# Roadmaps to Ocean Worlds

OPAG Update
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# 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

# Philosophy on Ocean Worlds

## *What is an Ocean World?*

- We want to be inclusive!
- All bodies which plausibly can have or are known to have an ocean will be considered as part of this study; the focus is on current liquid oceans, not necessarily global
- A goal is to study the entire spectrum of Ocean Worlds... to understand life in the context of all Ocean Worlds.
  - If we focus on one target and find life, we won't be done!
  - Why would life evolve at one world at not another?
  - Why would life take a particular form at one world and a different one at another?
- It's important to consider ties to the Earth and Earth's ocean here too
- After we carefully consider overall/general science objectives, we subdivided into groups to consider what questions need to be addressed at a target level, and are starting to consider potential mission plans

# Overarching Goal

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

**Identify ocean worlds, evaluate their habitability, and search for life**

# Ocean World Themes

- Four themes
  - Identify ocean worlds in the solar system
  - Characterize the oceans
  - Characterize the habitability of ocean worlds (Earth and beyond)
  - Understand how life might exist within ocean worlds and search for evidence of life within them
- Theme groups came up with an initial set of science questions for each theme
  - Ranging from high level to very detailed

# 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?
  - Is the planet 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?

# Theme 2: Characterize the ocean of each ocean world
## (wording in this theme is still under discussion)

- Characterize the ocean's physical properties
  - What is the thickness, salinity, density and composition of the ocean? How do these properties vary spatially and /or temporally?
- Characterize the ocean interfaces
  - Characterize the seafloor; High-pressure ocean – silicate interaction
  - Ice shell: What is the thickness, composition (including the presence of any organics), porosity of the ice shell (crust) and how do these properties vary spatially and /or temporally?
  - 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 radiation available? In what wavelengths 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?

# 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 life 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 life on an ocean world remotely (from orbit or during a flyby)?
  - How can we look for life on an ocean world in situ (landed, underwater, plume) investigations?
  - How can we look for life on an ocean world with sample return science?

# Target teams

- We formed target teams for the following (groups of ) targets
  - Enceladus
  - Europa
  - Pluto & KBOs
  - Ceres & small bodies
  - Ganymede and Callisto
  - Triton
  - Titan
  - Other satellites (“up and coming”)
- Target teams have been working to assess 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”

# Investigations Roadmap*


| | Energy Sources for Ocean Worlds | Signatures of Oceans | Availability of Water | Energy Required for Life | Physiochemical Conditions Required for Life | Potential for the Origin and Support of Life | Biomarkers of Life | Search for evidence of life |
|---|---|---|---|---|---|---|---|---|
| **Enceladus** | | | | | | | | |
| **Europa** | | | | | | | | |
| **Titan** | | | | | | | | |
| **Ganymede** | | | | | | | | |
| **Callisto** | | | | | | | | |
| **Triton** | | | | | | | | |
| **Ceres & SB** | | | | | | | | |
| **Pluto, Charon & KBOs** | | | | | | | | |

*idealized version of the Investigations Roadmap is shown here. The real version is still under discussion.

# Goals, Objectives, Investigations report

- We are working on a Goals, Objectives and Investigations (GOI) report/document to deliver to HQ in the next 2-3 months
  - Things are moving forward at HQ in terms of OW activities (e.g. COLDTech) and we want to advise HQ (through OPAG) of OW science goals to guide activities/decisions
- Ultimately the final polished GOI document, and a report on recommended mission strategies/roadmaps, will be input for the next decadal

# Ocean Worlds R&A program needed

- ***A major finding of this study*** is that in order to map out a coherent Ocean Worlds program, significant input is required from studies here on Earth: a rigorous R&A program is called for, to enable future Ocean Worlds missions to be thoughtfully planned. Research objectives/investigations involve questions that can be addressed here on earth – through modeling, field studies, lab work etc. so that spacecraft data can be undertaken and interpreted properly.
- More details (e.g. specific questions to be addressed through an R&A program) on later slides

# ROW findings to OPAG

- Existing (or new) R&A investments should support fundamental research vital to Ocean World exploration in order to maintain the momentum of the Ocean World program. The ROW effort has identified fundamental science questions that can support the identification of new Ocean Worlds, the knowledge needed to assess their potential habitability, and identify bio-signatures to find extant life. Such fundamental research will have immediate science impact on the Europa Missions and upcoming New Frontiers and Discovery mission AO calls.
- R&A investments to support maturation of instruments and technologies vital to Ocean World exploration should build on the augmentation of funding to PICASSO, MATISSE and the COLDTech programs.
- Efficient, capable, robust energy sources and frequent launch capability is critical for supporting a healthy Ocean Worlds exploration program.

# Current & Future Activities

- In work:
  - Identify mission concepts and measurements needed to address science questions
  - to be put into a final report around the end of year
    - Feedback at winter/spring AG meetings, LPSC
    - Then will go through red team review
  - Along with GOI document, will go through red team review for use in next decadal

# Team members

- Amend Jan
- Aye Michael
- Bannister Michele
- Barge Laurie
- Beauchamp Patricia
- Bland Michael
- Bowman Jeff
- Braun Bobby
- Brinckerhoff William
- Byrne Paul
- Cabrol Nathalie
- Castillo-Rogez Julie
- Collins Geoffrey
- Cooper John
- Diniega Serina
- Elder Catherine

Furfaro Roberto
German Chris
Glein Chris
Goodman Jason
Hand Kevin
Hayes Alex
Hibbard Kenneth
Hibbitts Karl
Hoehler Tori
Howett Carly
Kargel Jeffrey
Lindensmith Chris
Lopes Rosaly
MacKenzie Shannon
Malaska Michael
McKay Chris
Neish Catherine
Neveu Marc
Olkin Cathy
Pappalardo Robert
Phillips Cynthia
Portyankina Ganna

Quick Lynnae
Rhoden Alyssa
Schenk Paul
Schmidt Britney
Sherwood Brent
Shock Everett
Singer Kelsi
Soderblom Jason
Sotin Christophe
Turtle Elizabeth
Vance Steve
Westlake Joseph
Wray James
Such Pamela
Ricco Antonio
Hosseini Sona
Metzger Philip
Eubanks Marshall
Buratti Bonnie
Schaible Micah
Holler Bryan

Patterson Wes
Schaible George
Poston Michael
Walker Catherine
Dhingra Rajani
Nordheim Tom
Verbiscer Anne
Cable Morgan
Scully Jennifer
Patthoff Alex
Martin Emily

# Extra slides

# Some Additional R&A questions – goal 1

- How do materials behave under conditions relevant to any particular target body?
  - 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?
- C.5 What are the thermophysical properties of material under conditions relevant to ocean worlds?

# Some Additional R&A questions – goal 2

- Field work/analogue studies : oceans/ice shells/habitability (mostly currently through NSF); some through PSTAR, Exobio? Habitable Worlds
- Interfaces with Earth oceanography people & collaborative studies (NOAA, NSF; the NASA Earth Science Oceans program – mostly remote sensing)
- Studies related to ice shell – radar reflectivity etc in prep for Europa mission
- Studies related to seafloor/silicate interactions & high-pressure stuff (Habitable Worlds); thermodynamics/chemistry of water-rock interactions (HW/SSW); Reactions between water-rock (NSF & NASA)
- Equipment: Simulation chambers- for creating relevant environments

# Some Additional R&A questions – goal 3

- **"Fundamentals of Habitability" questions:**
- Solvent
  - What solvents are suitable for life?
    - Are there limits (water activity, ionic strength, other) to the composition of aqueous environments that can support life? If so, what are they?
    - Are solvents other than water capable of supporting life? If so, what are they?
  - How do the temporal and spatial extents of liquid environments factor into habitability? How short/transient/small is insufficient? Can a liquid environment be too extensive in space and time to be habitable?
- Energy
  - Can life take advantage of energy sources other than those known to support life on Earth (redox or visible-near IR light)?
  - When and how does energy availability constrain the type, diversity, and/or abundance of life?
  - Are there organismal, local, or planetary scale limits on how much energy is enough to support life? If so, what are they, and how do they depend on the physicochemical environment?
  - Are there upper limits to the amount of energy that can be constructively harnessed by life (vs. that same energy becoming destructive)?
- Elemental and molecular raw materials
  - Can biochemistry be based on elements other than those utilized by life on Earth?
  - Are there lower limits on the abundance or constraints on the chemical form of elemental and molecular resources required for habitability?
- Physicochemical environment
  - Can life transcend the physicochemical limits exhibited by life on Earth? Of particular importance for ocean worlds, what are the high pressure limits for life?
  - How do the physicochemical limits for life change under conditions of compound "extremes" or energy limitation?
- Origin of Life
  - Under what physicochemical conditions, with what energy sources, and with what abundance and chemical form of elemental and molecular raw materials can life emerge? How does the probability of an origin of life vary within the range of permissive conditions?
  - How does the time scale required for life to emerge vary as a function of conditions within the permissive set?
  - Are there processes essential to the origin of life that definitively do not occur in sub-ice oceans?

- Furthermore, basic research also needs to be undertaken to understand signatures of life. (**Goal 3 How might life exist within ocean worlds? Including non-H2O-based life**

# Some Additional R&A questions – goal 4

- basic biology/metabolism/conditions/survival (NAI; NSF?)
- Survival of amino acids/biomolecules under various conditions (e.g radiation) (Biosignatures working group of NAI
- Validation of biology technologies for application to ocean worlds
- Disconnect between chemical detection & life detection – how to get past this; think of ecosystems & whole cells
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- Studies of non-water-based life (Habitable Worlds, Exobio)
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- Biopreservation potential for liquid h2o interacting with organics on OW surfaces (e.g. what to look for; cryobiology)
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- Planetary protection. E.g. Would an Earth-based biomolecule definitely end up in an extraterrestrial ocean?