Satellites of the giant planets

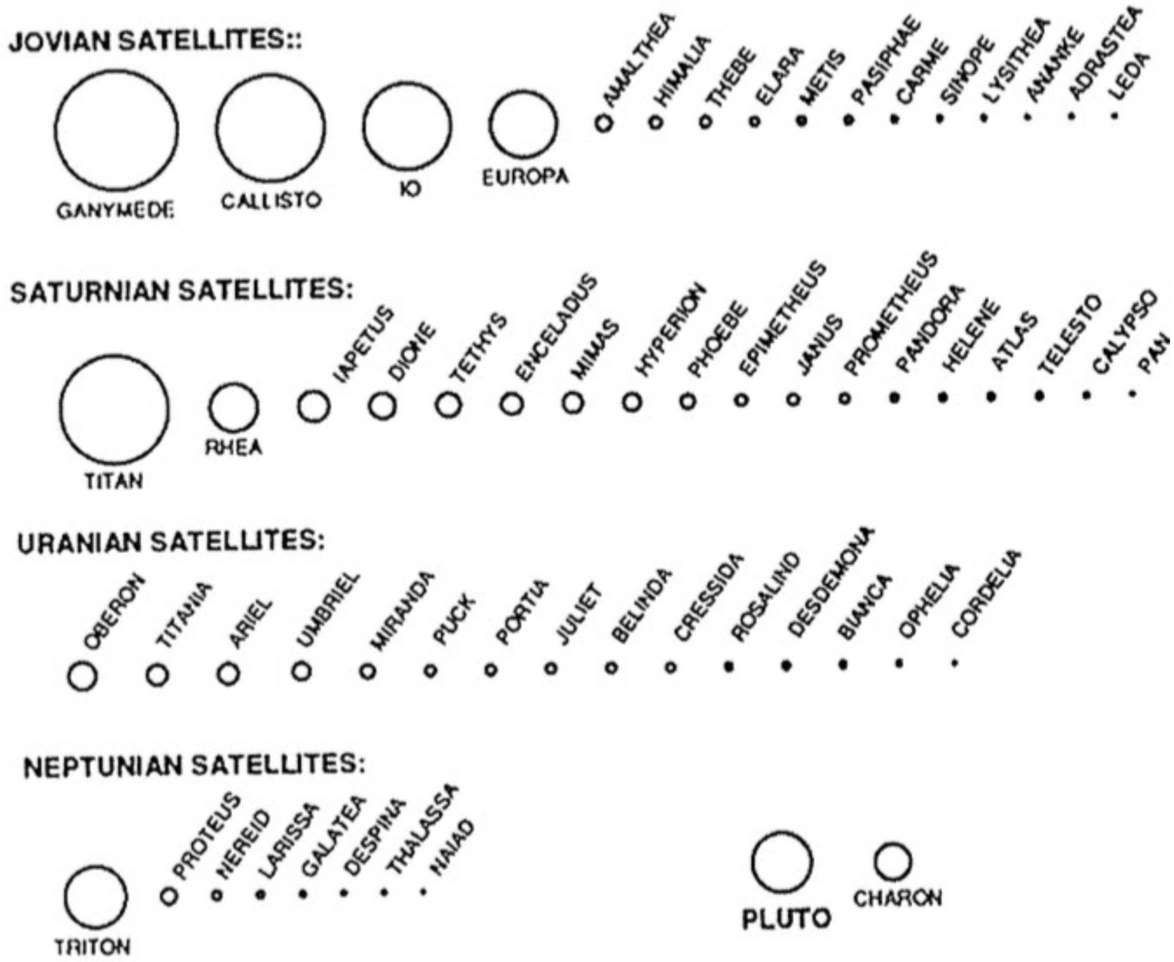
Planets and Astrobiology (2020-2021)

G. Vladilo and S. Ivanovski

Satellites of giant planets

Giant planets have a large number of satellites

The largest ones have sizes comparable to Mercury



Satellites of giant planets

- Regular and irregular satellites
  - Regular satellites:

    The orbits around the planet have low eccentricity and are approximately coplanar with the equatorial plane of the planet
  - The dynamical characteristics of regular satellites suggest a common origin with the planet

  - Irregular satellites:

    Do not share the dynamical properties and are usually found at large distances from the planet
  - These facts suggest an independent origin, probably by gravitational capture, of bodies originated elsewhere

Comparison of Satellite Systems

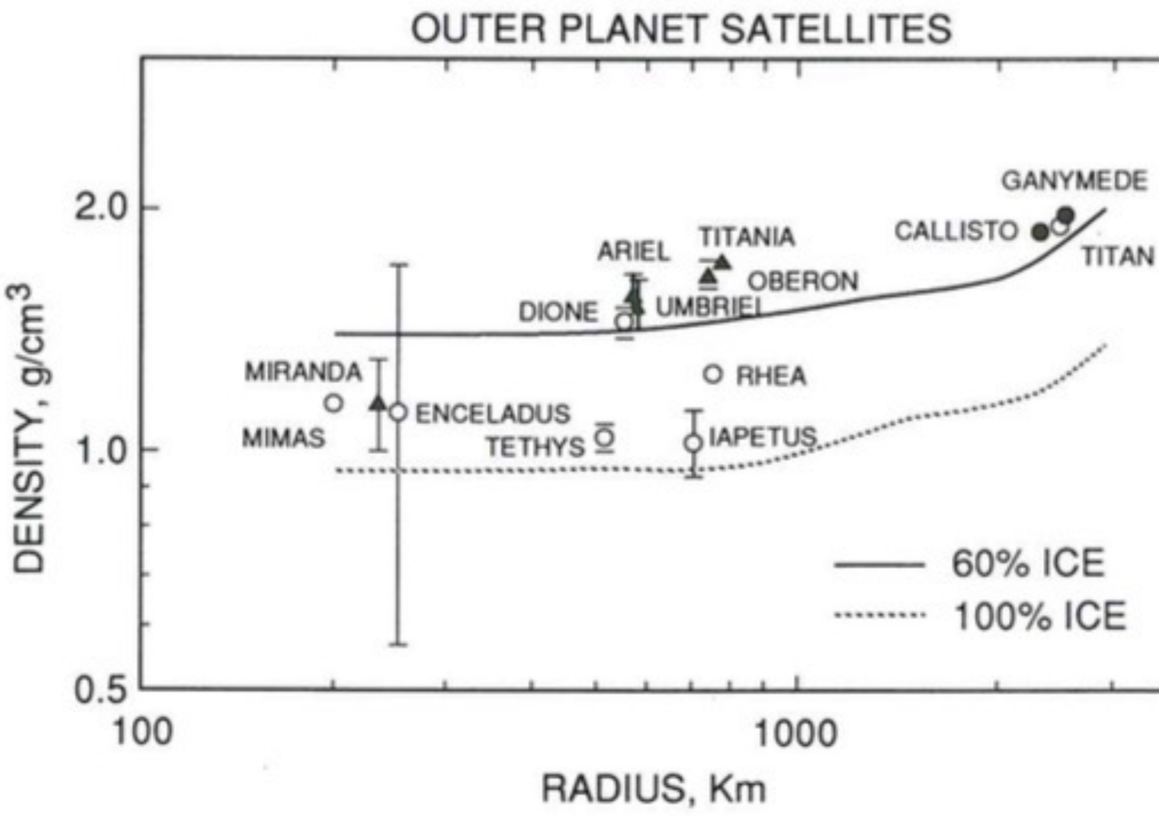
Property[a]	Jupiter	Saturn	Uranus	Neptune
Regular Satellites				
Number	8	17	15	(1)+6
Location (R_p)	1.8–27	2.3–59	2.0–23	1.9–4.7 and (15)
M_{sat}/M_{pl}	2.1×10^{-4}	2.4×10^{-4}	1.1×10^{-4}	2.9×10^{-4}
J_{sat}/J_{pl}	6.5×10^{-3}	6.6×10^{-3}	6.5×10^{-3}	2.1×10^{-2}
Irregular Satellites				
Number	8	1	0	1
Location (R_{pl})	156–333	216		227
Rings				
Location (R_{pl})	1.3–1.8	1.1–8[b]	1.6–2	1.7–2.5
M_{ring}/M_{pl}		6×10^{-8}	6×10^{-11}	
Max τ	5×10^{-5}	>1.5	>1.5	

[a] The symbols R, M and J refer to radius, mass and angular momentum, respectively; subscripts sat, pl, and ring refer to satellite, planet and rings, respectively; and max τ is the maximum value of the normal optical depth at visible wavelengths.

[b] The major rings of Saturn, the A, B and C rings, are located between 1.2 and 2.3 R_{pl}.

Density and radius of outer satellites

Consistent with the existence of a large fraction of ice



Regular satellites of giant planets

- Main regular satellites of giant planets

  Here we discuss only some of them, those that are important from the astrobiological point of view

  - Jupiter

    Io, Europa, Ganymede, Callisto, Amaltea
  - Saturn

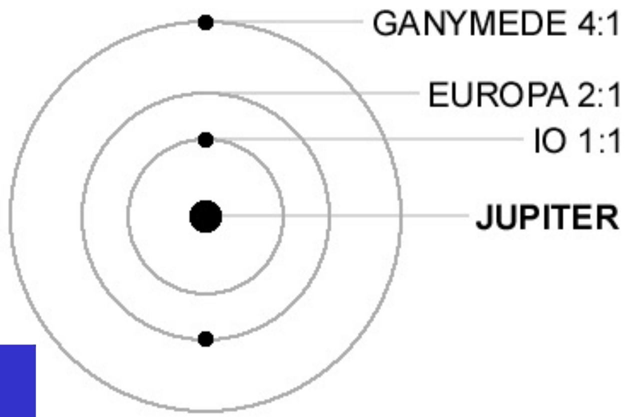
    Mimas, Enceladus, Tethys, Dione, Rhea, Titan, Hyperion
  - Uran

    Ariel, Umbriel, Titania, Oberon
  - Neptun

    Triton, Nereid, Proteus

Jupiter's satellites

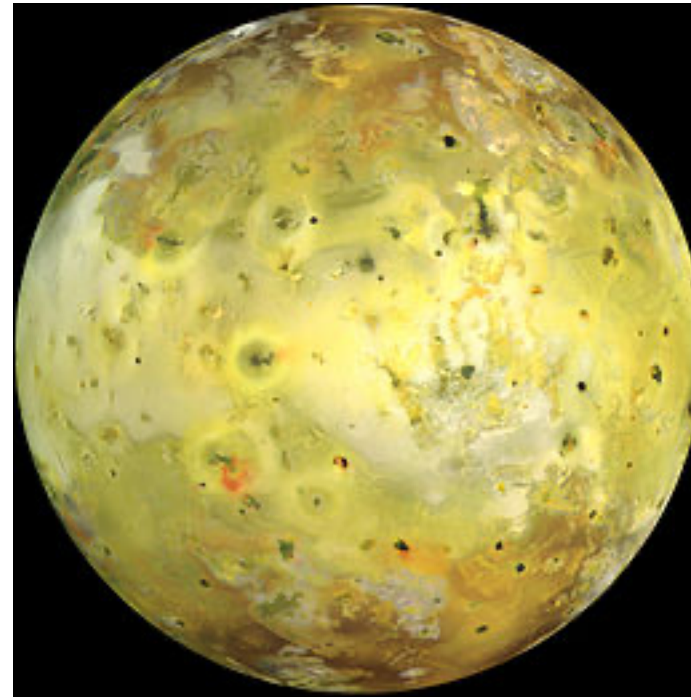
- The four Galileian satellites are the most prominent ones
  - Discovered by Galileo in 1610
  - Extremely regular
  - The orbital periods are locked by tidal forces and resonances
- Observed with space probes
  - Particularly, *Voyager* and *Galileo*



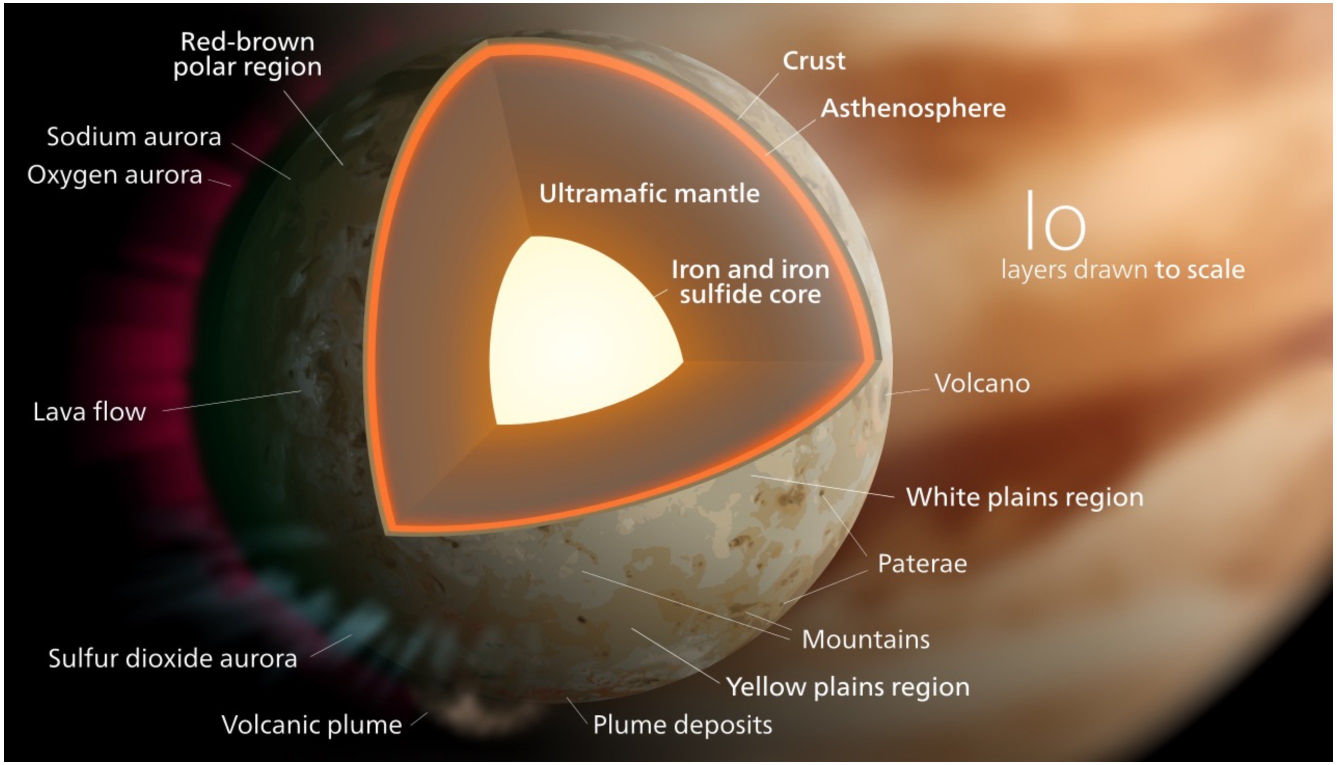
Name	M [g]	R [km]	e	i [º]
Io	8.9×10^{25}	1820	0.004	0.04
Europa	4.8×10^{25}	1565	0.009	0.47
Ganymede	1.5×10^{26}	2634	0.002	0.21
Callistus	1.1×10^{26}	2403	0.007	0.51

Io

- The surface is characterized by a very intensive volcanic activity
  - The activity shows signatures of variability
  - The activity is induced by the tidal and magnetic interactions with Jupiter
  - Whitish and yellowish surface areas: volcanically deposited sulphur dioxide frost
- Surface temperature
  - T ~ 90 K – 130 K



- Io's mean density and interior
  - The mean density, 3.5 g/cm^3 , is the highest of any moon in the Solar System
  - Composed primarily of silicate rock and iron, closer in bulk composition to the terrestrial planets than to other satellites in the outer Solar System
  - The volatile compounds (such as H_2O and CO_2) have been probably lost due to continuous recycling of internal material to the surface
  - The interior is believed to be melted and differentiated

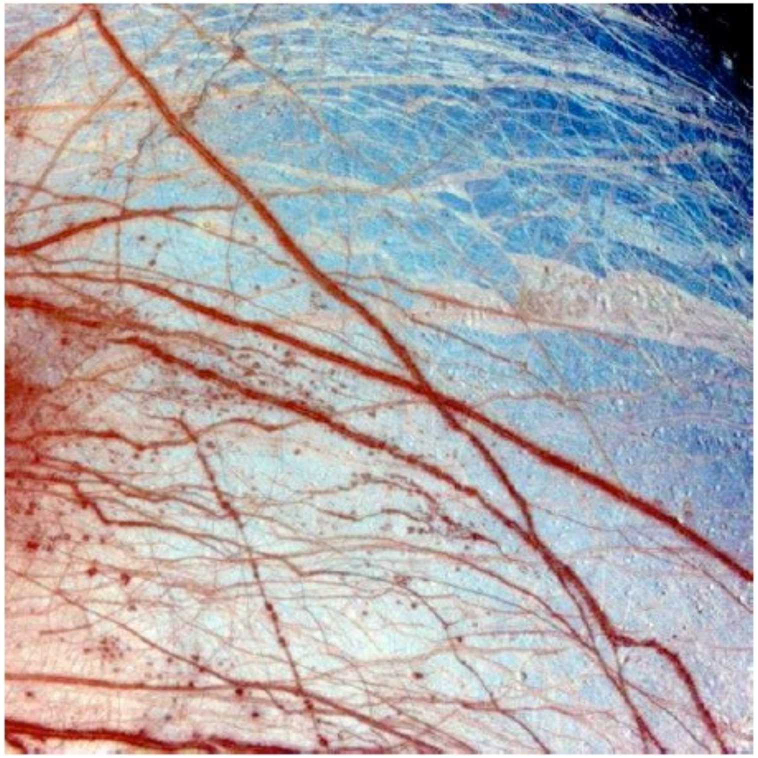


Europa

A. Coradini (2010)

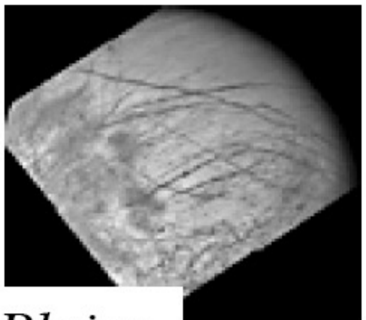
- The surface is composed of H_2O ice
  - The gravimetric measurements indicate that the thickness of the ice layer might be of some tens of kilometeres

    The surface ice is "contaminated" by coloured compounds, probably salts that may have an endogenous origin
- Extremely rarified atmosphere
  - Composed mostly of O_2
  - Surface pressure: 0.1 μPa

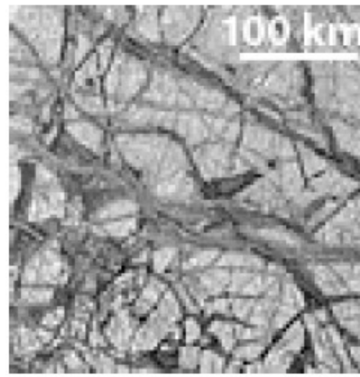


Europa

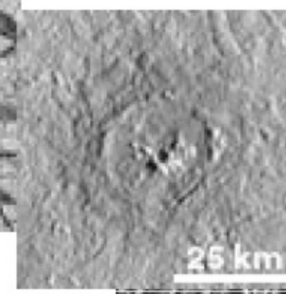
A variety of structures are visible on the surface, suggesting the presence of a remarkable activity



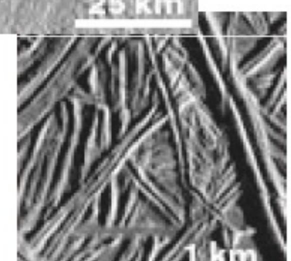
Plains



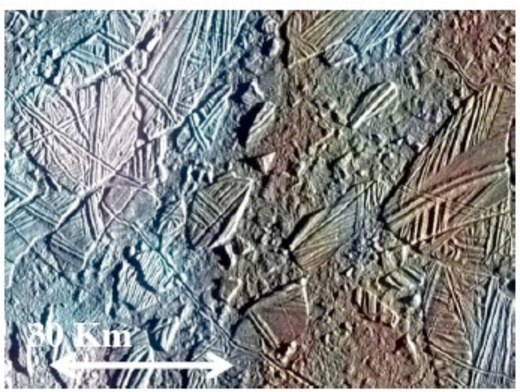
Bands



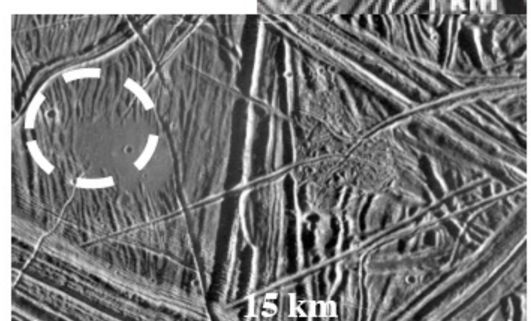
Craters



Ridges



Chaos →The Conamara region



Volcanism

A liquid water ocean below the surface of Europa

- Experimental evidence (1)
  - Magnetometric measurements indicate the presence in the interior of a compound with conductivity typical of a salty ocean
  - The experimental data are better fitted by $MgSO_4$ salt, rather than NaCl
  - Europa’s magnetic field is induced by Jupiter’s field (there is no intrinsic dynamo)

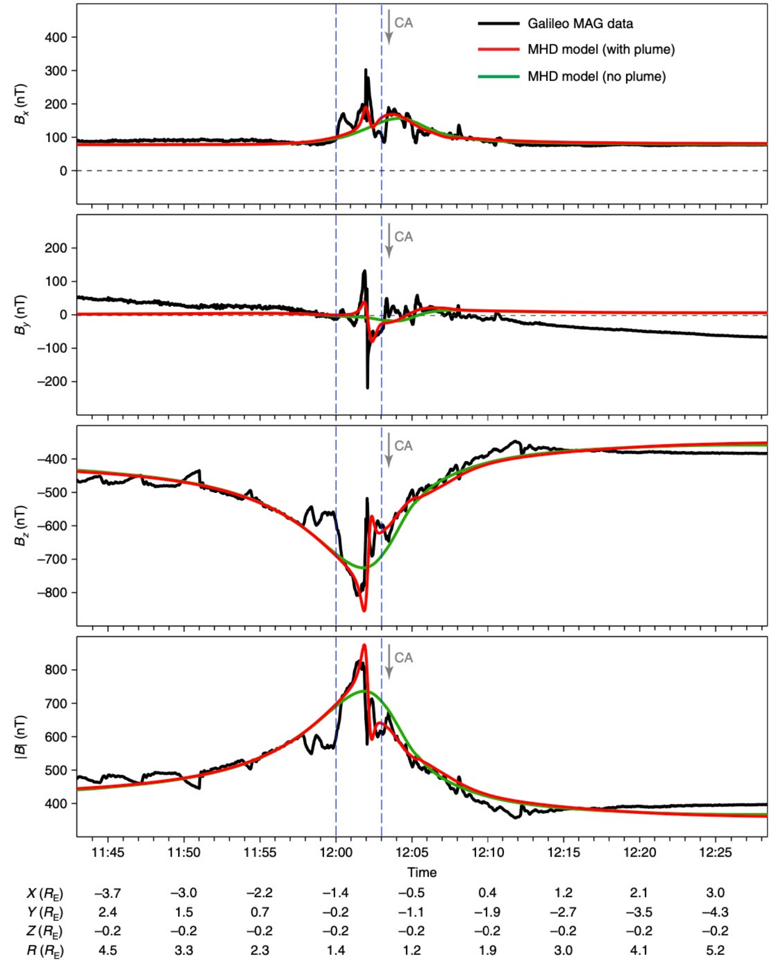


Fig. 1 | Galileo MAG data for the E12 flyby. Black lines show the MAG data. Green and red lines, respectively, show traces extracted from the MHD simulations without and with a plume included. Results are presented in EphiO coordinates, with *x* parallel to Europa’s orbital velocity, *y* directed towards Jupiter and *z* completing the right-handed system. The interval of anomalous changes (~12:00 to 12:03 UT) is bounded by vertical dashed lines, and closest approach is marked by ‘CA’ and a grey arrow. In the range used for these measurements, the MAG sensor digitization step[8] was 0.25 nT. Between 11:55 and 12:05 UT, one or another of the 3 sensors saturated at the spacecraft rotation period. This required special processing, which increased the uncertainty to a level of a few nT. *X*, *Y*, *Z* and *R* given at the bottom of the figure indicate the spacecraft location and its radial distance from Europa’s centre in units of R_E in EphiO coordinates.

Jia et al. (2018)

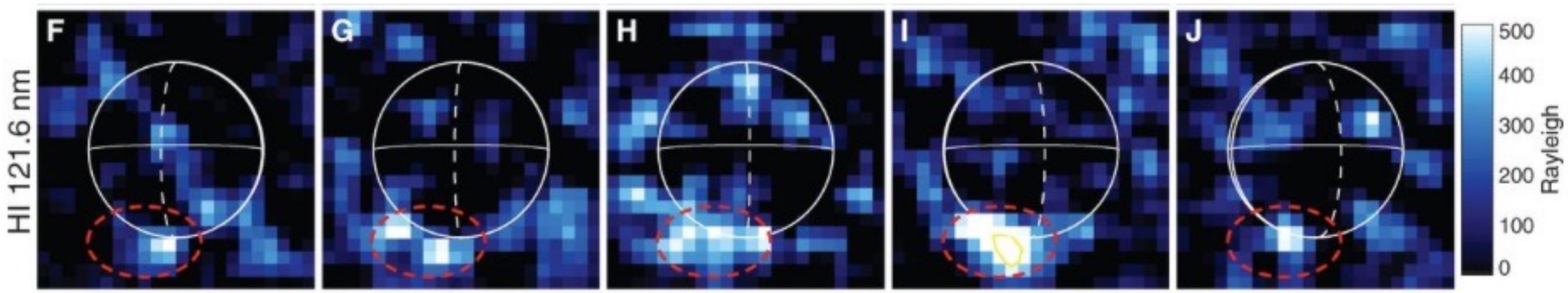
A liquid water ocean below the surface of Europa

- Observational evidence (tentative)
  - Water vapour jets from the surface

    Detected from the analysis of HST ultraviolet data after subtraction of the disk reflectance

    Roth et al. 2014, Science

    The jets show evidence of variability with the orbital period

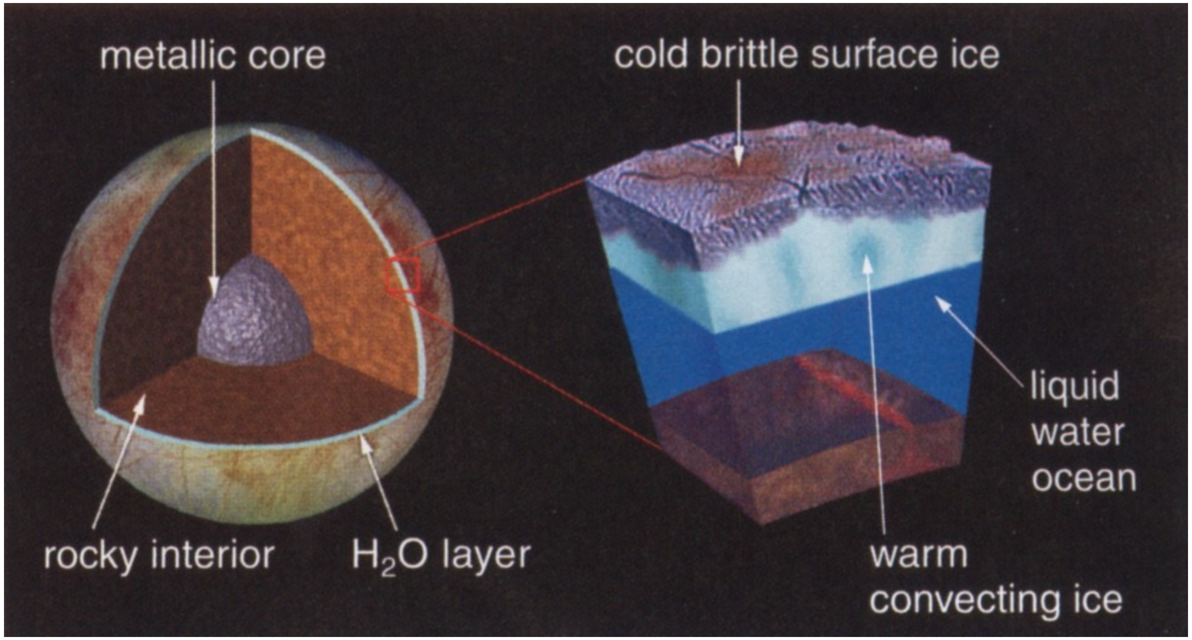


A liquid water ocean below the surface of Europa

- The water ocean is expected to be present below the surface ice, given a suitable heating mechanism in the interior of Europa
- The example of Io indicates that tidal heating may provide internal heating
- Jupiter may keep Europa's oceans warm by generating large planetary tidal waves on Europa because of its small but non-zero obliquity. This generates so-called Rossby waves that travel quite slowly, at just a few kilometers per day, but can generate significant kinetic energy
- Dissipation of this kinetic energy could be the principal heat source of Europa's ocean
- To help water to be in liquid phase, other volatile compounds with lower melting point, such as NH_3, may be interdispersed in the water

Europa's interior

- Mean density
  - Mean density: 3.0 g/cm^3
- Internal structure
  - The water layers (ice plus ocean) are relatively thin compared to the radius of the satellite
  - The internal structure is believed to feature a metallic core surrounded by a rocky mantle



Ganymede

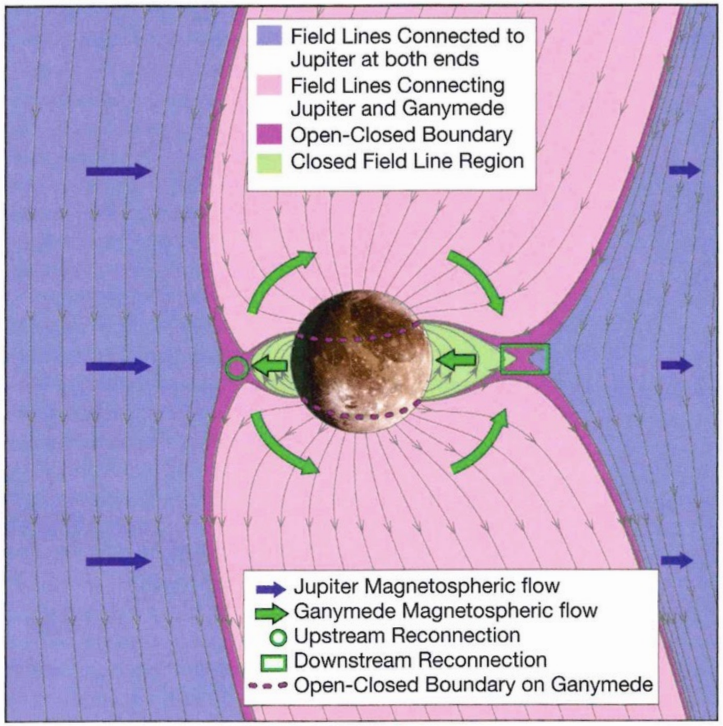
- Surface characteristics
  - Water ice seems to be ubiquitous on the surface, with a mass fraction of 50–90%
  - Two main types of terrain:

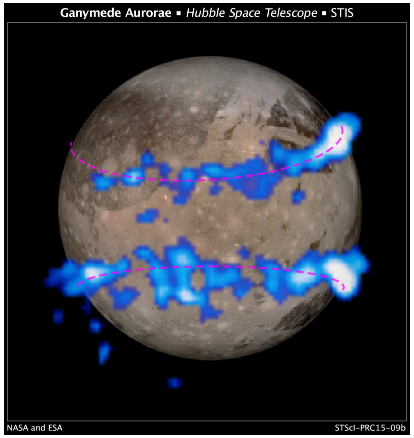
    dark regions, saturated with impact craters and dated to four billion years ago, cover about a third of the satellite

    lighter regions, crosscut by extensive grooves and ridges and slightly less ancient, cover the remainder two thirds
  - The heating mechanism required for the formation of the grooved terrain is an unsolved problem
  - Possibly the grooved terrain is due to tectonic processes

Ganymede

- Magnetic field
  - Ganymede is the only satellite with *endogenous* magnetic field suggestive of an internal dynamo mechanism (Europa and Callisto have *induced* magnetic fields)
  - The magnetic field of Ganymede interacts with Jupiter's magnetic field
  - The magnetometric measurements indicate the presence of a liquid and conductive internal layer
  - A liquid Fe core could be responsible for the magnetic field

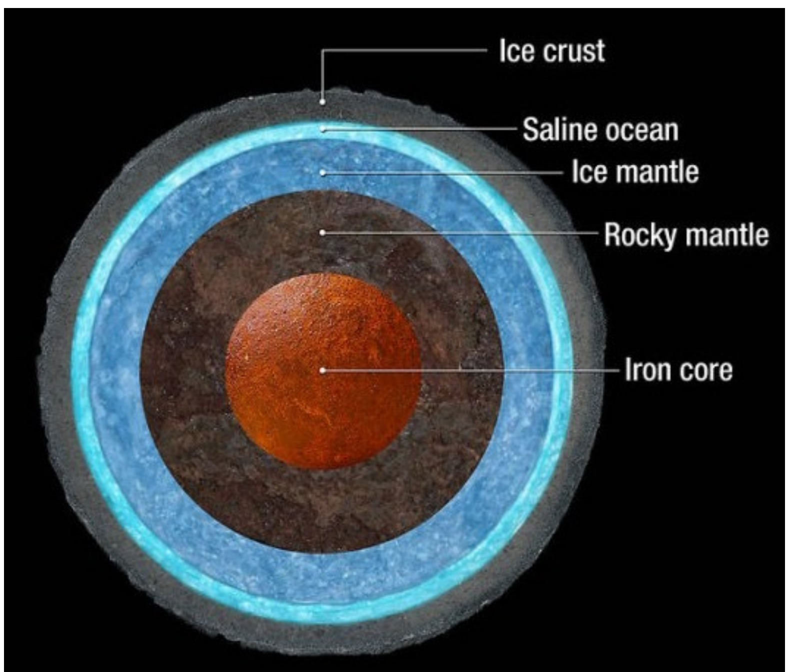


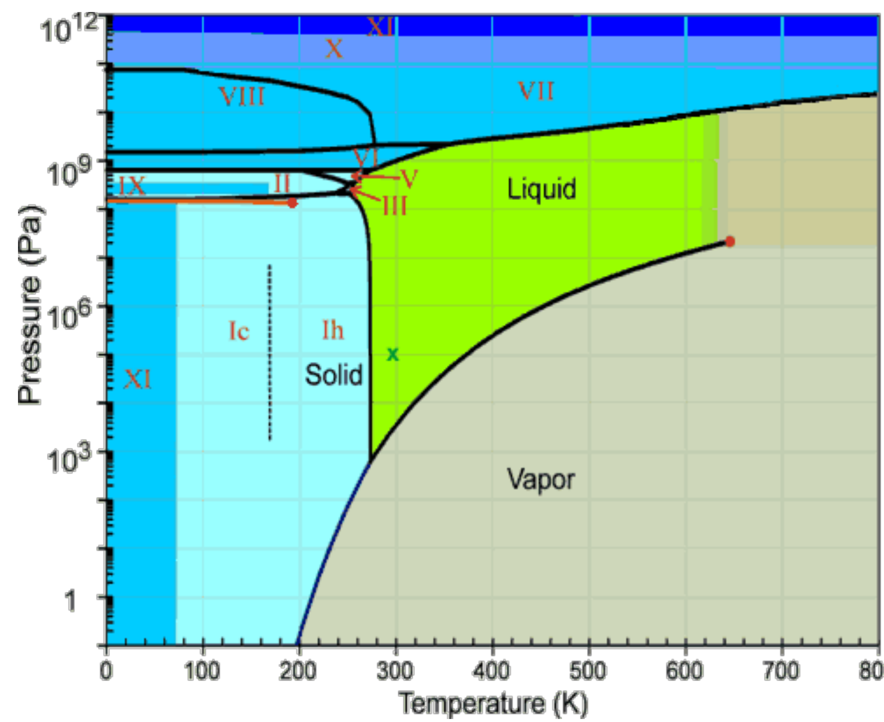


NASA HST images of Ganymede's auroral belts (colored blue in this illustration) lie on top of a Galileo orbiter image of the moon. The amount of rocking of the moon's magnetic field supplied evidence that the moon possesses a subsurface saltwater ocean. Image released March 12, 2015. (Image credit: NASA/ESA)

Ganymede

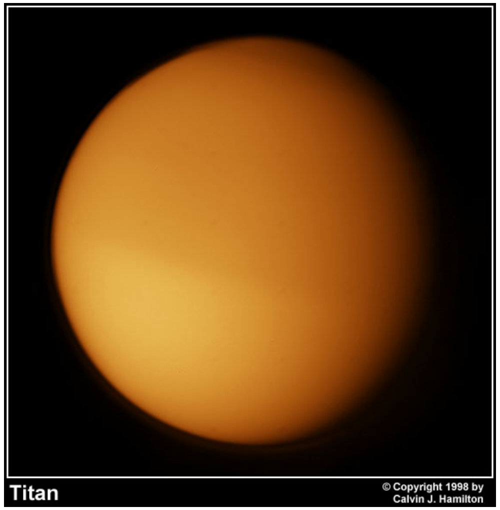
- Interior
  - Density, gravity and magnetometric data suggest the presence of a liquid Fe core
  - The Fe core is surrounded by a rocky mantle
  - Interior models suggest that an internal ocean of liquid water may exist, sandwiched between the surface layer of Ice-I and the higher pressure phases of ice below





Saturn satellites:
Titan

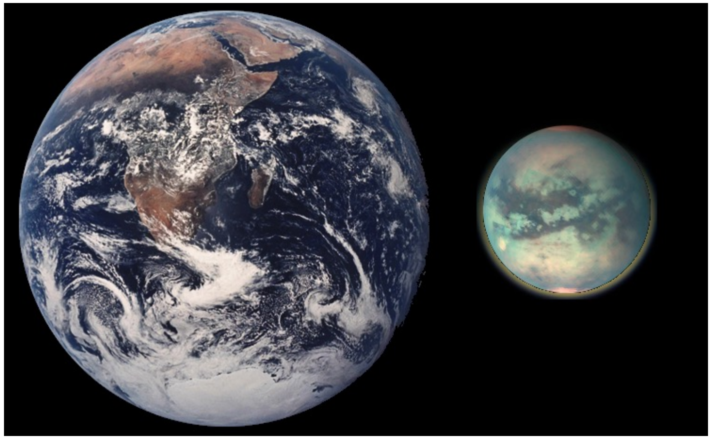
Voyager image of Titan in the optical band



Largest among Saturn's regular satellites

- Only Solar System satellite with a thick atmosphere
  - Surface pressure larger than on Earth: P=1.5 bar
- Factors that contribute to the existence of a thick atmosphere
  - Not too low escape velocity (v_{esc}=2.65 km/s)
  - Sufficiently low surface temperature (T= ~94 K)

    This temperature is sufficiently high to avoid solidification of the volatiles that are present in the atmosphere



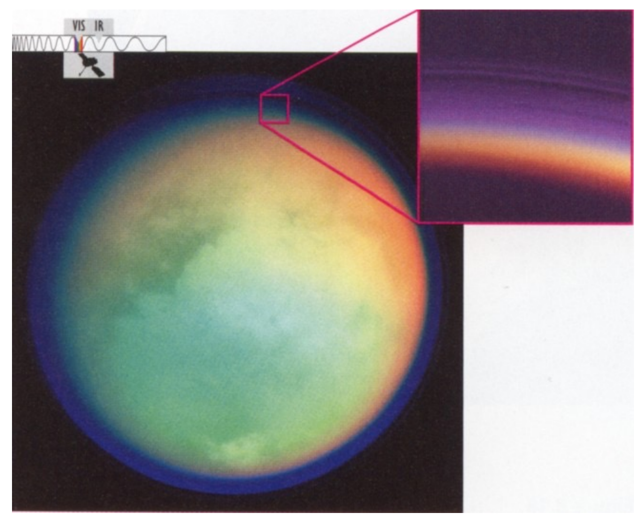
- Chemical composition of Titan's atmosphere
  - Main constituent: N_2, as on Earth

    However, O_2 is not present
  - Rich of hydrocarbons, mainly methane CH_4, but also ethane C_2H_6
  - The atmosphere is surrounded by a brownish-reddish haze
  - The haze is composed of "tholins":

    Nitrogen-rich organic molecules produced by the photo-dissociation of CH_4

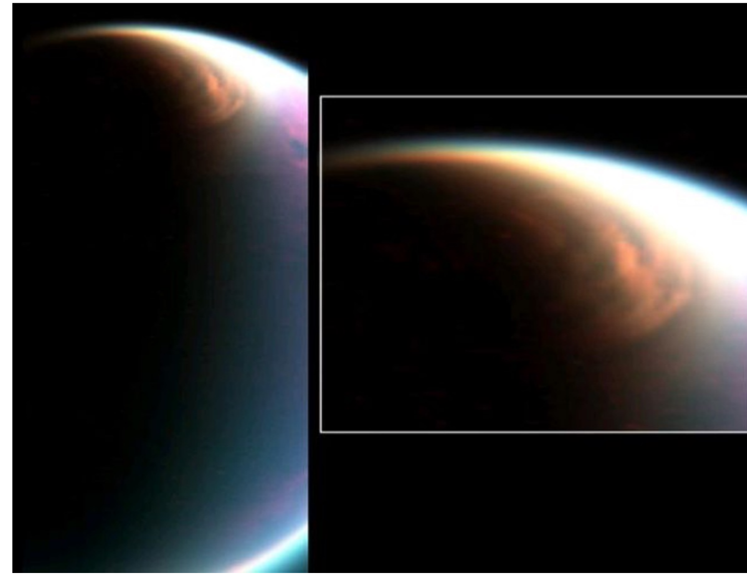
	Titan	Earth
N_2	82-99 %	78%
CH_4	2-10 %	2 ppm
O_2	-	21%
CO_2	0.01 ppm	350 ppm
Ar	< 1-6 % ?	0.9%

False color image obtained by *Cassini*, evidentiating the haze layer



- Surface
  - Lakes of methane CH_4 and ethane C_2H_6 discovered by the lander *Huygens*

- Possible hydrological cycle
  - Methane evaporates and forms clouds, which occasionally causes methane rain.
  - Clouds of methane ice and cyanide gas float over the moon's surface.
- Surface
  - Sand dunes of hydrocarbon found in large areas of Titan's surface.
- Astrobiology
  - "The same kind of light that drives biological chemistry on Earth's surface could also drive chemistry on Titan, even though Titan receives far less light from the Sun and is much colder." M. Gudipati



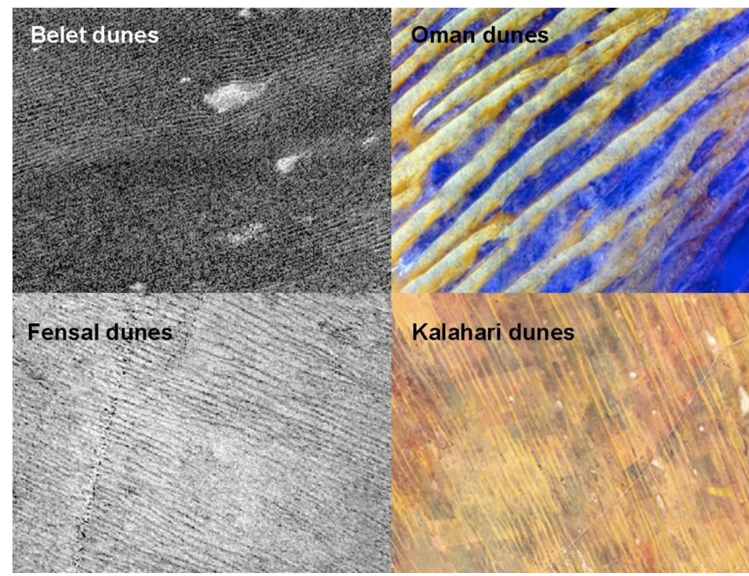
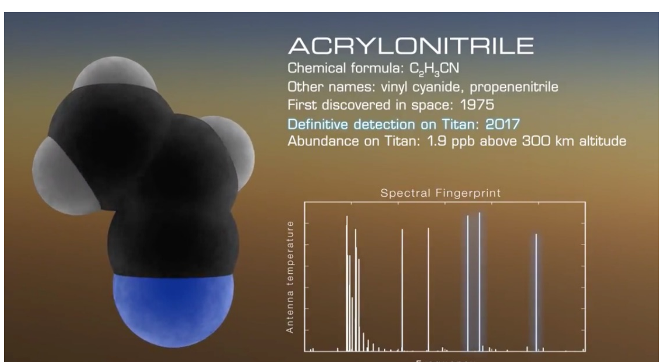
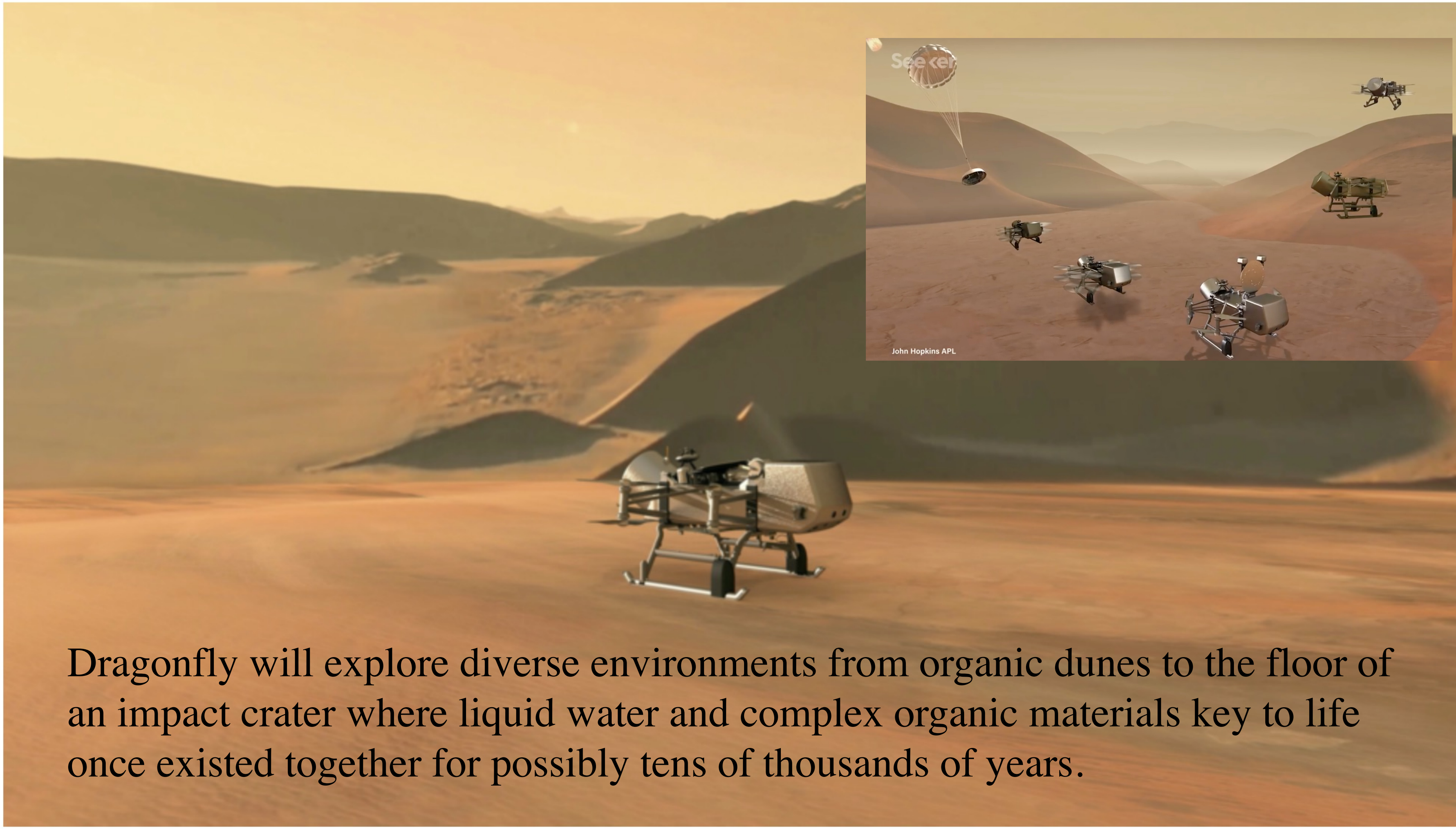


Image: © NASA/JPL-Caltech; NASA/GSFC/METI/ERSDAC/JAROS and U.S./Japan ASTER Science Team



NASA Dragonfly will arrive at Titan in 2034

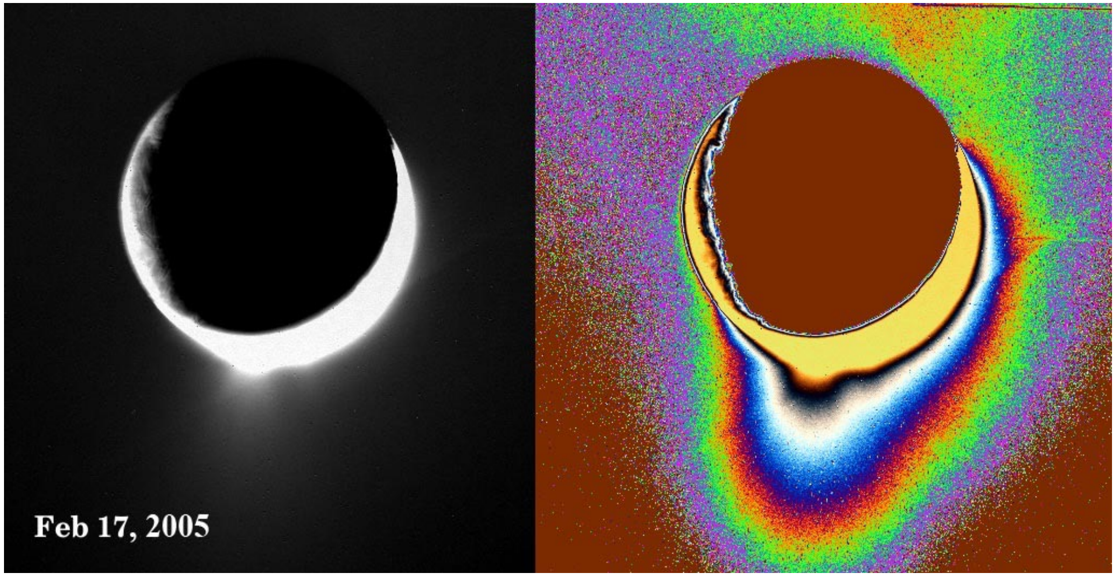


This illustration shows NASA's Dragonfly rotorcraft-lander approaching a site on Saturn's exotic moon, Titan. Taking advantage of Titan's dense atmosphere and low gravity, Dragonfly will explore dozens of locations across the icy world, sampling and measuring the compositions of Titan's organic surface materials to characterize the habitability of Titan's environment and investigate the progression of prebiotic chemistry.

Credits: NASA/JHU-APL

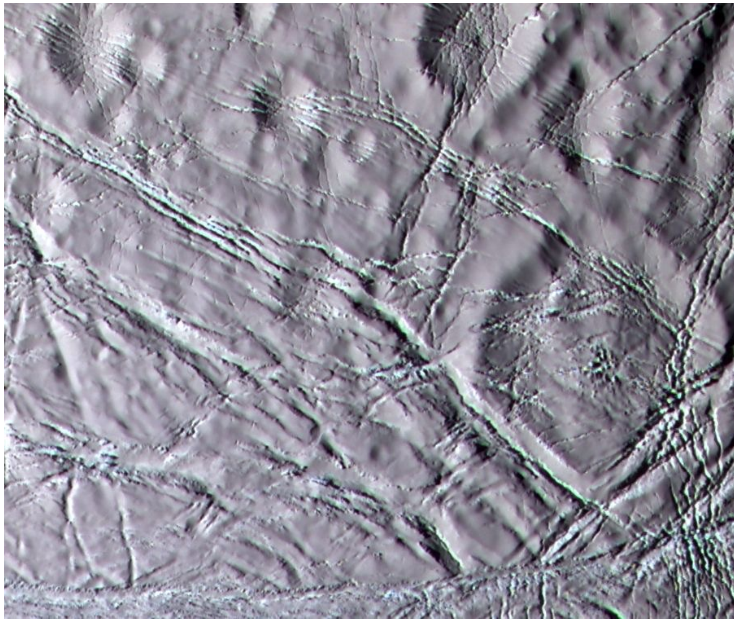
Enceladus

- Small satellite of Saturn
  - Jets of ice particles and water vapour have been found in the South pole of this satellite
    - The jets suggest the presence of a geothermic energy source
    - The water vapour in the jets exhibits simple organic compounds
      - McKay et al. (2008, AsBio, 8, 909)

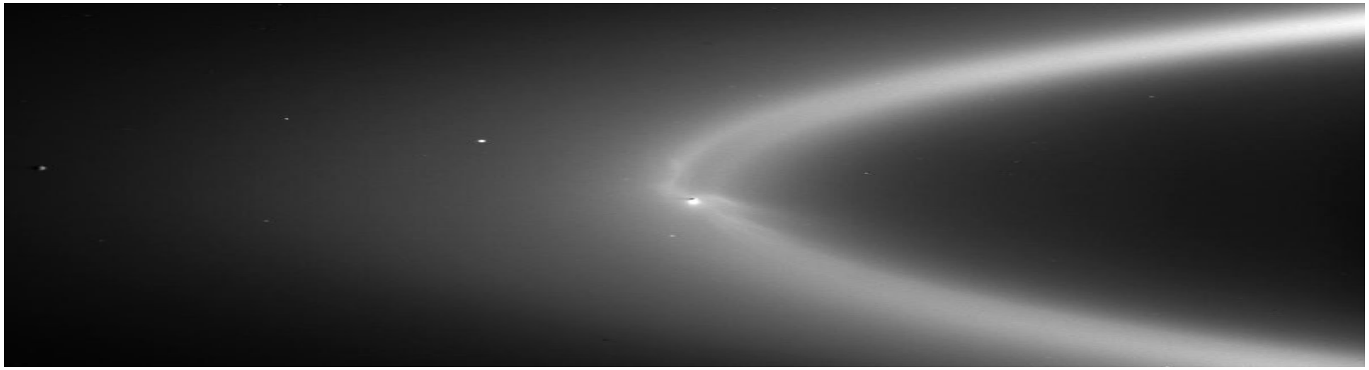


Enceladus

- Surface
  - Cracks in the surface, known as ‘tiger stripes’, which periodically vented materials into space
  - The icy jets contributes to Saturn’s massive E-ring, the largest planetary ring in the solar system (over a million kilometres)



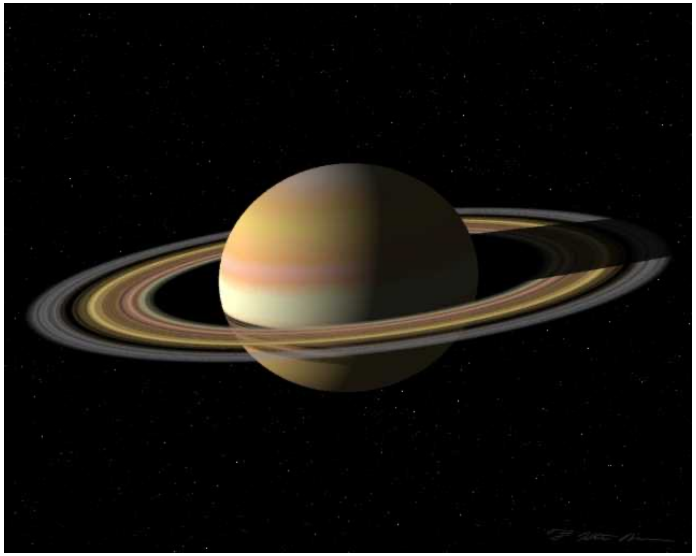
Cassini color image of "snowy" landscape of Enceladus. This terrain lies north of the geologically active south polar ridges and features a rolling terrain crosscut by narrow fractures. (Image credit: NASA/Processing by Paul Schenk (Lunar and Planetary Institute, Houston))(www.space.com)



Rings of giant planets

- All giant planets of the Solar System have ring systems
  - Thin, complex structures that differ from planet to planet
  - Composed of solid debris with sizes ranging from a fraction of micron (dust) up to meter-size boulders
  - Interesting as a laboratory of physics

    A variety of dynamical processes are required to explain their characteristics, including resonances with satellites and limits of disruption of astronomical bodies under a gravitational field



Roche limit

Distance within which a celestial body, held together only by its own gravity, will disintegrate due to a second celestial body's tidal forces

The Roche limit is obtained by equating gravitational and tidal forces inside the body

$$F_G = F_T$$

From this equality one obtains an expression of the type:

$$d_{Roche} \sim 2.44\, R_M\, (\varrho_M/\varrho_m)^{1/3}$$

R_M: radius of the main body

ϱ_M , ϱ_m: mean density of the main and minor bodies, respectively

The value of the constant (2.44) depends on the assumptions used to derive the above equation

Ring-moon systems of the giant planets scaled to a common planetary radius (solid central circle)

Dotted line:

Roche radius for a satellite density 0.9 g/cm^3