KISS: Tidal Heating Workshop

Future missions to tidally heated worlds

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Tidally Heated Worlds

• Jupiter System
  - Io
  - Europa
  - Ganymede

• Saturn system
  - Titan
  - Enceladus
  - Others likely or possible

• Neptune
  - Possibly Triton

• Uranus
  - Possibly Ariel

• Exoplanets and ExoMoons

From top to bottom, Moons (to scale) of Jupiter, Saturn, Uranus, and Neptune.
## Missions on the horizon

### To Tidally Heated Worlds

<table>
<thead>
<tr>
<th>Tidally heated worlds</th>
<th>Mission concepts</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europa</td>
<td>Europa Clipper</td>
<td>NASA project, arrival 2025-2030</td>
</tr>
<tr>
<td></td>
<td>Europa Lander</td>
<td>Pre-phase A study</td>
</tr>
<tr>
<td>Ganymede</td>
<td>JUICE</td>
<td>ESA project, arrival 2030</td>
</tr>
<tr>
<td>Io</td>
<td>Io Volcanic Observer</td>
<td>Discovery Proposal</td>
</tr>
<tr>
<td></td>
<td>Io Observer</td>
<td>New Frontiers 5 candidate</td>
</tr>
<tr>
<td>Titan</td>
<td>Dragonfly</td>
<td>Finalist New Frontiers 4</td>
</tr>
<tr>
<td></td>
<td>Titan Orbiter/TMME/Titan Explorer</td>
<td>Study concepts</td>
</tr>
<tr>
<td></td>
<td>TiME</td>
<td>Finalist Discovery 12</td>
</tr>
<tr>
<td>Enceladus</td>
<td>ELF</td>
<td>Proposed Discovery and NF4</td>
</tr>
<tr>
<td></td>
<td>Life</td>
<td>Proposed Discovery 14</td>
</tr>
<tr>
<td></td>
<td>Elsah</td>
<td>Proposed NF4, <strong>Tech Dev Efun</strong></td>
</tr>
<tr>
<td>Neptune and Uranus</td>
<td>Ice Giant missions</td>
<td>2017 NASA study</td>
</tr>
<tr>
<td>Exoplanets</td>
<td>TESS, JWST, WFIRST, PLATO</td>
<td>NASA, ESA missions</td>
</tr>
</tbody>
</table>

Bold items are currently funded projects
Europa Clipper

- Europa mission concepts have been studied by NASA for nearly two decades
- The 2011 NRC Decadal Survey stated that the $4.7B Jupiter Europa Orbiter mission concept had extremely high science value but was unaffordable, and requested a de-scoped option
- Subsequent studies by a joint JPL-APL team resulted in a multiple-flyby concept (referred to as Europa Clipper) that retains high science value at significantly reduced cost
- In June 2015 NASA selected the Europa multiple-flyby mission as its next outer planet flagship mission. PDR held in August 2018.
  - Use flyby concept to buildup global regional coverage
  - Solar powered spacecraft

“Because of this ocean’s potential suitability for life, Europa is one of the most important targets in all of planetary science.”

–2011 Planetary Decadal Survey
Europa Clipper Mission Concept

ETHEMIS
[Day/Night Coverage]

Trajectory

The technical data in this document is controlled under the U.S. Export Regulations; release to foreign persons may require an export authorization.
**NASA-Selected Europa Clipper Instruments**

- **Europa-UVS** UV Spectrograph
  - Surface & plume/atmosphere composition

- **MASPEX** Mass Spectrometer
  - Sniffing atmospheric composition

- **SUDA** Dust Analyzer
  - Surface & plume composition

- **ICEMAG** Magnetometer
  - Sensing ocean properties

- **MISE** IR Spectrometer
  - Surface chemical fingerprints

- **REASON** Ice-Penetrating Radar
  - Plumbing the ice shell

- **EIS** Narrow-Angle Camera + Wide-Angle Camera
  - Mapping alien landscape in 3D & color

- **E-TEHMIS** Thermal Imager
  - Searching for hot spots

- **MIME**
  - Faraday Cups
  - Plasma environment

- **Gravity Science**
  - X-band telecom
  - Ice depth, ocean properties

**View of Clipper instrument deck/vault**

- **Remote Sensing**
- **In Situ**
Europa Lander Mission Concept

Launch
- SLS Block 1B
- Nov 2026

Cruise/Jovian Tour
- Jupiter Orbit Insertion: June 2031
- Europa Landing: 2033

Carrier Stage
- 1.5 Mrad radiation exposure
- Elliptical disposal orbit

Deorbit, Descent, Landing
- Guided deorbit burn
- Sky Crane landing system
- 100-m accuracy
- DTE tones only

Surface Mission
- Biosignature Science
- 20+ days
- 3 samples from 1 trench
- Direct to Earth Comm or Clipper (backup)
- 1.5 Gbit data return
- 50 kWh battery
- 2.0 Mrad radiation exposure

Leverage past flight experience and high-TRL tech development to reduce mission risk
Science Definition Team (SDT) Sample Payload Accommodation

- Context Remote Sensing Instrument (CRSI)
- Organic Compositional Analyzer (OCA)
- Vibrational Spectrometer (VS)
- Microscope for Life Detection (MLD)
- Geophysical Sounding System (GSS)
Juice: Jupiter Icy Moons Explorer

- ESA mission to Jupiter system
  - Launch in 2022
  - Jupiter orbit insertion 2030
  - 3.5 years in Jovian system
  - Ganymede orbit insertion 2033

- Solar powered spacecraft
  - ~100 m² solar arrays with 820W EOM

- Science Objectives
  - Ganymede
    - Characterization of the ocean layers and detection of putative subsurface water reservoirs;
    - Topographical, geological and compositional mapping of the surface;
    - Study of the physical properties of the icy crust;
    - Characterization of the internal mass distribution, dynamics and evolution of the interior;
    - Investigation of Ganymede's tenuous atmosphere;
    - Study of Ganymede's intrinsic magnetic field and its interactions with the Jovian magnetosphere
  - Two Europa flybys
  - Io distant monitoring
Europa Clipper – Juice instrument comparison 1 of 2

<table>
<thead>
<tr>
<th>Europa Clipper</th>
<th>JUICE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>PIMS: Key Instrument Parameters</strong></td>
<td><strong>PEP-JEI</strong></td>
</tr>
<tr>
<td>Ion Energy Range</td>
<td>0.1 - 50 meV</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>&lt;15%</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.5 - 12^3 pC/mm^2</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>1 - 4 s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ICEMAG: Key Instrument Parameters</th>
<th>J-MAG: Key Instrument Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vector magnetic field accuracy</td>
<td>&lt; 0.6 µT</td>
</tr>
<tr>
<td>Range</td>
<td>±1000 µT</td>
</tr>
<tr>
<td>Precision</td>
<td>0.5 µT</td>
</tr>
<tr>
<td>Resolution stability</td>
<td>&lt; 0.1 µT over &gt; 3 yr</td>
</tr>
<tr>
<td>Spacecraft magnetic field knowledge</td>
<td>&lt; 0.5 µT</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>24 samples/sec</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RPW: Key Instrument Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron and ion detectors</td>
</tr>
<tr>
<td>DC electron fields</td>
</tr>
<tr>
<td>Spacecraft potential</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Overview Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Instrument</strong></td>
</tr>
<tr>
<td>UV Spectrometer</td>
</tr>
<tr>
<td>Camera System</td>
</tr>
<tr>
<td>IR Spectrometer</td>
</tr>
<tr>
<td>Ice Penetrating Radar</td>
</tr>
<tr>
<td>Magnetometer</td>
</tr>
<tr>
<td>Plasma Instrument</td>
</tr>
<tr>
<td>Radio Emission</td>
</tr>
<tr>
<td>Thermal Emission</td>
</tr>
<tr>
<td>Mass Spectrometer</td>
</tr>
<tr>
<td>Dust Analyzer</td>
</tr>
<tr>
<td>Radio Science</td>
</tr>
<tr>
<td>Radio Science</td>
</tr>
<tr>
<td>Sub Millimeter Wave</td>
</tr>
<tr>
<td>Laser Millimeter</td>
</tr>
</tbody>
</table>

Source: Clipper-Juice workshop 2018
### Europa Clipper – Juice instrument comparison 2 of 2

**Source:** Clipper-Juice workshop 2018

<table>
<thead>
<tr>
<th><strong>Europa Clipper</strong></th>
<th><strong>Juice</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EUROPA-UVS:</strong> Key Instrument Parameters</td>
<td><strong>JUICE:</strong> Key Instrument Parameters</td>
</tr>
<tr>
<td>Wavelength Range</td>
<td>1.55 – 2.30 μm</td>
</tr>
<tr>
<td>Field of View</td>
<td>0.1” x 0.3”</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>0.16” (low res), 0.06” (high res) Neptunian sampled</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>Aλ/Δλ = 220: &gt;0.6 nm @PM (point source)</td>
</tr>
<tr>
<td>Spectral Cube Size</td>
<td>2464 (spectral) x 612 (spatial)</td>
</tr>
<tr>
<td><strong>EIB:</strong> Key Instrument Parameters</td>
<td><strong>JANUS:</strong> Key Instrument Parameters</td>
</tr>
<tr>
<td>Wavelength Range</td>
<td>350 – 1050 (370 – 1050) nm</td>
</tr>
<tr>
<td>Instantaneous Field of View</td>
<td>7 x 7 μm (at 50 km)</td>
</tr>
<tr>
<td>Spectral Resolution</td>
<td>3.47 μm x 2.17 μm, 0.49 x 0.349 μm</td>
</tr>
<tr>
<td><strong>MISE:</strong> Key Instrument Parameters</td>
<td><strong>MAJJS:</strong> Key Instrument Parameters</td>
</tr>
<tr>
<td>Field of View</td>
<td>250 μrad</td>
</tr>
<tr>
<td>Spatial Resolution</td>
<td>3.3 μm/pix, full-disk images at 40,000 km range, 25 μm/pix at 100 km range</td>
</tr>
<tr>
<td>Spectral Cube Size</td>
<td>300,000 x 810 x 500, 451 spectral channels</td>
</tr>
<tr>
<td>Emiss Spectral Cube</td>
<td>150 x 100 x 600</td>
</tr>
<tr>
<td>Signal-to-noise Ratio</td>
<td>&gt;100:1 from 0.02 – 0.6 μm, 10:1 between 2.6 and 3.2 μm, &gt;25 from &lt;3.2 μm</td>
</tr>
<tr>
<td><strong>E- THEMIS:</strong> Key Instrument Parameters</td>
<td><strong>SWI:</strong> Key Instrument Parameters</td>
</tr>
<tr>
<td>Thermal Emission</td>
<td>3.7–14.28, 28–70 μm</td>
</tr>
<tr>
<td>Image width</td>
<td>5.7” cross-track (720 pixels)</td>
</tr>
<tr>
<td>Radiometric Resolution</td>
<td>&gt;2K</td>
</tr>
<tr>
<td>Radiometric Accuracy</td>
<td>±2%</td>
</tr>
<tr>
<td><strong>SULDA:</strong> Key Instrument Parameters</td>
<td><strong>DUSTANA:</strong> Key Instrument Parameters</td>
</tr>
<tr>
<td>Dust Analyzer</td>
<td>Impact Speed Range: 4–7 km/s (± 6%)</td>
</tr>
<tr>
<td>Mass Measurement</td>
<td>&gt;0.25 cm (± 10%)</td>
</tr>
<tr>
<td>Size Range</td>
<td>0.1–1.2 μm (± 25%)</td>
</tr>
<tr>
<td>Surface Resolution</td>
<td>Better than spacecraft altitude</td>
</tr>
<tr>
<td><strong>GALA:</strong> Key Instrument Parameters</td>
<td><strong>SWI:</strong> Key Instrument Parameters</td>
</tr>
<tr>
<td>Dust Size</td>
<td>Radiometric Resolution</td>
</tr>
<tr>
<td>Frequency</td>
<td>±0.1” (SWI) for m &gt; 200 μm</td>
</tr>
<tr>
<td><strong>PEP-NIM:</strong> Key Instrument Parameters</td>
<td><strong>DRAKE:</strong> Key Instrument Parameters</td>
</tr>
<tr>
<td>Mass Range</td>
<td>1000–10,000 u</td>
</tr>
<tr>
<td>Mass Resolution</td>
<td>m/Δm &gt; 16,000</td>
</tr>
<tr>
<td>Dynamic Range</td>
<td>±100%</td>
</tr>
<tr>
<td><strong>MASEXP:</strong> Key Instrument Parameters</td>
<td><strong>RADON:</strong> Key Instrument Parameters</td>
</tr>
<tr>
<td>Energy Range</td>
<td>3.3 MeV – 40 MeV (monitor) &amp; &gt;1 MeV (Dissipators)</td>
</tr>
<tr>
<td>Total Dosimeters</td>
<td>12</td>
</tr>
<tr>
<td>Time Resolution</td>
<td>seconds (node dependent)</td>
</tr>
<tr>
<td><strong>RADIM:</strong> Key Instrument Parameters</td>
<td><strong>RIM:</strong> Key Instrument Parameters</td>
</tr>
<tr>
<td>Phantom Energy Range</td>
<td>0.3 to 40 MeV</td>
</tr>
<tr>
<td>Phantom Energy Range</td>
<td>5 MeV to 250 MeV</td>
</tr>
<tr>
<td>Simultaneous Range</td>
<td>Time resolution trim (by default, can be reapplied)</td>
</tr>
</tbody>
</table>

**JUICE:**
- Dual Frequencies: 63 MHz (3-5 m), Very High Frequency (VHF) globally, and 9 MHz (A = 33.3 MHz) High Frequency (HF) anti-Jupiter
- Vertical Resolution: 2 km depth with vertical resolution of up to 10-15 km in the ionosphere
- Antenna: 1 deployable HF

**REASON:**
- Dual Frequencies: 63 MHz (3-5 m), Very High Frequency (VHF) globally, and 9 MHz (A = 33.3 MHz) High Frequency (HF) anti-Jupiter
- Vertical Resolution: 2 km depth with vertical resolution of up to 10-15 km in the ionosphere
- Antenna: 1 deployable HF
Io Volcanic Observer

**Background:**
Discovery 2014
U Arizona/APL

- Io multiple flyby mission
- Suite of five instruments
- Solar powered spacecraft

**Mission Overview:**
- Launch May 29, 2021
- DVEGA (Earth gravity assist) trajectory, asteroid flyby opportunities
- Jupiter orbit insertion (JOI) in February 2026 with 500 km Io encounter (IO) and capture into orbit inclined 42° relative to Jupiter’s equator
- Eight additional Io encounters over 22 months with high-resolution views of active volcanism in daylight and darkness
- Four of the encounters are designed for optimal measurement of induced magnetic signature from mantle melt
- Mission design minimizes total ionizing radiation dose (372 krad at 100 mil Al, design margin of 2), <10% of that experienced by Galileo
- Collect 20 Gb science data per encounter: 100 times the Io data from the 8-year Galileo tour; playback near apoposis
- Encounters last 1–week, including global monitoring and four Io eclipses
- Nearly polar approach and departure from Io is ideal for study of polar regions, key to testing tidal heating models

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**Objectives (Gain Understanding of)** | **Key Measurements**
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A1. Io’s active volcanism | High-resolution repeat imaging at UV to thermal-IR wavelengths.
B1. Nature of Io’s lithosphere & unique tectonics | Image & measure topography of key tectonic structures.
B2. Connections between Io’s volcanism & its surface & atmosphere | Measure mass spectra & temporal & spatial variability of neutral species, & map spectral variations of surface.
B3. Io’s mass loss & magnetospheric interactions | Acquire in situ & remote observations of Io’s exosphere, sodium cloud, & plasma torus.
B4. Limits to active volcanism on Europa | Distant repeat imaging to search for plumes or surface changes.
C1. Jupiter system science | Observe Jupiter, rings, moons, & magnetosphere.
Dragonfly

Background:
New Frontiers 2017 finalist
APL/Penn State/Langley/Ames/GSFC/JPL

- Launch in 2025
- Two years sampling surface of Titan
- Multiple flights provide access to diverse locations on surface
- Nuclear powered quadcopter rotorcraft
- Could be first seismometer experiment on an ocean world
- CRYOSADS sample system

Source: JHUAPL website
Oceanus

History:
New Frontiers 2017
JPL/??

- Titan flyby and orbiter mission
- Imaging and radar of Titan surface from orbit; mass spectrometer
- Gravity science
- Solar powered spacecraft
Titan Orbiter mission concepts

- **Titan Explorer** - 2007 NASA flagship mission study
  - Lander and Balloon

- **TSSM** – NASA-ESA study concept
  - Joint mission to combine Titan Explorer with ESA Enceladus mission
  - Orbiter, lander and balloon

- **Titan Mare Explorer**
  - Titan Lander proposed NASA mission

Enceladus Life Finder ELF

History:
New Frontiers 2017
Cornell/JPL/SwRI/Univ of Stuttgart

- Fly through Enceladus Plumes (Jets)
- 10 orbits of Saturn
- 2 mass spectrometers
- Solar powered spacecraft

- Fly through the Enceladus plume just like Cassini did....
- But do it with instruments of today’s capabilities...Cassini instruments are 20 years old.

Source: OPAG 2-2015: Cable, Lunine
Enceladus Life sample return mission

History:
Discovery 2014
JPL/Ball/JAXA

Trajectory
- Saturn Orbit Insertion Pump down to Enceladus via Titan
- 13.5 year mission duration
- Encounter speeds 2-4 km/s
- Multiple flybys

Spacecraft
- Nuclear powered
- 2 instruments
Elsah
Enceladus life signatures and habitability

History:
New Frontiers 2017
Ames/GSFC/APL

• Habitability mission
  - Search for life
  - Fly through plumes
  - Plume sample collection system
  - 2 Cameras and Mass Spec

• Enceladus Funnel sample system
  - Technology development COLDTech grant to develop cost-effective techniques that enable life detection measurements on cost-capped missions
  - Ice particle capture and retention

Source: OPAG 2-2018 Hurford and Cospar 2018 Adams
Ice Giants Missions

- NASA study report in 2017
- Uranus and Neptune systems seen as equally important in this study
  - However, Roadmaps of Ocean Worlds (ROW) study prioritized Neptune, due to Triton
  - Both worlds should be explored
  - Optimal launch dates 2029-2033

- Highest Priority Science
  - Interior structure of the planet
  - Bulk composition of the planet (including isotopes and noble gases)

- Internal structure of satellites also included
  - Tilted magnetospheres enable magnetic sounding for conductive layers

- 2018 decadal mid-term review recommended a new study
Telescopic Observations of Exoplanets

- Spacecraft: JWST, TESS, WFIRST, PLATO
- Ground-based extremely large telescopes
- 2018 National Academies report recommends direct imaging mission that can measure the reflected light spectra of Earth-sized planets orbiting in the habitable zones of sun-like stars.
  - HabEx or LUVOIR

Orbital resonances are common in exoplanet systems, leading to tidal heating. This increases importance of understanding tidal heating in our system.
Mission architecture trades

• Mission architecture
  - Flyby
  - Orbiter
  - Lander
  - Balloon

• Power
  - Solar
  - Nuclear
  - Batteries (primary or rechargeable)
  - Fuel cells (primary or regenerative)*

• Propulsion
  - Chemical
  - Solar electric propulsion
  - Solar sails*

*Developmental