Space exploration of icy moons with undersurface oceans

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Habitability: four requirements

- Water
- Essential elements (CHNOPS...)
- Chemical energy
- Stable environment

Diagram:
- Global ocean
- Chondritic composition
- Radiolytic chemistry
- Exogenous delivery
- Tidal dissipation
- ~4 Gyr history
Habitability in the Solar System: extended HZ

Are icy satellites like Ganymede, Europa, Titan or Enceladus habitable worlds?

The habitable zone is not restricted to the Earth’s orbit...
What are the habitable worlds?

Lammer et al., 2009
Oceans in the Solar System

- Ganymede (5.4% Liquid Water)
- Enceladus (14% Liquid Water)
- Europa (6.4% Liquid Water)
- Mars’ Past (0.01% Liquid Water)
- Titan (11% Liquid Water)
- Earth (0.02% Liquid Water)

(mass percent of liquid water between parenthesis, excluding water ice)
What are the habitable worlds in the outer solar system?

Around JUPITER

Habitats in the Jupiter system
Emergence of the habitable zone around Jupiter

Three large icy moons to explore

**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
About the existence of deep liquid layers: EUROPA

Hyperspectral evidences

Composition of ices

from McCord et al. (1999)
About the existence of deep liquid layers: Europa

Water plumes on Europa

Credits: NASA/ESA/W. Sparks (STScI)/USGS Astrogeology Science Center
What are the habitable worlds?

Class III: subsurface oceans in contact with silicates - Europa

Europa-like

- Water:
  - Warm salty H₂O ocean.
- Essential elements:
  - Accretion of CO₂?
  - Impactors.
  - But radiation destroys organics in upper ~10s cm of ice.
- Chemical energy:
  - Radiation of H₂O ⇒ 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

H₂O ice and liquid diagram studied since 1912 (Bridgman)
Modern experiments are devoted to complex mixtures and indicate you can have liquid between ice layers.
About the existence of deep oceans: GANYMEDE

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

Geologic activity

Indications for young surface from water flooding

Questions
- Which depth?
- Which size?
- What is its composition?
What are the habitable worlds in the outer solar system?
Around SATURN

Habitats in the Saturnian system
Enceladus plumes

• 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

Composition of plumes

- Water vapor ejecta far away from the Sun (strong implications for the habitability zones)
- Indications for the presence of organic chemistry

Diagram showing the plume's composition with water vapor, methane, carbon monoxide, carbon dioxide, simple organics, and complex organics. White brackets show the range of cometary values.
What are the habitable worlds in the outer solar system? Around SATURN

Class III: subsurface oceans in contact with silicates – Enceladus

From Hsu et al. 2015
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.
Titan’s spin and large tides on the surface indicate the presence of an internal liquid water ocean between ice layers (Iess et al., 2012).

Huygens measures radio wave at extremely low frequency which supports the subsurface ocean theory.
Titan as an astrobiological object

- The physical conditions
- The organic chemistry
- The methane cycle
- The undersurface water ocean
- Climatology/seasonal effects
Habitable worlds in the outer solar system?

Future exploration

Need for further in-depth and in situ exploration of the deep habitats and the extended habitable zone around gas giants.
JUICE: Spacecraft, Payload & scenario
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
Topics:
Planet, moons, rings, magneto

- Interior
- Subsurface
- Geology
- Atmosphere
- Plasma
- Habitability
- Link to exoplanets

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** ~2200 kg, **propellant mass** ~2900 kg
- **Launcher - Ariane 5 ECA** (mass : ~5.1 tons), **High Δv required**: 2700 m/s
- **Payload** ~219 kg, ~ 180 - 230 W
- **3-axis stabilized s/c**
- **Power:** solar array ~ 70 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>
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</thead>
<tbody>
<tr>
<td><strong>Remote Sensing Suite</strong></td>
<td></td>
<td></td>
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<tr>
<td>JANUS</td>
<td>P. Palumbo</td>
<td>Italy</td>
<td>Narrow Angle Camera</td>
</tr>
<tr>
<td>MAJIS</td>
<td>Y. Langevin, G. Piccioni</td>
<td>France, Italy</td>
<td>Vis-near-IR imaging spectrometer</td>
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<tr>
<td>UVS</td>
<td>R. Gladstone</td>
<td>USA</td>
<td>UV spectrograph</td>
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<tr>
<td>SWI</td>
<td>P. Hartoghs</td>
<td>Germany</td>
<td>Sub-mm wave instrument</td>
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<tr>
<td><strong>Geophysical Experiments</strong></td>
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<tr>
<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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<tr>
<td>3GM</td>
<td>L. Iess</td>
<td>Italy</td>
<td>Radio science experiment</td>
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<tr>
<td>PRIDE</td>
<td>L. Gurvits</td>
<td>Netherlands</td>
<td>VLBI experiment</td>
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<tr>
<td><strong>Particles and Fields Investigations</strong></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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<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>
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### Mission design

<table>
<thead>
<tr>
<th>Spacecraft Design</th>
<th>Model instruments</th>
<th>Mission phases</th>
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<tbody>
<tr>
<td><strong>Launch</strong></td>
<td>June 2022</td>
<td></td>
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<tr>
<td><strong>Interplanetary transfer (Earth-Venus-Earth-Earth)</strong></td>
<td>7.6 years (8 years)</td>
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<tr>
<td><strong>Jupiter orbit insertion and apocentre reduction with Ganymede gravity assists</strong></td>
<td>11 months</td>
<td></td>
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<tr>
<td><strong>2 Europa flybys</strong></td>
<td>36 days</td>
<td></td>
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<tr>
<td><strong>Reduction of (v_{\text{inf}}) (Ganymede, Callisto)</strong></td>
<td>60 days</td>
<td></td>
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<tr>
<td><strong>Increase inclination with 10 Callisto gravity assists</strong></td>
<td>200 days</td>
<td></td>
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<tr>
<td><strong>Callisto to Ganymede</strong></td>
<td>11 months</td>
<td></td>
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<tr>
<td><strong>Ganymede (polar)</strong></td>
<td>10,000x200 km &amp; 5000 km, 500 km circular, 200 km circular (TBC)</td>
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<tr>
<td><strong>Total mission at Jupiter</strong></td>
<td>3 years</td>
<td></td>
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</tbody>
</table>
Ganymede: planetary object and potential habitat

Main investigations

- Elliptical (1000x10000 km) & high (~5000 km) circular orbit
- Medium (500 km) circular orbits
- Favorable illumination conditions (β-angle 30°-70°)
- Dedicated pointing modes
- Sub-surface sounding down to ~9 km depth
- Imaging: global ~400 m/px, selected targets ~3 m/px
- Mineralogical mapping (especially of non-ice materials): globally 1-5 km/px, selected targets ~25 m/px
Europa: study of recently active regions

Composition of non-ice material

Liquid sub-surface water

Active processes

Atmosphere, ionosphere

Main investigations

- At least 1 Europa flyby with CA ~400 km over the most active regions
- Favorable illumination conditions at CA
- Anti-Jovian side at CA
- Simultaneous operations of all experiments (including 3GM as a goal)
- Non-ice materials in selected sites mapped at regional (>5 km/px) and local (<500 m/px) scales & processes in active sites

Geometry of two baseline Europa flybys
1. Extent of the ocean and its relation to the deeper interior

JUICE measurements
- Eccentric orbit -> 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

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
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 2022-2025
  - Cruise: 2 or 7 years
  - Nominal mission: 3-4 years

Possible extra probe, penetrator or lander provided by ESA is being discussed.
The Saturnian system: a Post-Cassini mission...
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)

« Life beyond Earth: habitable worlds in the Universe », A. Coustenis and Th. Encrenaz, CUP, 2013.)
The Saturnian system is rich in worlds that could bring insights on important aspects of Earth’s climate, organic chemistry and emergence of life.

- The Saturnian system is rich in worlds that could bring insights on important aspects of Earth’s
  - *climate*,
  - *organic chemistry* and
  - *emergence of life*.
The Cassini spacecraft just performed its first successful dive through the rings on its way to destruction in Saturn by 15/9/17.
Future Saturnian system exploration

**TIME: Lake lander**
(Stofan et al. 2013)

**AVIATR /plane**
(Barnes et al. 2010)

**TSSM: Balloon, lander & orbiter**
(Coustenis et al. 2009)
From the icy moons to extrasolar planetary systems

**Waterworlds and giant planets**

**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

**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
From the Jovian system to extrasolar planetary systems

Waterworlds and giant planets

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

SUPER-EARTHS
INTERMEDIARY
GIANTS

Iron-rich
B1257 +12A
Kepler 22b
GJ1214b

>140
>530
THE FUTURE OF EXPLORATION

Rich future for exploration of habitable worlds in the outer solar system with JUICE as L1 and more: missions to Europa, Titan, Enceladus, and exoplanets.

Credit N. Powell, Imperial College
Exo-oceans study

Initiated from discussions between the European Space Sciences Committee and the European Marine Board

Study objectives:

◆ Review and synthesize the current status of astrobiological knowledge about the worlds in the outer solar system with possible subsurface liquid water oceans.

◆ Bring together our understanding from planetary exploration and Earth observations

◆ Bring forward future investigations needed to improve our knowledge of waterworlds from space, ground and laboratory work

◆ Lead to a better understanding of the emergence of life on Earth and initial conditions in the oceans

◆ Identify and prioritize mission concepts or payload that can make the most appropriate and useful measurements, and an analysis of our ability to interpret mission data and support further exploration.
Exo-oceans
Approach

• Setting up a joint Working Group between ESSC and the European Marine Board, with support from ESSC and EMB (also coordination), ISSI, PSL IRIS-OCAV. Interest declared by ESA. Looking for interest from NAS CAPS…

ESSC Secretariat to provide coordination

→ 10-12 marine scientists, planetary scientists and astrobiologists.

→ Three workshops – 8 months study
Exo-oceans

Outcome

• a book within the Space Science Series of ISSI
• a report detailing a science strategy for space exploration of the outer solar system icy moons oceans