Habitability potential of icy moons around Jupiter and Saturn

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Organics, deep oceans within the giant icy moons and more: implications for the habitability of the Outer Solar System

**Context**
- What is habitability
- Previous missions to the OP

**Jovian system**
- Ganymede and Europa
- JUICE

**Saturnian system**
- Titan and Enceladus
- Cassini and the future
Habitability: four requirements

- Water
- Essential elements (CHNOPS...)
- Chemical energy
- Stable environment
What are the habitable worlds?

Evolutionary time line

Water-rich bodies at the beginning

Class. I

Classical habitable zone

Earth-like

Habitats suitable for the evolution of higher life forms on the surface

Class. II

Inner and outer edge of the habitable zone or habitable zones of low mass stars

Venus-like

Microbial life may have evolved and habitats in subsurface, ice/H_2O, may have remained

Mars-like

Class. III

Beyond the ice-line

Europa-like

Life forms may have evolved and populate subsurface H_2O oceans

Class. IV

Bodies with subsurface oceans or oceans with no contact to silicate-rich sea floors

Migrating “super-Ganymeds”, hot ice giants, “Ocean planets”

If life evolves it will only populate oceans

Lammer et al., 2009
Classes I-II: habitable zones on the surface, not much water, small domain
Beyond the snow-line: deep habitats within the hydrospheres. Icy moons, Ganymede and Europa and Titan and Enceladus, are the archetypes of classes III-IV of habitable worlds
<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Ganymede</th>
<th>Titan</th>
<th>Enceladus</th>
<th>Triton</th>
<th>Pluto</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{\text{planet}}$</td>
<td>14.99 $R_j$</td>
<td>20.25 $R_S$</td>
<td>3.95 $R_S$</td>
<td>14.33 $R_N$</td>
<td>[39.53 AU]</td>
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<tr>
<td>$M$ $[10^{22} \text{ kg}]$</td>
<td>14.82</td>
<td>13.5</td>
<td>0.011</td>
<td>2.14</td>
<td>1.31</td>
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<tr>
<td>$R_e$ [km]</td>
<td>2631</td>
<td>2575</td>
<td>252</td>
<td>1352</td>
<td>1150</td>
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<td>$\rho$ $[\text{kg/m}^3]$</td>
<td>1936</td>
<td>1880</td>
<td>1608</td>
<td>2064</td>
<td>2030</td>
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<td>$g$ [m/s$^2$]</td>
<td>1.43</td>
<td>1.35</td>
<td>0.12</td>
<td>0.78</td>
<td>0.4</td>
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<tr>
<td>$T_O$ [days]</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>[248.5 yr]</td>
</tr>
<tr>
<td>$T_S$ [days]</td>
<td>7.16</td>
<td>15.95</td>
<td>1.37</td>
<td>5.877</td>
<td>[6.38]</td>
</tr>
<tr>
<td>i [deg]</td>
<td>0.18</td>
<td>0.33</td>
<td>0.02</td>
<td>157</td>
<td>17.14</td>
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<tr>
<td>e</td>
<td>0.001</td>
<td>0.029</td>
<td>0.005</td>
<td>0.000</td>
<td>0.25</td>
</tr>
<tr>
<td>A</td>
<td>0.4</td>
<td>0.2</td>
<td>1.4</td>
<td>0.4</td>
<td>0.52</td>
</tr>
<tr>
<td>$v_e$ [km/s]</td>
<td>2.75</td>
<td>2.64</td>
<td>0.235 ($&lt;v_T!$)</td>
<td>1.50</td>
<td>1.1</td>
</tr>
<tr>
<td>Surface T [K] P</td>
<td>110</td>
<td>94</td>
<td>114-157</td>
<td>38</td>
<td>40</td>
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<tr>
<td></td>
<td>X</td>
<td>1.5 bar</td>
<td></td>
<td>16 $\mu$b</td>
<td>58 $\mu$b (var)</td>
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<tr>
<td>Atmosphere</td>
<td>$O_3$, $(H_2O_2-i)$</td>
<td>$N_2$, $CH_4$</td>
<td>$H_2O$, $N_2$, $CH_4$, $CO_2$, $CO$</td>
<td>$N_2$, $CH_4$</td>
<td>$N_2$, $CH_4$, $(H_2O-i)$</td>
</tr>
</tbody>
</table>
Some interesting considerations for astrobiology

Astrobiological aspects: organic chemistry, liquid water (on the surface or in the interior), sources of energy (internal activity), stability

Icy moons with
- organic chemistry: Titan, Enceladus, Triton
- with subsurface liquid water oceans (TBC): Europa, Ganymede, Callisto, Enceladus, Titan…
- evident (cryovolcanic or tectonic) activity (Enceladus, Triton, Io, Titan?)

With the exception of Titan the icy moons with possible subsurface oceans and/or activity reside in giant planet magnetospheres, Enceladus and Triton, are not in the giant planet magnetosphere section with the most extreme surface irradiation harmful to organics.

What is the astrobiological potential of these objects?
Jupiter’s satellites
Previous missions

A few flybys and an orbiter (Galileo)
Present mission (cruise phase) - JUNO

JUNO science goals: Understand the formation, evolution and structure of Jupiter
The habitable zone around Jupiter

Three large icy moons

**Ganymede - class IV**
- Largest satellite in the solar system
- A deep ocean
- Internal dynamo and an induced magnetic field – unique
- Richest crater morphologies
- Archetype of waterworlds
- 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
The closer a moon is to Jupiter, the hotter its interior and better chance of differentiation, while the surface is subject to dynamic movements.
Hyperspectral evidences on Europa

Composition of ices

from McCord et al. (1999)
What are the habitable worlds in the outer solar system?

Class III: subsurface oceans in contact with silicates - Europa

Europa-like

- Water:
  - Warm salty $\text{H}_2\text{O}$ ocean.
- Essential elements:
  - Accretion of $\text{CO}_2$?
  - Impactors.
  - But radiation destroys organics in the upper ~10s cm of ice.
- Chemical energy:
  - Radiation of $\text{H}_2\text{O} \Rightarrow$ oxidants.
  - Mantle contact: serpentinization and possible hydrothermal activity.
- Relatively stable environment:
  - Large satellite retains heat.
  - But activity might not be steady-state.
What are the habitable worlds?

Class IV: subsurface oceans without any contact with the silicates

**Ganymede-like**

- Liquid water
- Chemistry: silicate needed...
- Energy: heat transfer?
- Stable environment

$H_2O$ Well-known since 1912 (Bridgman)
Modern experiments (for planetology) devoted to complex mixtures.
JUICE: JUpiter Icy moons Explorer

JUICE Science Goals
- Emergence of habitable worlds around gas giants
- Jupiter system as an archetype for gas giants

Cosmic Vision Themes
- What are the conditions for planetary formation and emergence of life?
- How does the Solar System work?

JUICE: the 1st Large CV mission concept
- Single spacecraft mission to the Jovian system
- Investigations from orbit and flyby trajectories
- Synergistic and multi-disciplinary payload
- European mission with international participation
Jupiter system: largest planet, largest storm, fastest rotation, largest magnetic field, largest moon, largest moon system, most active moons
Main features of the spacecraft design

- **Dry mass** ~2000 kg, **propellant mass** ~3000 kg
- **Launcher** - Ariane 5 ECA (mass : 5-5.5 tons), High Δv required: 2600 m/s
- **Payload** ~110 kg, ~ 150 W
- **3-axis stabilized s/c**
- **Power**: solar array ~ 100 m², ~ 800 W
- **HGA**: ~3 m, fixed to body, X & Ka-band
- **Data return** >1.4 Gb per day
## JUICE Payload

<table>
<thead>
<tr>
<th>Acronym</th>
<th>PI</th>
<th>LFA</th>
<th>Instrument type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Remote Sensing Suite</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JANUS</td>
<td>P. Palumbo</td>
<td>Italy</td>
<td>Narrow Angle Camera</td>
</tr>
<tr>
<td>MAJIS</td>
<td>Y. Langevin</td>
<td>France</td>
<td>Vis-near-IR imaging spectrometer</td>
</tr>
<tr>
<td></td>
<td>G. Piccioni</td>
<td>Italy</td>
<td></td>
</tr>
<tr>
<td>UVS</td>
<td>R. Gladstone</td>
<td>USA</td>
<td>UV spectrograph</td>
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<td>SWI</td>
<td>P. Hartogh</td>
<td>Germany</td>
<td>Sub-mm wave instrument</td>
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<td><strong>Geophysical Experiments</strong></td>
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<td>GALA</td>
<td>H. Hussmann</td>
<td>Germany</td>
<td>Laser Altimeter</td>
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<tr>
<td>RIME</td>
<td>L. Bruzzone</td>
<td>Italy</td>
<td>Ice Penetrating Radar</td>
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<td>L. Iess</td>
<td>Italy</td>
<td>Radio science experiment</td>
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<td>PRIDE</td>
<td>L. Gurvits</td>
<td>Netherlands</td>
<td>VLBI experiment</td>
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<td><strong>Particles and Fields Investigations</strong></td>
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<td></td>
<td></td>
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<tr>
<td>PEP</td>
<td>S. Barabash</td>
<td>Sweden</td>
<td>Plasma Environmental Package</td>
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<tr>
<td>RPWI</td>
<td>J.-E. Wahlund</td>
<td>Sweden</td>
<td>Radio &amp; plasma Wave Instrument</td>
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<tr>
<td>J-MAG</td>
<td>M. Dougherty</td>
<td>UK</td>
<td>Magnetometer</td>
</tr>
<tr>
<td>Spacecraft Design</td>
<td>Model instruments</td>
<td>Mission phases</td>
<td></td>
</tr>
<tr>
<td>-------------------</td>
<td>-------------------</td>
<td>----------------</td>
<td></td>
</tr>
<tr>
<td>Launch</td>
<td>June 2022</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interplanetary transfer (Earth-Venus-Earth-Earth)</td>
<td>7.6 years (8 years)</td>
<td></td>
<td></td>
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<tr>
<td>Jupiter orbit insertion and apocentre reduction with Ganymede gravity assists</td>
<td>11 months</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Europa flybys</td>
<td>36 days</td>
<td></td>
<td></td>
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<tr>
<td>Reduction of $v_{inf}$ (Ganymede, Callisto)</td>
<td>60 days</td>
<td></td>
<td></td>
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<tr>
<td>Increase inclination with 10 Callisto gravity assists</td>
<td>200 days</td>
<td></td>
<td></td>
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<tr>
<td><strong>Callisto to Ganymede</strong></td>
<td><strong>11 months</strong></td>
<td></td>
<td></td>
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<tr>
<td>Ganymede (polar) 10,000x200 km &amp; 5000 km</td>
<td>150 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500 km circular</td>
<td>102 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200 km circular</td>
<td>30 days</td>
<td></td>
<td></td>
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<tr>
<td><strong>Total mission at Jupiter</strong></td>
<td><strong>3 years</strong></td>
<td></td>
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</table>
Characterise Ganymede as a planetary object and possible habitat

1. Extent of the ocean and its relation to the deeper interior

<table>
<thead>
<tr>
<th>10</th>
<th>20</th>
<th>30</th>
<th>40</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
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<tbody>
<tr>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>200</td>
<td>300</td>
<td>400</td>
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<td></td>
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<tr>
<td>Ice crust thickness (km)</td>
<td>Ocean thickness (km)</td>
<td>Surface deformations</td>
<td>Rotation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Magnetic induction

**JUICE measurements**

- Surface deformations
- Periodic variations in the rotation (librations)
- Magnetic induction from the field vector

**Instrument Packages**

- In situ Fields and Particles
- Imaging
- Sounders and Radio Science

<table>
<thead>
<tr>
<th>Year</th>
<th>2030</th>
<th>2031</th>
<th>2032</th>
<th>2033</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ganymede</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
</tr>
</tbody>
</table>

Internal structure

- Icy crust
- Liquid layer
- Icy mantle
- Silicates
- Metallic core
Exploration of the Jupiter system

The biggest planet, the biggest magnetosphere, and a mini solar system

Jupiter
- Archetype for giant planets
- Natural planetary-scale laboratory for fundamental fluid dynamics, chemistry, meteorology, ...
- Window into the formational history of our planetary system

Magnetosphere
- Largest object in our Solar System
- Biggest particle accelerator in the Solar System
- Unveil global dynamics of an astrophysical object

Satellite system
- Tidal forces: Laplace resonance
- Electromagnetic interactions to magnetosphere and upper atmosphere of Jupiter

Coupling processes
- Hydrodynamic coupling
- Gravitational coupling
- Electromagnetic coupling
From the Jupiter system to extrasolar planetary systems

<table>
<thead>
<tr>
<th>Waterworlds and giant planets</th>
<th>Habitable worlds</th>
<th>Astrophysics Connection</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Waterworlds:</strong> If habitable, the liquid layers are trapped between two icy layers</td>
<td><strong>Europa-like:</strong> If habitable, the liquid layers may be in contact with silicates as on Earth</td>
<td></td>
</tr>
</tbody>
</table>

**Occurrence:**
Largest moons, hot ice giants, ocean-planets...
Most common habitat in the universe?

**Key question:**
Are these waterworlds habitable?

**What JUICE will do:**
Via characterisation of Ganymede, will constrain the likelihood of habitability in the universe

**Occurrence:**
Europa, Enceladus
Only possible for very small bodies

**Key question:**
How are the surface active areas related to potential deep habitats?

**What JUICE will do:**
Pave the way for future landing on Europa
Better understand the likelihood of deep local habitats

---

**Waterworlds**
If habitable, the liquid layers are trapped between two icy layers.

**Europa-like**
If habitable, the liquid layers may be in contact with silicates as on Earth.
From the Jovian system to extrasolar planetary systems

Waterworlds and giant planets

Habitable worlds

Astrophysics Connection

By studying Ganymede, we can characterise an entire family of exoplanets: the waterworlds.

Jupiter system
Three waterworlds
One giant planet

Exoplanets
Five families
> 1800 planets

Five families
> 1800 planets

SUPER-EARTHS
INTERMEDIARY
GIANTS
NASA Europa “Clipper” mission

- Spacecraft in orbit around Jupiter
- Science goal: Europa’s habitability
- Multiple (45) flybys of Europa
  - Altitudes: 25 – 2700 km
- 9 instruments selected: cameras, magnetometers, radar, dust analyser, spectrometers, plasma + mass spectrometer
- Schedule
  - Launch 2020-2025
  - Cruise: 2 or 7 years
  - Nominal mission: 3-4 years

Possible extra probe, penetrator or lander provided by ESA is being considered
Saturn’s satellites
Saturn's Satellites and Ring Structure

All bodies are to scale except for the eight small, starred (*) bodies whose sizes have been exaggerated by a factor of 5.
Cassini-Huygens spacecraft

- 12 instruments on the orbiter
- 6 instruments on the probe

« Human » functions of Cassini-Huygens
Enceladus
What are the habitable worlds?

Class III: subsurface oceans in contact with silicates – Enceladus

- "Tiger stripes" and icy geysers …
• What is the origin of the plumes
• Replenishment of E-ring?
• Water vapor ejecta far away from the Sun (strong implications for the habitability zones)
• Indications for the presence of organic chemistry
What are the habitable worlds?

Class III: subsurface oceans in contact with silicates – Enceladus

From Hsu et al. 2015
What are the habitable worlds?

Class IV: subsurface oceans without any contact with the silicates - Titan
Titan Through Time

• Christianus Huygens discovers Titan, 1655
• Ground-based:
  ▪ atmospheric limb darkening (Comas Solas, 1908)
  ▪ CH$_4$ detected (Kuiper, 1944)
• Voyager (1980)
  ▪ radius = 2575 km (0.98 Ganymede; 1.48 x Moon; 0.76 x Mars)
  ▪ mass = 1.35x 10$^{23}$ kg (0.023 x Earth’s)
  ▪ mean density = 1.88 g/cm$^3$ (50% ice, 50% rock)
  ▪ mean distance from Saturn = 1,211,850 km (~ 3.1 x Earth-Moon distance)
  ▪ Follows Saturn around the Sun (inclined by 26.7°); a season is 7.5 years
  ▪ orbital period= 15.94 days (Earth’s moon 27.3 days)
  ▪ atmospheric pressure = 1.5 bars
  ▪ atmospheric density = 4.4 x Earth’s atmosphere
  ▪ N$_2$ detected as main component, CH$_4$ and other organics (Voyager, 1980)
  ▪ Temperature inversions at tropopause (70° at 40 km altitude) and higher and green-house effect
  ▪ mean surface temperature = 93.5 K (-179.5 °C, -291 °F)
• Ground-based and Earth-bound observatories (HST, ISO) – 1990s
  ▪ Heterogeneous surface
  ▪ Interesting atmospheric phenomena
• Cassini arrives at Saturn on 30 June 2004
• Huygens lands on Titan 14 January 2005

Wow !!!
TITAN: WHY ARE WE INTERESTED?

• It is of general interest to the study of chemical evolution:
  – N$_2$, CH$_4$ and other abundant organic gases (nitriles and hydrocarbons) are present in the atmosphere
  – An orange-brown cloud deck globally covers the satellite, in which aerosol layers and, methane/ethane clouds are also present.
  – The products of atmospheric chemistry may have been preserved over all of Titan’s history.
  – The surface has a pressure of 1.5 bar and hosts several complex features like Earth (dunes, lakes, volcanoes, channels, etc) but with different actors/materials.
  – Atmosphere and surface are and subjected to seasonal effects.

• Conditions on Titan are not identical to those on Early Earth:
  – The temperatures are too low in the atmosphere (70-200 K) and on the surface (T~94 K), where liquid water is absent
  – The composition of the atmosphere is different (CH$_4$-N$_2$ vs CO-CO$_2$-N$_2$) with very little oxygen
  – Methane cycle vs water cycle
  – The solar UV radiation is only about 1% of that at the Earth
  – The infall of carbonaceous material is smaller today than in the past
Titan as an astrobiological object

- The physical conditions
- The organic chemistry
- The methane cycle
- The undersurface water ocean
- Climatology/seasonal effects
Titan and the Earth

Titan provides a good analogue as a natural laboratory in which chemical and physical processes can be studied on a planetary scale and help us understand early chemical evolution in the primordial atmosphere on Earth.
Waite et al., 2005, 2009; Vuitton et al., 2009

Cassini INMS

Cassini CIRS

Huygens GCMS

Titan

Sunlight

Energetic Particles

Molecular Nitrogen and Methane

Dissociation

C₂H₂, C₂H₄,

C₂H₆, HCN

Ionization

C₂H₅⁺, HCNH⁺,

CH₅⁺, C₄N₅⁺

Benzene (C₆H₆)

Other Complex Organics (100~350 Da)

Negative Organic Ions (20~8000 Da)

Tholins
Huygens: the descent module

December 26, 2004
Cassini releases the Huygens probe. The two spacecraft travel in tandem.

December 17, 2004
Cassini maneuvers, capturing its trajectory to intersect with Titan.

January 14, 2005
Cassini continues around Saturn while Huygens descends for Titan’s surface.

Huygens

SPIN/EJECT DEVICE

AFTER CONE

EXPERIMENT PLATFORM

BACK COVER

FRONT SHIELD

TOP PLATFORM

FORE DOME
Titan after Huygens

Reflectivity Vs. Wavelength

Surface I/F Reflectivity

Wavelength (nm)
Surface Observations with the GCMS


Detection of various organic compounds on the surface:
Ethane, acetylene, cyanogen, benzene and in addition carbon dioxide.

Methane evaporated from the surface after warming from the heated sample inlet as observed by an increase of the methane signal after impact. A moist area with liquid methane in the near sub-surface is indicated.
Cassini/RADAR/Titan

Rivers and lakes in the North Pole: the missing CH4 reservoir?
Titan the only place with the Earth having liquid surface bodies
Titan’s lakes made of ~65% ethane and ~30% methane with many minor species dissolved

- Other hydrocarbons ethylene and propane: several%
  C_3-C_7 alkanes, alkenes and benzene: several % - 1 ppm
  Acetylene: 400 ppm  diacetylene: ~1 ppm

Nitriles  50 – 1 ppm
  HCN: 3 ppm  -  HC_3N: 5 ppm

Heterocyclic bases Pyrimidine 2 ppm  -  Adenine 10 ppb

Inorganics  CO_2: 10 ppm
  NH_3: 5 ppm
  H_2O: 0.2 ppt !
  CO: ~4 ppm
  Ar, other noble gases very soluble:

=> A large variety of organics, with much higher concentration in the lakes than in the atmosphere and easily quantitatively analysable by in situ measurements
Titan’s spin and large tides on the surface indicate the presence of an internal liquid water ocean (less et al., 2012)

Huygens measures radio wave at extremely low frequency which supports the subsurface ocean theory
Titan’s complex surface and atmosphere

Cassini/ISS map

- Titan lakes (RADAR)
- Menrva crater fluvial system
- Sinlap crater (RADAR)
- Cryovolcano (VIMS)
- Huygens landing site
- Fluvial networks (DISR)
- Dune (RADAR)
- Huygens landing site
- Titan’s sierras
- Dunes (VIMS)

Athena Coustenis
Titan

- Analogies with the Earth in atmosphere and pressure
- Complex organic chemistry
- Potential habitat (undersurface water ocean)
- Energy sources: cryovolcanism

Enceladus

- Complex organic chemistry
- Potential habitat (liquid water under the surface)

The Saturnian system is rich in worlds that could bring insights on important aspects of Earth’s

- climate,
- organic chemistry and
- emergence of life.
What are habitable worlds?
Ideas/studies for returning to Titan

TSSM: Balloon, lander & orbiter

TIME: Lake lander

Predecisional - for discussion and planning purposes only
Conclusions

Rich future for exploration of habitable worlds in the outer solar system with JUICE as L1: Studies of Jupiter, the magnetosphere, the icy moons and the interactions

From discovery to characterisation of deep habitats
Thank you and au revoir!