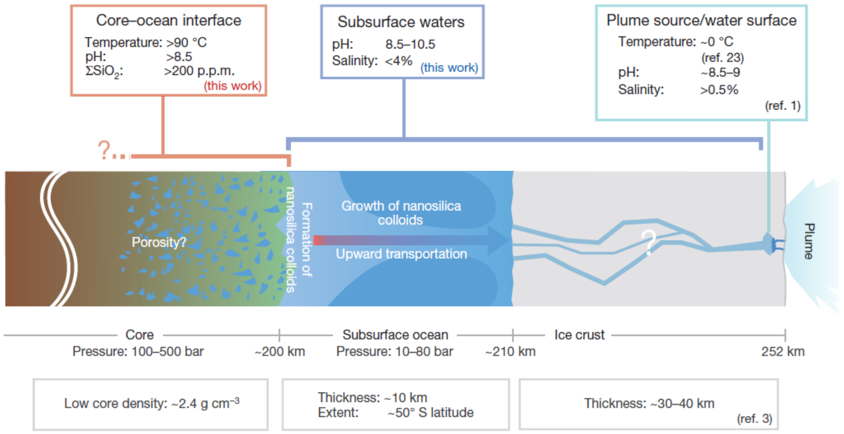
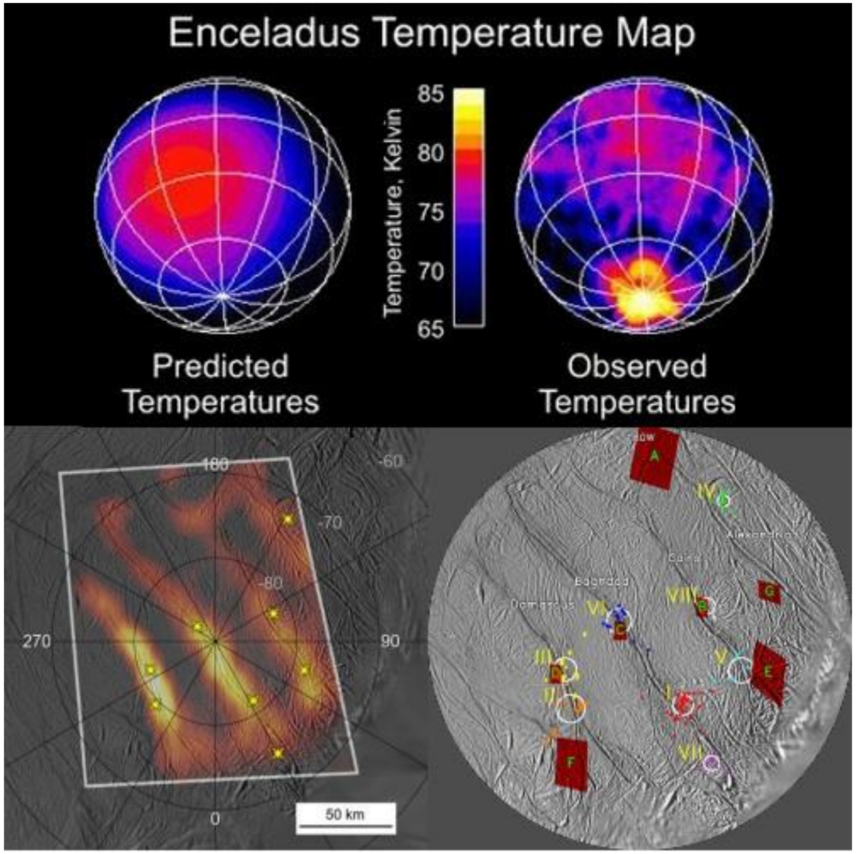


TABLE 4. A PLANETARY HABITABILITY TABLE FOR ENCELADUS

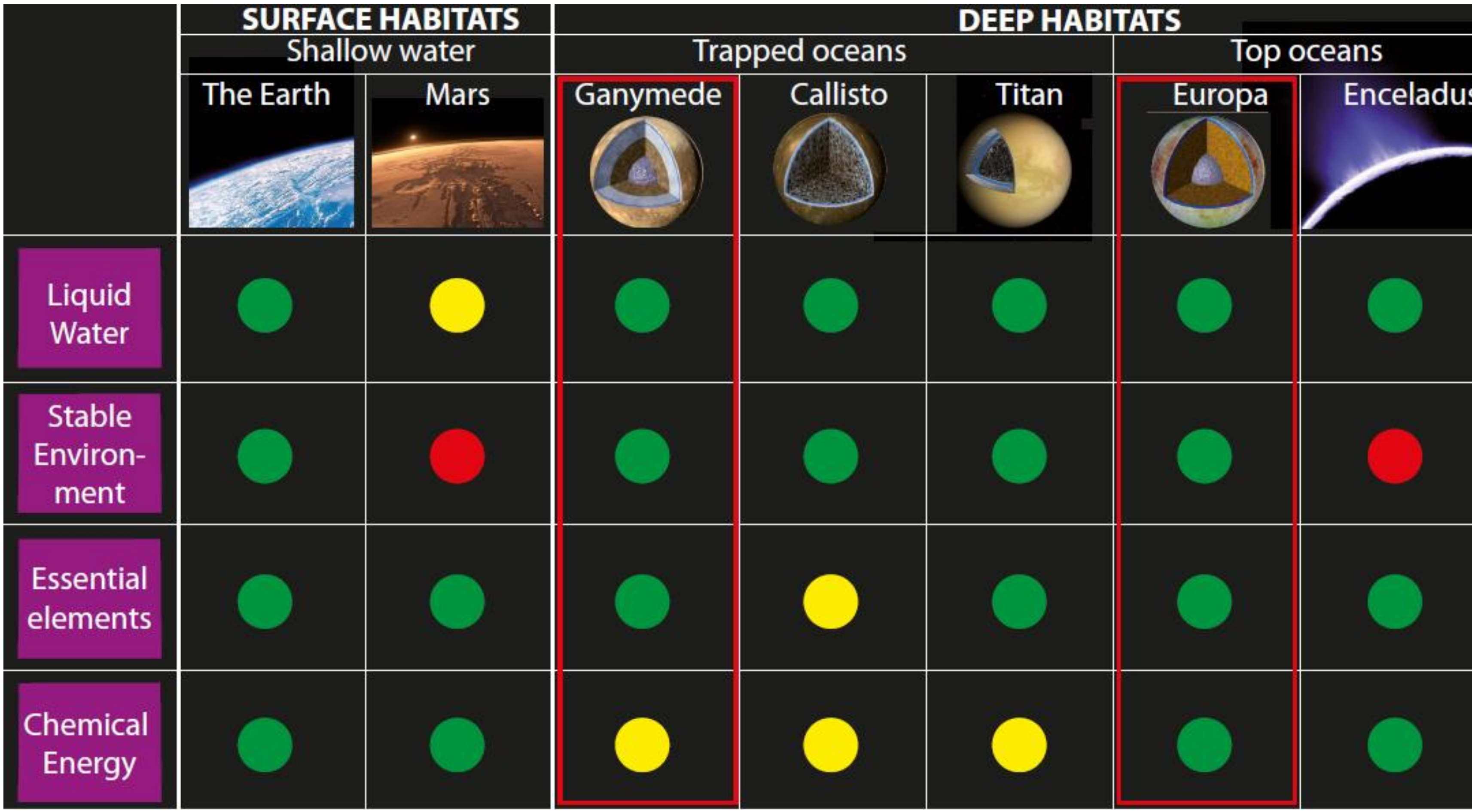
Requirement			*Comments and references*
Liquid water	Present in subsurface ocean		Waite *et al.*, 2009
Main elements			
C	CO, CO_2, carbonic acid, methane, organics		Waite *et al.*, 2009
H	H_2, ^2H, H_2O, organics		Waite *et al.*, 2009
N	N_2, ammonia, HCN (hydrogen cyanide)		Waite *et al.*, 2009
O	H_2O, CO, CO_2, CH_3OH, C_2H_4O, C_2H_6O		Waite *et al.*, 2009
P	?		
S	H_2S		Waite *et al.*, 2009
Other elements	Na, K		Postberg *et al.*, 2009
Energy—full redox couples	***Electron donor***	***Electron acceptor***	
Chemolithotrophy			
Methanogenesis, acetogenesis	H_2	CO_2	
Chemoorganotrophy			
Sulfate reduction	Organics	SO_4^{2-}	Organics expected from meteoritic input
Other forms of energy	Photosynthesis unlikely in ocean as ice layer expected to block all light. Fermentation with organics may be possible. The presence of hydrogen and organics raises the possibility of sulfate and iron reduction if these ions are available.		

Has there been enough time for life to evolve?

- Computer modeling was used to infer the past dynamic behavior of Saturn’s icy inner moons.
- All of their orbits slowly grow due to tidal effects, but at different rates, causing them to occasionally enter orbital resonances.
- In these configurations, even small moons with weak gravity can strongly affect each other’s orbits, making them more elongated and tilting them out of their original orbital plane.
- The current orbital state of the moons of Saturn within Titan's orbit is compatible with no more than 100 million years of dynamical evolution.
- It has been concluded that these moons are not primordial, and they re-accreted from a disk about 100 Myr ago, during which time Titan acquired its significant orbital eccentricity.
- It is speculated that this disk has formed through orbital instability and massive collisions involving the previous generation of Saturn’s midsized moons.

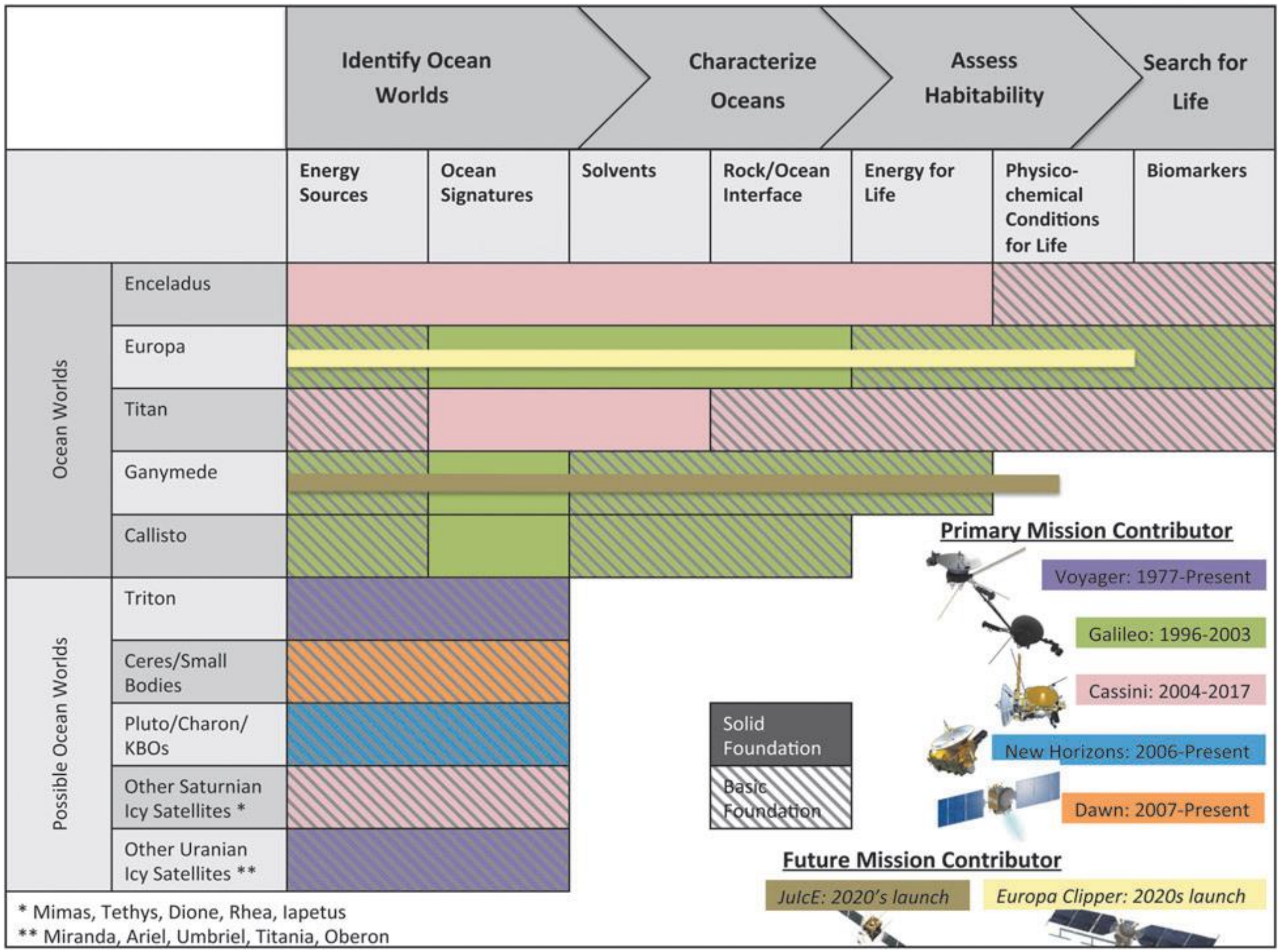


Existing and past habitable worlds in the Solar System



Taken from JUICE assessment study report (2011)

Investigations roadmap



THEO concept mission: Testing the Habitability of Enceladus's Ocean

Theme	Science Questions	Science Tasks	Science Measurements	Instrument	Deliverables
	1. How are the plumes connected to the subsurface ocean?	A. Determining the relative abundance of phases of water in the plumes	Ice particle abundance: constrained by images over 200 orbits at 500 km	DRIPS (Camera)	images of plumes with <10 km/px spatial resolution
			Water vapor abundance: constrained by spectral radial profiles over 200 orbits at 500 km	WAVES (Sub-mm)	spectral line strength of the H216O molecular transition at 556936.002 MHz with spatial resolution 1.1 km
		B: Constrain the thermochemical conditions at the vent source	Evidence of larger-chain (>C3) organics in the vapor phase in 300 orbits at 30 km	SWAMP (Mass Spectrometer)	mass spectra with mass range 36:1000 amu with 1 amu sensitivity
			Measurement of surface temperature at the fracture zones in 300 orbits at 30 km and 30 orbits at 100 km	WAVES (Sub-mm)	radiometric measurements of brightness temperature in mm/sub-mm continuum channels with sensitivity < 1K, spatial resolution 692/217 m at 100 km and 207/65 m at 30 km
			Plasma environment near plume the plume by time sampling of 1Hz for 600 orbits 30km	OSMOSIS (Magnetometer)	three component B field with 1.0 nT field strength resolution; fed into fluid models for ion flux derivation
		C: Constrain the temperature of the internal ocean	16O/17O/18O isotope ratios constrained by spectral radial profiles over 200 orbits at 500 km	WAVES (Sub-mm)	spectral line strengths of the H216O H217O H218O molecular transitions at 556936.002 MHz, 552020.960 MHz and 547676.440 MHz respectively
			Abundances of volatiles CO2, CO, H2O, CH4, N2, NH3, and OH from samples over 200 orbits at 500 km, 30 orbits at 100 km, and 300 orbits at 30 km	SWAMP (Mass Spectrometer)	mass spectra with mass range up to 44 amu with 30,000 M/dM
		D: Determine the rate of transport of vapor and particles from the subsurface ocean to the surface	Physical distribution of plume particles from high phase images of the plume over 200 orbits at 500km	DRIPS (Camera)	images of plumes with <20 km/px spatial resolution
			Mass flux of vapor from spectral radial profiles over 200 orbits at 500 km	WAVES (Sub-mm)	spectral line strength of the H216O molecular transition at 556936.002 MHz with spatial resolution 1.1 km at 500km
		E: Determine the chemical and physical mechanisms driving plume material transport	Ice particle abundance and extent as a function of orbital position in observations of plume at increments of 4 deg of mean anomaly at 500 km	DRIPS (Camera)	images of plumes with <20 km/px spatial resolution
			Vapor abundance and extent as a function of orbital position from observations of plume at increments of 4 deg of mean anomaly at 500 km	WAVES (Sub-mm)	spectral line strength of the H216O molecular transition at 556936.002 MHz with spatial resolution 1164 m at 500km.
			Abundance of gas species CO2, N2, CO, CH4, NH3, and H2O by vapor sampling 300 orbits at 30 km, 30 orbits at 100 km, and 100 orbits at 500 km.	SWAMP (Mass Spectrometer)	mass spectra in mass range up to 44 amu with 30,000 M/dM

THEO concept mission (2)

Is Enceladus habitable?	2. Is the abiotic environment suitable for life?	A: Determine the pH of the subsurface ocean	Abundance of CO_2 constrained by vapor sampling over 300 orbits at 30 km, 30 orbits at 100 km, and 100 orbits at 500 km	SWAMP (Mass Spectrometer)	mass spectra with 30,000 M/dM sensitivity
			Temperature of the plume source by mapping the brightness temperature in 300 orbits at 30 km and 100 orbits at 500 km	WAVES (Sub-mm)	radiometric measurements of brightness temperature in both mm & sub-mm continuum channels with sensitivity < 1K
		B: Determine the salinity of the subsurface ocean	Abundance of Na, Cl, K, N determined from vapor sampling over 300 orbits at 30 km	SWAMP (Mass Spectrometer)	mass spectra with 30,000 M/dM sensitivity
			Conductivity of the subsurface ocean from sampling magnetic field at a rate >5,000 samples/sec in 30 orbits at 30 km	OSMOSIS (Magnetometer)	Three component periodic B field with 1.0 nT resolution.
		C: Determine the state of hydrothermal activity of the subsurface ocean.	Relative abundances of noble gases 40/38/36Ar, 4/3He, 20/22Ne, Kr, 128-136Xe via vapor sampling regime Relative concentrations of N, NH_3, HCN via vapor sampling regime	SWAMP (Mass Spectrometer)	mass spectra with >5,000 M/dM sensitivity
			Resolve D/H and 16O/17O/18O isotope ratios from spectra of resolution of $v/\delta v \sim 10^7$	WAVES (Sub-mm)	spectral line strengths of the H216O H217O H218O molecular transitions at 556936.002 MHz, 552020.960 MHz and 547676.440 MHz respectively
	3. How stable is the ocean environment?	A: Determine the extent and thickness of Enceladus' liquid ocean	Longitudinal extent of librations due to 1.37 day and 3.7 year perturbations detected in surface images	DRIPS (Camera)	Images of the limb with <15 m/px spatial resolution
			Conductivity of the subsurface ocean constrained by magnetic field sampling sampling at 1 Hz in 30 orbits at 30 km	OSMOSIS (Magnetometer)	Three component periodic B field with 1.0 nT resolution.
		B: Constrain the radial structure of Enceladus' interior and the magnitude and spatial distribution of tidal dissipation within the ice shell	Moment of inertia, tidal love number, and quality factor derived from Doppler tracking of spacecraft to determine gravity field to degree 4+ in 30 orbits at 30 km	GEISER (Radio Science)	Deviations from nominal orbital path determined to the 10^{-5} m/s resolution
			Determine non-hydrostatic part of gravity field in 30 orbits at 30 km		
		C: Determine the thermal history of the ice shell to constrain the longevity of the subsurface ocean	Radiometric temperature of the near tiger-stripe terrain from radiance temperature maps from 100 km and 30 km	WAVES (Sub-mm)	radiometric measurements of brightness temperature in both mm & sub-mm continuum channels with sensitivity < 1K and resolution 692 & 218 m/pix at 100 km and 208 & 65 m/pix at 30 km
			Measure the relaxation of simple craters in the near-SPT terrain from images over 300 orbits at 30 km	DRIPS (Camera)	topographic map with ~10m vertical resolution and 10 m/px spatial resolution

THEO concept mission (3)

	4. Is there evidence of biological processes?	A: Determine resources available for biological processes, including those necessary for redox	Abundances of C,H,N,O,P,S and shorter chain organics constrained by vapor sampling in 300 orbits at 30 km CH3D abundance constrained by vapor sampling in 300 orbits at 30 km, 30 orbits at 100 km, and 100 orbits at 500 km.	SWAMP (Mass Spectrometer)	mass spectra with 30,000 M/dM sensitivity
		B: Determine whether the isotopic ratio of C is indicative of biological processes	Relative abundances of 12C and 13C by vapor sampling constrained by 300 orbits at 30 km, 30 orbits at 100 km, and 100 orbits at 500 km	SWAMP (Mass Spectrometer)	mass spectra with 30,000 M/dM sensitivity
		C: Distinguish biomarkers present in the plumes and determine their abundances	Abundances of amino acids, lipids, and nucleic acids constrained by sampling over 300 orbits at 30 km		

References

- This presentation is largely based on Chapter 13 of the book "Astrobiology – A Multidisciplinary Approach", by Jonathan I. Lunine, Addison Wesley, 2005

Further reading

- The JUICE assessment study report is freely available at the following URL: http://sci.esa.int/juice/49837-juice-assessment-study-report-yellow-book/