Roadmaps to Ocean Worlds

OPAG
September 2017
La Jolla

Amanda Hendrix (PSI), Terry Hurford (GSFC)
co-chairs

Congressional Direction

- From the Commerce, Justice, Science, and Related Agencies Appropriations Bill, 2016
  - **"…The Committee directs NASA to create an Ocean World Exploration Program whose primary goal is to discover extant life on another world using a mix of Discovery, New Frontiers and flagship class missions consistent with the recommendations of current and future Planetary Decadal surveys**."
- Connected to the view of Ocean Worlds as perhaps habitable and potentially inhabited worlds

OPAG Charge to ROW

- *OPAG chartered ROW; we are coordinating with SBAG since some "SBAG-owned" bodies could be ocean worlds*
- Identify and prioritize science objectives for Ocean Worlds
  - tied to the Decadal Survey
- Design roadmap to explore these worlds to address science objectives
  - Mission sequences, sustained exploration effort
- Assess where each Ocean World fits into the overall roadmap
- Summarize broad mission concepts
  - Considering mission dependences & international cooperation
- Recommend technology development and detailed mission studies in support of the next decadal survey
- Place exploration of Ocean Worlds into the larger context of Solar System exploration

Team members

Amend, Jan
Aye, Michael
Bannister, Michele
Barge, Laurie
Beauchamp, Patricia
Beddingfeld, Chloe
Bland, Michael
Bowman, Jeff
Braun, Bobby
Brinckerhoff, William
Buratti, Bonnie

Byrne, Paul
Cable, Morgan
Cabrol, Nathalie
Cartwright, Richard
Castillo-Rogez, Julie
Collins, Geoffrey
Cooper, John
Crary, Frank
Dhingra, Rajani
Diniega, Serina
Elder, Catherine

Emerson, Dave
Eubanks, Marshall
Furfaro, Roberto
German, Chris
Glein, Chris
Goodman, Jason
Hand, Kevin
Hayes, Alex
Hibbard, Kenneth
Hibbitts, Karl
Hoehler, Tori

Holler, Bryan
Hosseini, Sona
Howett, Carly
Kargel, Jeffrey
Lindensmith, Chris
Lopes, Rosaly
MacKenzie, Shannon
Malaska, Michael
Martin, Emily
McKay, Chris
Moore, Jeff,

Neish, Catherine
Neveu, Marc
Nordheim, Tom
Olkin, Cathy
Pappalardo, Robert
Patterson, Wes
Patthoff, Alex
Phillips, Cynthia
Pontefract, Alexandra
Portyankina, Ganna
Poston, Michael

Quick, Lynnae
Rhoden, Alyssa
Ricco, Antonio
Schaible, Micah
Schaible, George
Schenk, Paul
Schmidt, Britney
Scully, Jennifer
Sherwood, Brent
Shock, Everett
Singer, Kelsi

Soderblom, Jason
Sotin, Christophe
Such, Pamela
Turtle, Elizabeth
Vance, Steve
Verbiscer, Anne
Walker, Catherine
Westlake, Joseph
Wray, James

Ocean World Definition

We defined an "ocean world" as a body with a current liquid ocean (not necessarily global). All bodies in our solar system that plausibly can have or are known to have an ocean will be considered.

The Earth is a well-studied ocean world that we use as a reference ("ground truth") and point of comparison.

Overarching Goal

- The ROW team has focused on a draft for the main goal for Ocean Worlds in order to start formulating driving science questions:

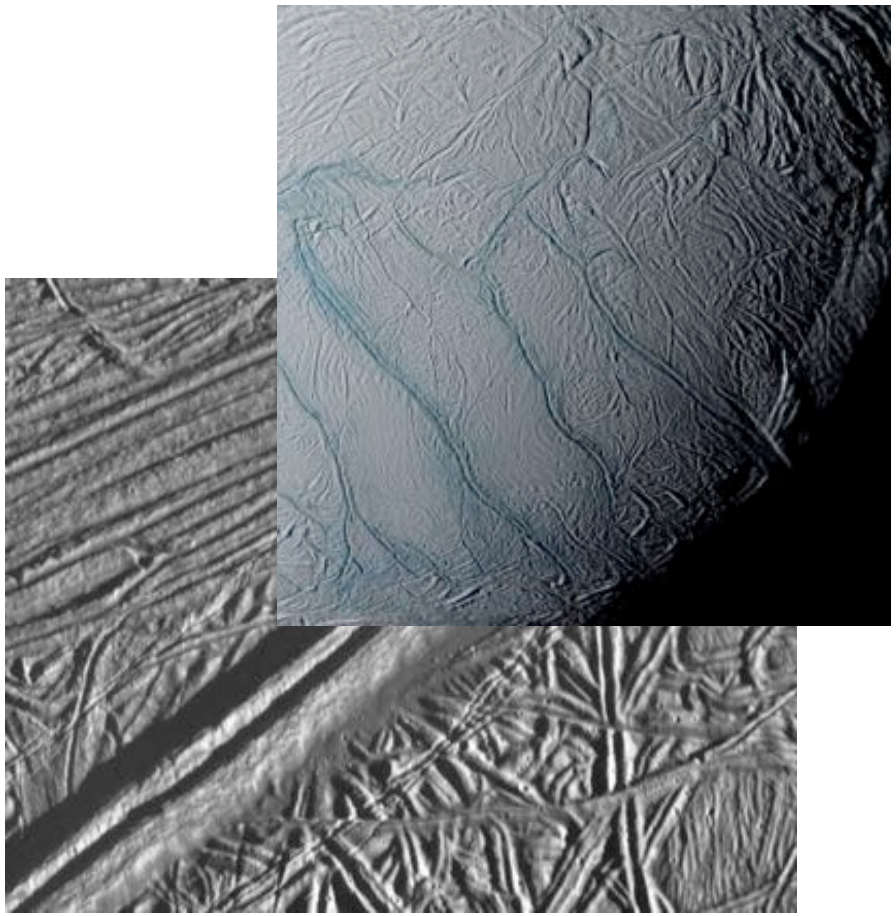
Identify ocean worlds, characterize their oceans, evaluate their habitability, search for life, and ultimately understand any life we find.

Explore Ocean Worlds

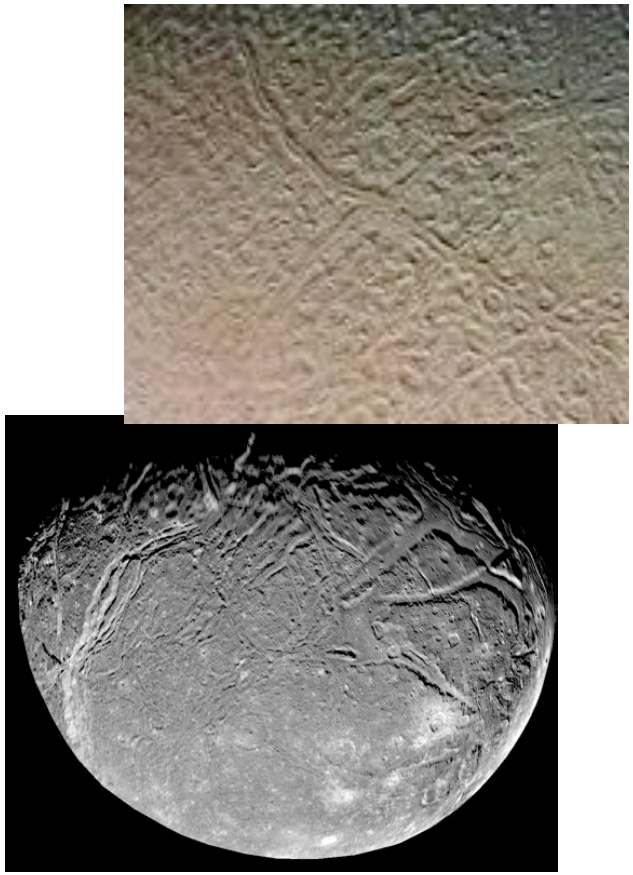
Identify Ocean Worlds

Example of Indirect Evidence: Tectonics

Known Ocean Worlds

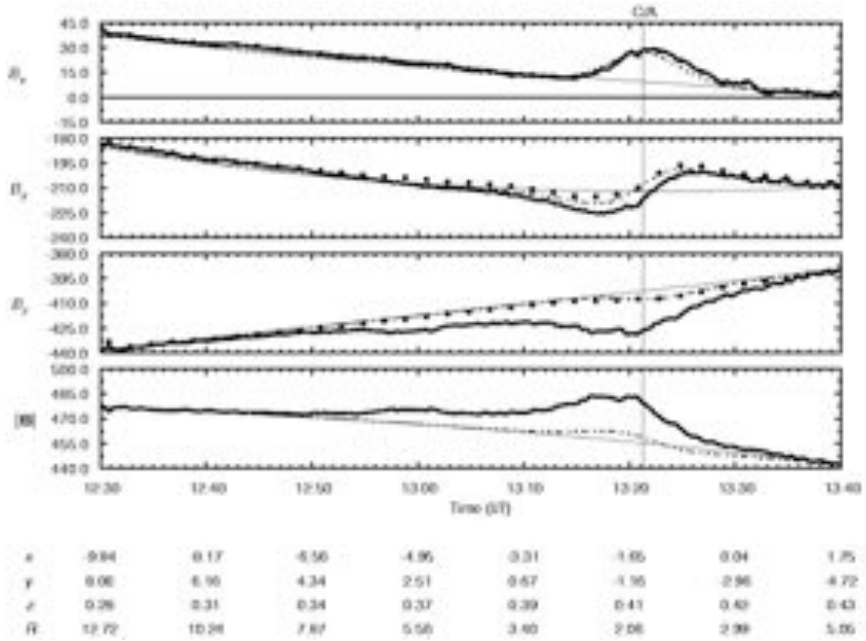


Possible Ocean Worlds



Identify Ocean Worlds

Confirmation of Oceans Worlds



Magnetometer Example (Khurana et al., 1998)

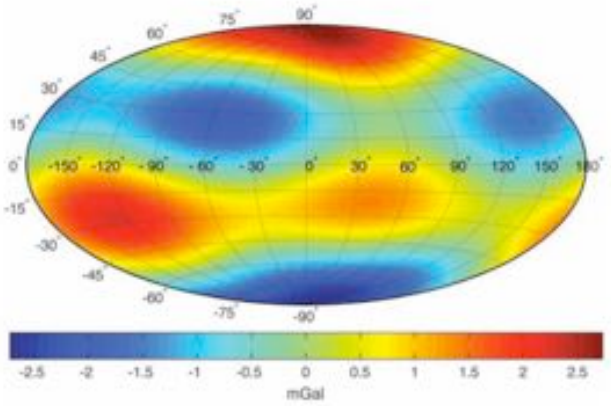


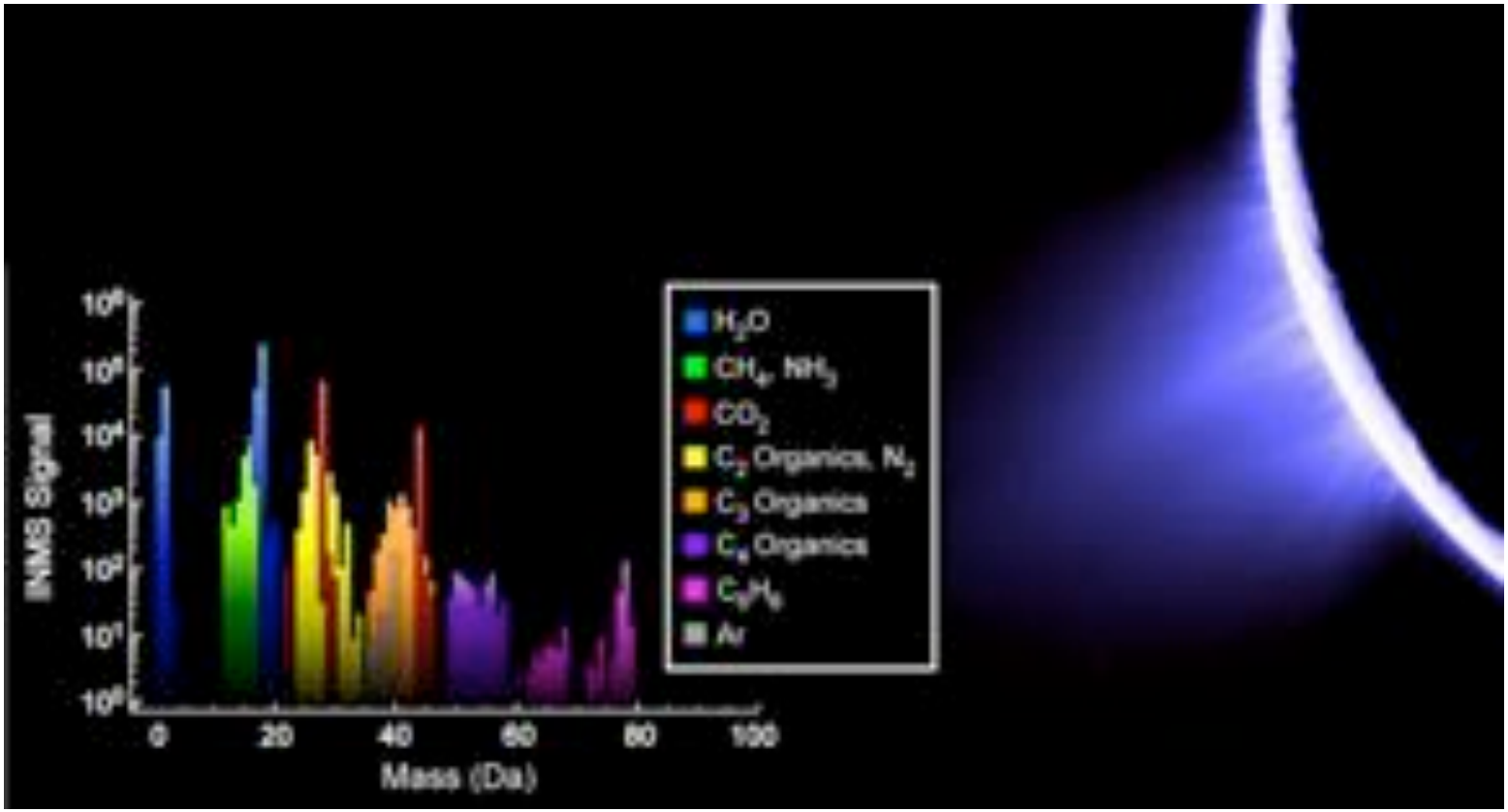
Fig. 1. Enceladus's gravity disturbances. The gravity field due to C21, S21, S22, and J3 (SOL1) is mapped onto the reference ellipsoid. The negative anomaly at the south pole, representing the asymmetry between the two hemispheres, is −2.5 mGal.

Gravity Science Example (Iess et al.)

Theme 1: Identify ocean worlds in the solar system

- Is there a sufficient energy source to support a persistent ocean?
  - Is there remnant radiogenic heating?
  - Is there gravitational energy from a parent planet or satellite?
  - Can the planet or satellite convert available tidal energy into heat?
  - Are the planet's or satellite's orbital or rotational properties favorable to tidal dissipation?
- Are signatures of ongoing geologic activity (or liquids) detected?
  - Do signatures of geologic activity indicate the possible presence of a subsurface ocean? (surface hotspots, plumes, crater-free areas, volcanoes, tectonics)
  - Does the body exhibit tidal and/or rotational evidence indicating the presence of a sub-surface ocean?
  - Does the gravity and topography of the body indicate the presence of a sub-surface ocean?
  - Are temporal changes observed at the body that would indicate the presence of a sub-surface ocean?
  - Is there an atmosphere or exosphere that could be linked with the presence of a sub-surface ocean?
  - Does the electromagnetic response of the body indicate the presence of a sub-surface ocean?
  - Can the surface composition be linked with the presence of a sub-surface ocean?
  - Is the signature of a surface liquid observed (e.g. specular reflection)?
- How do materials behave under conditions relevant to any particular target body? (*R&A*)
  - What are the phase relations of material composing ocean worlds at relevant pressures and temperatures?
  - What is the composition and chemical behavior of materials composing ocean worlds?
  - What are the rheologic mechanisms by which material deforms under conditions relevant to ocean worlds?
  - How does energy attenuation/dissipation occur under conditions relevant to ocean worlds?
  - What are the thermophysical properties of material under conditions relevant to ocean worlds?

Characterize Oceans
&
Assess Habitability



Waite et al., 2009

Theme 2: Characterize the ocean of each ocean world

- Characterize the ocean's physical properties
  - What is the thickness, composition, and porosity of the ice shell (crust) and how do these properties vary spatially and /or temporally?
  - What is the thickness, salinity, density and composition of the ocean? How do these properties vary spatially and /or temporally?
  - What are the drivers for, and pattern of, fluid motion within the ocean?
- Characterize the ocean interfaces
  - Characterize the seafloor, including the high-pressure ocean – silicate interaction
  - Characterize the ice-ocean interface

Theme 3: Characterize the habitability of each ocean world

- What is the availability (type and magnitude/flux) of energy sources suitable for life, how does it vary throughout the ocean and time, and what processes control that distribution?
  - What environments possess redox disequilibria, in what forms, in what magnitude, how rapidly dissipated by abiotic reactions, and how rapidly replenished by local processes?
  - (Where) is electromagnetic (or other energetic) radiation available? In what wavelengths (or energy) and intensity?
- What is the availability (chemical form and abundance) of the biogenic elements, how does it vary throughout the ocean and time, and what processes control that distribution?
  - What is the inventory of organic compounds, what are their sources and sinks, and what is their stability with respect to the local environment?
  - What is the abundance and chemical form of nitrogen, oxygen, phosphorus, sulfur, and inorganic carbon, what are their sources and sinks, and are there processes of irreversible loss or sequestration relative to the liquid environment?

Search for Life

We don’t have any examples of this yet! But we’re working on it!

Theme 4: Understand how life might exist at each ocean world and search for life

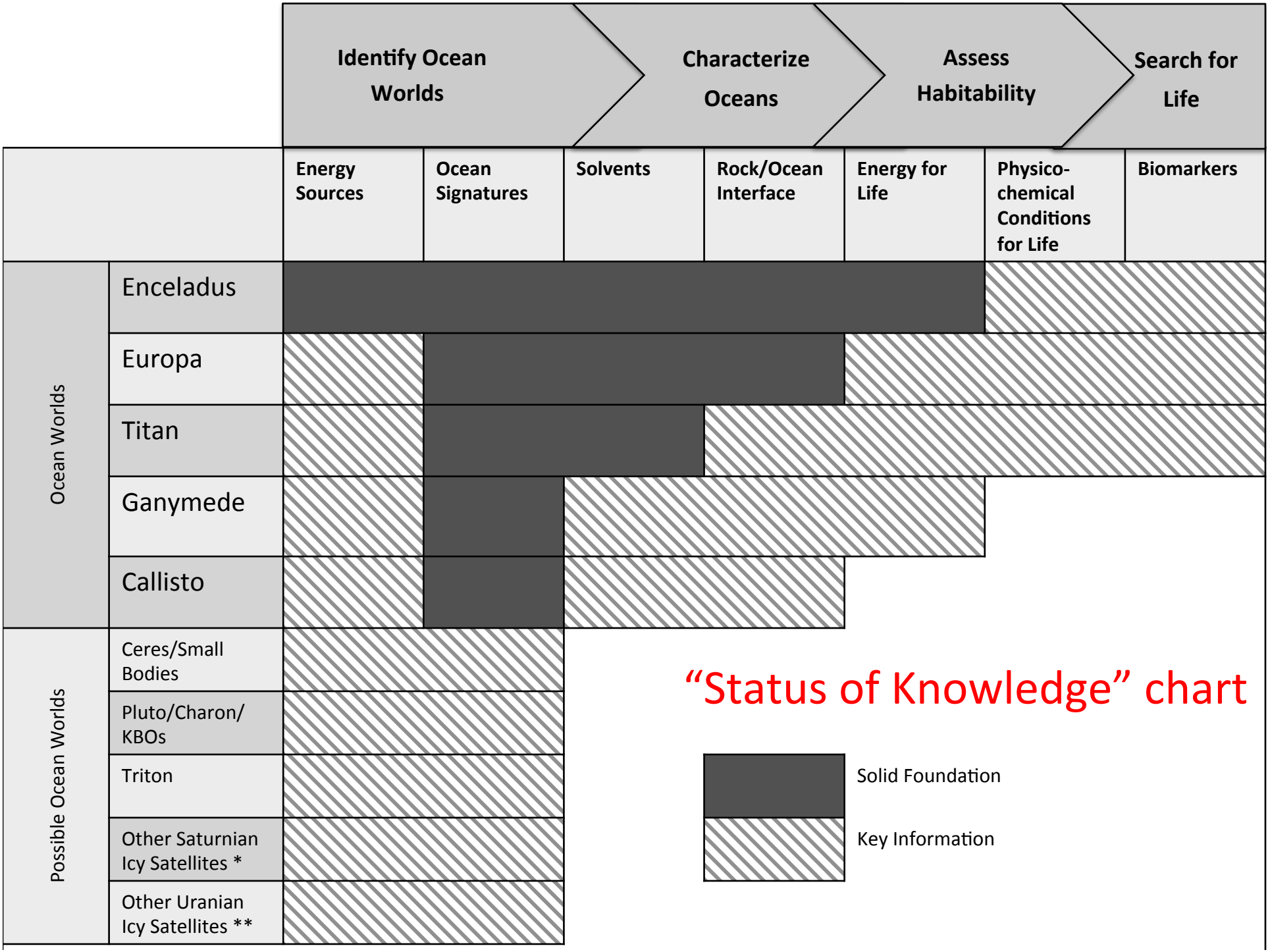
- What are the potential biomarkers in each habitable niche? (determine what we're looking for)
  - What can we learn about life on ocean worlds from studying Earth?
  - What niches for life are possible on ocean worlds?
  - What can we learn about life by understanding the history of ocean worlds from their formation to the present?
  - What should be our target indicators? (Life Detection Ladder)
  - How do we distinguish extant from extinct life in environments in which life might develop, and which timescales (e.g., for metabolism, reproduction, dormancy) matter?
- How to search for and analyze data in different environments?
  - How can we look for extant life on an ocean world remotely (from orbit or during a flyby)?
  - How can we look for extant life on an ocean world in situ (landed, underwater, plume) investigations?
  - How can we look for extant life on an ocean world with sample return science?
  - Which science operational strategies should be used to detect life on ocean worlds?

Target teams

- We formed target teams for the following (groups of) targets
  - Enceladus
  - Europa
  - Pluto, Charon & KBOs
  - Ceres & small bodies
  - Ganymede and Callisto
  - Triton
  - Titan
  - Other satellites (“up and coming”)
- Target teams assessed the status of each target: how well are each of the Theme science questions known, what do we know about them, what is their level of their “ocean-worldness”

Goals, Objectives, Investigations (GOI) Document (http://www.lpi.usra.edu/opag/ROW/)

Table of Contents


Identify Ocean Worlds
Characterize Oceans
Assess Habitability
Search for Life
Energy Sources
Ocean Signatures
Solvents
Rock/Ocean Interface
Energy for Life
Physico-chemical Conditions for Life
Biomarkers
Ocean Worlds
Enceladus
Europa
Titan
Ganymede
Callisto
Possible Ocean Worlds
Ceres/Small Bodies
Pluto/Charon/ KBOs
Triton
Other Saturnian Icy Satellites *
Other Uranian Icy Satellites **
"Status of Knowledge" chart
Solid Foundation
Key Information

Next step: The Roadmap

- Philosophy
  - A balanced program is important
    - Address known ocean worlds to
      - Look for life (if considered habitable)
      - Characterize ocean (as needed)
      - Characterize habitability
      - Search for life
    - Use a variety of mission architectures (flagships -> small sats, as possible)
  - we want to advance our knowledge (extend the bars) on ALL of these bodies (eventually)
  - considering that in this community we do things via decadal surveys (DS)
  - A primary task of ROW is to make some well-defined recommendations for the next DS:
    - what they should consider to be high priority, and also
    - what mission concepts should be studied in advance of that DS.
  - focus on the important *next* missions to different classes of bodies
    - Known ocean worlds
    - Possible ocean worlds
- The concepts on the following slides have not been **fully** vetted by all of ROW yet, but has been distributed for comment and feedback has been positive *[results are not final]*

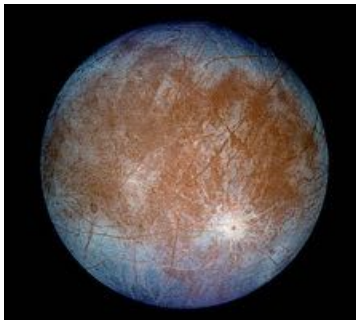
Ocean Worlds Roadmap, Missions Scenarios, & Technologies

- Target Teams have provided
  - input on key measurements needed to move our understanding of each target forward
  - input on future mission types needed
- Technology sub-group (P. Beauchamp) has provided
  - Input on needed technologies

Roadmap

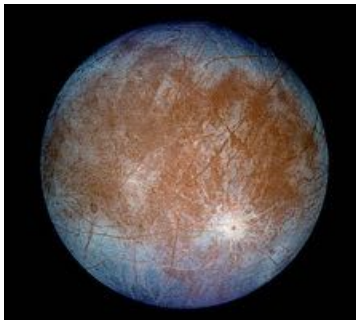
- The highest priority targets are the known ocean worlds (no priority implied):

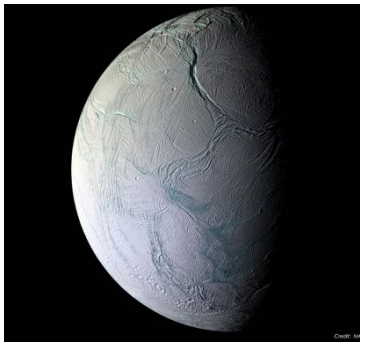
Roadmap



- The highest priority targets are the <u>known</u> ocean worlds (no priority implied)
  - Europa

Roadmap

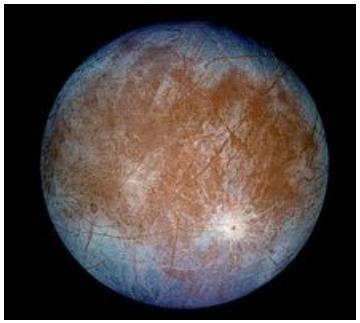


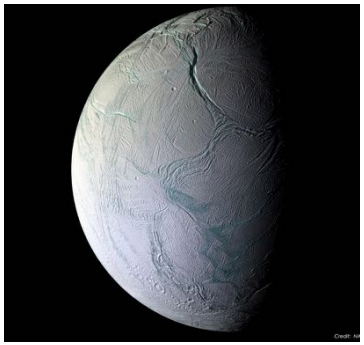


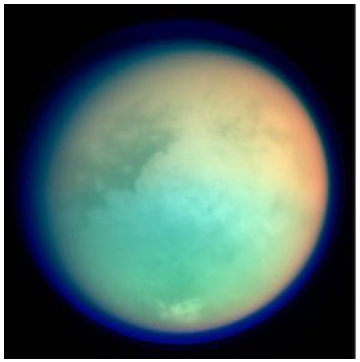
- The highest priority targets are the <u>known</u> ocean worlds (no priority implied)
  - Europa
  - Enceladus

Roadmap

- The highest priority targets are the known ocean worlds (no priority implied)
  - Europa
  - Enceladus
  - Titan

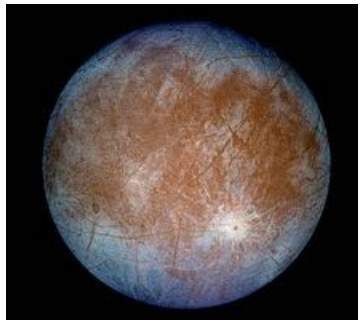


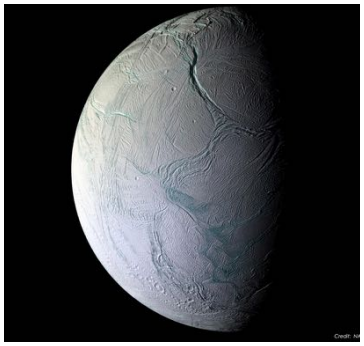


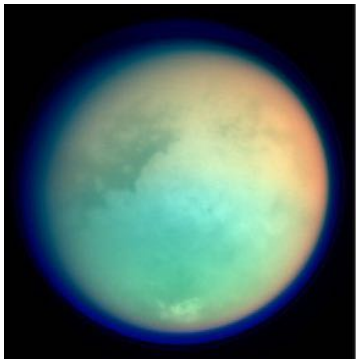


Roadmap

- The highest priority targets are the <u>known</u> ocean worlds (no priority implied)
  - Europa
  - Enceladus
  - Titan
- The OW program also needs to go after a <u>possible</u> ocean world in the next decade (for balance)



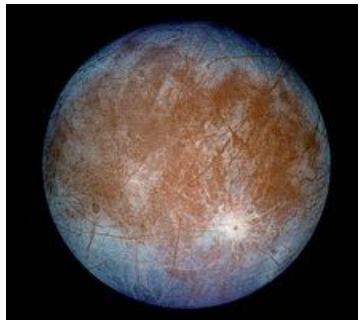
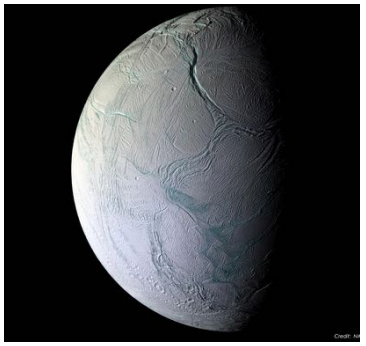
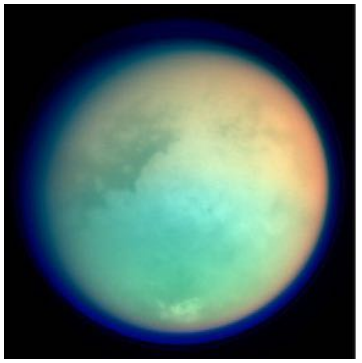




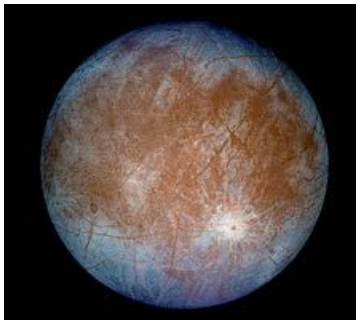
Roadmap

- The highest priority targets are the known ocean worlds (no priority implied)
  - Europa
  - Enceladus
  - Titan
- The OW program also needs to go after a possible ocean world in the next decade
  - Triton

[results are not final]


Europa

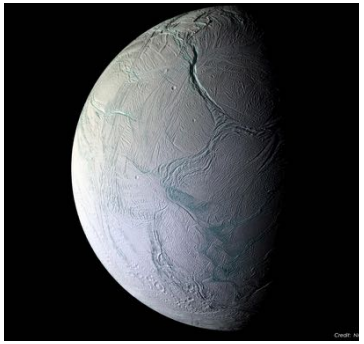


- **Europa:** Europa Clipper is a flagship mission in Phase B of development; the overarching goal of Clipper is to establish the habitability of Europa. Armed with recent observations of possible activity at Europa and in anticipation of Clipper results, a follow-on search-for-life mission could be sent to Europa. An astrobiology-focused Europa Lander mission has recently been studied (Hand et al., 2016).

- **Europa Recommendations** for Decadal Survey and Survey Preparation: The ROW team recommends that the Europa Clipper mission continue as planned for its importance in characterizing the habitability of Europa. The ROW team supports a Europa search-for-life mission, especially if a science payload can be included that can yield important information even if life signature results are ambiguous. Such a mission will advance the technologies needed to detect life signatures at OW targets, especially from in situ measurements.

[wording not final]

Enceladus

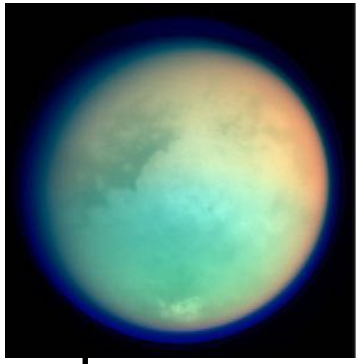


- **Enceladus:** The habitability of Enceladus' ocean has been established using Cassini measurements, and thus to address OW goals, a search-for-life mission could be sent as a next step. Given the ongoing New Frontiers 4 (NF4) competition, the ROW team does not prioritize any of these.

- **Enceladus Recommendations** for Decadal Survey and Survey Preparation: The ROW team recommends that a search-for-life mission at Enceladus be of high priority. If an Enceladus mission is selected for NF4, additional Enceladus mission architectures that address the search-for-life could be studied, potentially as a follow-on to the NF4. If an Enceladus mission is not selected for NF4, a search-for-life mission at Enceladus should be studied in advance of the next Decadal Survey.

[wording not final]

Titan



- **Titan:** The habitability of **Titan**'s subsurface ocean and any interfaces between the ocean and surface, along with the surface lakes and seas of methane/ethane, has yet to be established. Thus, a habitability/ocean characterization mission to Titan is a natural next step to advance OW goals at this body. Numerous types of mission at Titan are possible, and given the ongoing NF4 competition, ROW does not prioritize any of these.

- **Titan Recommendations** for Decadal Survey and Survey Preparation: ROW recommends that missions to characterize Titan's ocean or assess its habitability be of high priority. If a Titan mission is selected for NF4, additional Titan missions that advance the understanding of Titan as an OW should be studied prior to the Decadal Survey and considered by the DS panel.

[wording not final]

Lower-priority known ocean worlds

- **Ganymede:** The ESA JUICE mission is set to explore Ganymede. JUICE will characterize the subsurface ocean to better understand the formation and evolution of this OW.

- **Ganymede Recommendations** for Decadal Survey and Survey Preparation: The ROW team supports the ESA JUICE mission.

- **Callisto:** This known OW remains to be fully characterized. Its deep subsurface ocean and its location on the edge of the Galilean satellite system limits not only communication between the ocean and the surface, but also vital energy input to the ocean. It may serve as an end member on the OW spectrum and help, along with Ceres, to characterize the limit of the ability of bodies to maintain oceans with sparse tidal input. In addition, because Ganymede's ocean sits between layers of high pressure ices, communication between the subsurface ocean and the surface, and energy input into the ocean layer are also limited there. Future Callisto studies could therefore also inform studies of Ganymede's ocean, as they could place bounds on the habitability of oceans that are separated from their rocky mantles.

- **Callisto Recommendations** for Decadal Survey and Survey Preparation: The ROW team supports mission studies to characterize Callisto's ocean and its sustainability. A mission to Callisto should be studied to test if small mission classes can help advance OW objectives.

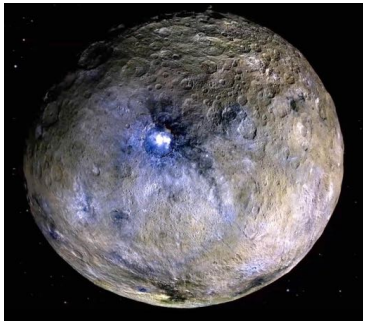
Triton

- **Triton:** Of the possible ocean worlds, Triton is deemed the highest priority target to address as part of an Ocean Worlds program. This priority is given based on the extraordinary hints of activity shown by the Voyager spacecraft (e.g. geyser-like activity; smooth, walled plains units; the cantaloupe terrain suggestive of convection in a liquid layer) and the potential for ocean-driven activity given Cassini results at Enceladus. Furthermore, many Triton mission architectures would simultaneously address Ice Giant goals on which high priority was placed in the Visions & Voyages Decadal Survey. Finally, as Triton likely represents a captured Kuiper Belt object (KBO), comparative planetology with KBOs could also be addressed in a Triton mission.

- **Triton recommendations** for Decadal Survey and Survey Preparation**:** Prior to the next Decadal Survey, a mission study should be performed that would address Triton as a potential Ocean World; such as study could be part of a larger Neptune orbiter mission. The Decadal Survey should place high priority on Triton as a target in the Ocean Worlds program.

[wording not final]

Ceres



- **Ceres:** Ceres is a unique case, a hydrous dwarf planet in the asteroid belt. Ceres harbors liquids (Ceres is ~50% H_2O in volume and has a 40 km thick shell dominated by volatiles, with a density of 1.25 g/cm^3) but whether this constitutes a current ocean is unlikely. Ceres is included in the OW roadmap not because it is considered a present-day ocean world, but because it may be an ancient ocean world; it is a small and heat-limited body, likely in the process of freezing, so it may provide an end-member scenario for medium-sized icy satellites without tidal heating. R&A funding for better modeling and experimental research in light of Ceres results from the Dawn mission are relevant to understanding ocean worlds as a whole.

- **Ceres Recommendations** for Decadal Survey and Survey Preparation: A Ceres mission with a primary objective to detect and characterize any liquids within Ceres should be studied to test if small mission classes can help advance OW objectives.

[wording not final]

Pluto

- **Pluto:** Pluto is the first large object visited in the Kuiper belt and it shows young, potentially cryovolcanic terrains indicating activity may have continued through much of its history. Like the case of Triton, the source of relatively *recent* internal heat on Pluto is not entirely constrained, but models suggest an ocean may persist into the present. Studying large KBOs opens up a new regime for exploring ocean worlds in the solar system, and by comparative planetology helps us understand what is possible for icy moons that are not currently tidally heated.

- **Pluto recommendations** for Decadal Survey and Survey Preparation**:** Mission studies should be performed to address technology advances allowing exploration of the Kuiper belt or a return to Pluto with an orbiter (necessary to study a potential ocean). Studies to explore a potential KBO rendezvous as an extended part of another mission to the outer solar system (e.g., to a gas giant) are also encouraged.

[wording not final]

Roadmap

- Next up for each body to maintain OW programmatic balance:

- **Europa** Habitability mission– *Clipper in progress*
- **Titan** Habitability/Ocean mission– *possibility of NF4 mission selection*
- **Enceladus** search-for-life mission - *possibility of NF4 mission selection*
- **Triton** ocean mission – *Triton orbiter or Neptune orbiter with many Triton flybys (with magnetometer, gravity)*

[results not final]

Decision Rules

- If a Titan mission is not selected in NF4, then the next Decadal Survey should rank highly a Titan mission (whatever the class) – orbiter, plains lander, aerial explorer, lake lander and/or submarine; such architectures could include in situ atmospheric study at a range of altitudes.

- If an Enceladus mission is not selected in NF4, then the next Decadal Survey should rank highly an Enceladus mission (whatever the class).

- If neither Enceladus nor Titan are selected in the NF4 call, the next Decadal Survey should place an especially high priority on a mission to study life/habitability at one or both of these bodies. A mission that addresses both Enceladus and Titan should be considered.

[wording not final]

ROW-Recommended Mission Studies

- Triton ocean characterization
- Enceladus and Titan missions or joint mission (regardless of NF4 outcome)
- Ceres and/or Callisto missions to detect/ characterize subsurface oceans/reservoirs (perhaps Discovery-class?)
- Pluto ocean characterization

[not final]

Finally

- We also say words in the report about other important but lower-priority bodies (e.g. Ariel, Miranda, Dione)
  - Just not discussed here
  - Important for understanding the spectrum of ocean worlds, though we do by necessity need to limit our recommendations to the next Decadal Survey

[not final]

Let's go out and study some ocean worlds!