Ocean Worlds, Icy Bodies, and RTG Concepts for Exploration

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More than a dozen ocean worlds within reach

Ocean Relicts
- Mars
- Ceres

Jovian icy moons
- Europa
- Ganymede
- Callisto

Saturnian icy moons
- Enceladus
- Dione
- Titan

Kuiper Belt Objects
- Triton
- Pluto
- Charon
**Known and Potential Ocean Worlds**

<table>
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<th>Distance from Sun, AU</th>
<th>Gravity, m/s²</th>
<th>Diameter (km)</th>
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<td>2.7</td>
<td>5.2</td>
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Mars (3390 km) Ceres (473 km) Europa (1561 km) Ganymede (2634 km) Callisto (2410 km) Titan (2576 km) Enceladus (252 km) Dione (561 km) Triton (1353 km) Pluto (1187 km) Charon (606 km)

**Jovian Icy Moons**
- Europa
- Ganymede
- Callisto

**Saturnian Icy Moons**
- Titan
- Enceladus
- Dione

**Kuiper Belt Objects**
- Triton
- Pluto
- Charon

Three—Jupiter's moon Europa, and Saturn's moons Enceladus and Titan—have subsurface oceans whose existence has been detected or inferred by two independent spacecraft techniques.

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B. Sherwood, J. Lunine, C. Sotin, T. Cwik, F. Naderi, *Program Options to Explore Ocean Worlds*, Global Space Exploration Conference Beijing, June 2017
Three steps: Europa, Enceladus, Titan

**Europa**
- Comprehensive investigation of the icy moon’s habitability
  - Near-global hyper mapping
  - Lander-scale surface imagery
- Land at ocean-surface exchange zone
- Mobility around touchdown point
- Subsurface access to pursue fresher material
- Trans-shell probe into ocean, sample return
- Under-ice exploration of ocean ceiling
- Open ocean exploration, including seafloor

**Enceladus**
- Direct access to material known to originate in a habitable place
  - Plume transects
  - Best compositional analyzers
- Wet-chemistry and microscopy of grain material
- Collection, preservation, and return of samples
- Under-ice exploration of ocean ceiling
- Open ocean exploration, including seafloor hydrothermal systems known to exist

**Titan**
- Comprehensive reconnaissance of a complex world
  - Atmospheric organics factory
  - Global surface mapping
  - Gravity, tidal mapping
- Aerial exploration
- Buoyant sea exploration
- Mobile surface exploration
- In situ analysis of weathered organics
- Sample return
- Through-crust ocean access
RTGs – General Purpose

- Converts heat produced from the decay of plutonium dioxide into quiet DC power.
- The US Department of Energy has produced a variety of RTGs that have been designed and flown over the last 5 decades by NASA.
- Designed to work in atmospheres and vacuum
- Most have been general-purpose systems
- Only the MMRTG can be procured today.
- Not well-suited for melt probe exploration: low efficiency, low waste heat
RTGs: A key technology common to all Ocean World targets

- Conceptual Next-Generation RTGs *

  Modular: 50 – 500 W (Beginning Of Life)
  20 – 60 kg

  Efficient: 10-15%

  Copious waste heat: 450 – 3500 Wth

  Within reach, available by 2028

A universal melt probe is unlikely. Weak gravity will require propulsion, ice thickness will change design life requirements, atmosphere or not at target, and so on.
A focus on Europa

Environments: *

- Radiation: up to 9 Mrad/day unshielded
- Temps: 70 – 132 K
- Thermophysical properties at temp
- Accumulated salts and acid
- Pressure: ~12 Mpa at 10 km

* More environmental factors described in paper

Worst-case dose in years given a continuous dose rate
A word about telecommunications

Number of line-of-sight communication days for given latitudes and 4 different longitudes in the year 2035.

Sun-Probe-Earth Angles for 2035 from Lat = 30 deg, Lon = 45 deg, ~143 days total
A concept driven by Europa

Landed Configuration

Deployment Configuration

- High-Gain Antenna
- Wellhead
- Melt Probe
- Deployment Arm
- Lander Electronics + RTG

Lander Petals

Lander Base Petal

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Pre-Decisional Information
A concept driven by Europa

Transceiver Puck Compartment

Science Payload, Avionics, & Telecomm Compartment

Radioisotope Thermoelectric Generator (RTG) in Pressure Vessel

- Tapered trailing pressure vessel to redirect side forces
- Differential heating for steering
- 17 year design Life of RTG
- 400 We, continuous, DC, for science, telecomm, avionics, thermal, etc.
Transit times and waste heat

- Theoretical Higher-Power-Density Heat Source, 7000 Wth compared with a
- Largest (16 GPHS) Next-Generation RTG, 3500Wth
Steering

- To maneuver around an obstacle of one-half width $w_o$ as soon as it is detected at a distance $d_o$, the robot must be capable of executing a turn with a radius of at least $r_c = (w_o^2 + d_o^2)/(2w_o)$.

- Ground penetrating radar has a range of 100s of meters in ice.

- Assuming a minimum sensor range of 100m, the minimum radius of curvature needed is on the order of 10,000m to avoid an obstacle of size 1m ($w_o=0.5m$).

- For a robot length of 2m, the lateral deviation it will need to make over its length of travel is $2\times10^{-4}m$ i.e. 0.2mm.