Astrobiology as a driving theme for Ocean Worlds exploration: Ocean Worlds Working Group input into DARES RFI

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Primary Topic: 4. Incorporate and synthesize recent recommendations
Secondary Topics: 2. Emerging themes and technologies, 6. Astrobio role in missions.

The Ocean Worlds Working Group (OWWG) is a cross-Assessment Group working group established by OPAG, SBAG, and NOW in 2023 at the recommendation of the 2023 Decadal Survey *Origins, Worlds, and Life* (OWL, National Academies, 2023). The objective of the OWWG is to formulate a coherent strategy for Ocean Worlds (OW) exploration that identifies the key questions driving OW exploration, the missions capable of addressing those questions, and the technology development required to substantiate those missions. Through a series of community workshops, and synchronous and asynchronous working sessions in 2023 and 2024, the OWWG collected input from across the OW community. Based on these discussions the OWWG has identified four questions that govern future exploration of OWs. Astrobiology is fundamental to the ongoing exploration of these worlds and is woven throughout these questions.

The driving questions for the exploration of Ocean Worlds are as follows.

OW1. Do water oceans exist in the interiors of outer solar system bodies?
OW2. How do ocean worlds form and evolve?
OW3. Do ocean worlds have past or present environments conducive to life?
OW4. Is there evidence for present or past life in plume material, on the surface, or in the interior of ocean worlds?

These questions closely follow goals defined by the Road Map for Ocean Worlds [Hendrix et al. 2019], which are to 1) identify ocean worlds in the Solar System, 2) characterize the ocean of each ocean world, 3) characterize the habitability of each ocean world, and 4) understand how life might exist in each ocean world, search for life, and understand the biology. Additionally, the OWWG questions stem directly from the OWL, which includes questions of dynamic habitability (Q10), the search for life elsewhere (Q11), accretion in the outer solar system (Q2), the evolution of solid body interiors and surface (Q5), and the evolution of circumplanetary systems (Q8) as priority science questions.

The limited resources dedicated to Ocean Worlds requires that the four questions driving ocean world exploration listed above must be prioritized. Given the scientific and societal impact of identifying extant, non-terrestrial biology, the highest priority science goals are to identify the ocean worlds with habitats most conducive to extant life and to search for life within them (OW3 and OW4 above). These goals are captured by the third science theme identified by OWL: "*Life and Habitability:* What conditions led to habitable environments and the emergence of life on Earth, and did life form elsewhere?", and specifically the high-priority questions Q10 and Q11. The objective of Ocean World exploration should therefore be to push as far down the Roadmap to Ocean Worlds (ROW) as quickly as possible by advancing toward the search for extant life. However, care should be taken not to exceed the limit of our current knowledge. Thus, given

limited resources, near-term missions should focus on characterizing the habitability of known ocean worlds, with follow-on missions to search for life. Mission architectures that combine the search for biomarkers with detailed characterization of habitability should also be considered. This avoids utilizing resources to search for life in less hospitable locales and risking the "Viking effect," in which a non-detection of biosignatures in an inhospitable environment derails future exploration.

Technological advances and facilities needed: To enable the exploration of these worlds with habitability and life detection foci, several technological advances have been identified for necessary advancement [see PESTO, 2024]. The Origins Worlds and Life (OWL) planetary decadal [National Academies, 2023] identifies technologies needing development in Table 21-1, including:

- In situ sample handling, preprocessing, and analysis
- In situ measurements with improved sensitivity and dynamic range, ability to mitigate noise sources, and reduced mass, power, and volume requirements
- Integrated instrument suites

Previous funding by NASA's Science Mission Directorate has supported technology advancements through Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO), Maturation of Instruments for Solar System Exploration (MatISSE), and Concepts for Ocean worlds Life Detection Technology (COLDTech) instrument development grants as well as that for subsurface access technologies through the Scientific Exploration Subsurface Access Mechanism for Europa (SESAME) program. These programs such continue to provide funding that focuses on technology and instrument development that enable access to and life detection capabilities within the harsh, yet extremely promising, environments of ocean worlds (see DARES papers e.g., Network for Ocean Worlds; Network for Life Detection; Outer Planets Assessment Group (OPAG); Craft et al.). Additionally, cryogenic test and sample analyses facilities that support and enable the development of these technologies and instruments must be established and maintained with adequate funding support (see DARES papers by OPAG and Pontefract et al).

Progress is being made on addressing critical OW science questions. Current missions that address the primary question OW3 include the following.

- Europa Clipper [Vance et al., 2023]
    - Specifically designed to characterize the habitability of Europa's ocean
- Dragonfly (in development) [Barnes et al., 2021]
    - Focus on prebiotic chemistry, but measurements will improve understanding of Titan's habitability. Has the capability for biosignature detections.
- JUICE [Grasset et al., 2013]
    - Non-NASA. Ganymede focused, but critical information on the Jovian system including characterizing the habitability of Europa, Callisto, and Ganymede.

No current missions address primary question OW4; however, several missions that address questions OW3 and OW4 have been proposed or studied. These include the following missions, the first of which was given a high priority by the OWL Decadal Survey.

- Enceladus Orbilander [MacKenzie et al., 2022] (OW4)

- Europa Lander [Hand et al., 2022] (OW4)
- Ocean World Subsurface Access [Oleson et al., 2019] (OW3 and OW4)
- Enceladus Multiple Flyby (*Included in NF5*) [Davila et al., 2020]
- Enceladus*
- Titan Orbiter and Probe* [Hayes et al., 2020]
- ESA L4 Enceladus [Martins et al., 2024]

*Previously included in OWL NF5 or NF6 but recommended for removal by the Committee on Astrobiology and Planetary Science (CAPS) [NASM 2025]

Although lower in priority, answering the questions of where water oceans exist (OW1) and how ocean worlds form and evolve (OW2) is also important. If life is detected (via a collection of biomarkers) within a known ocean world, immediate follow-on questions include 1) "how common is non-terrestrial life?" and 2) "what are the conditions that permit the origin of life?". These questions are best addressed by answering questions OW1 and OW2 above. Question OW1 specifically addresses the distribution and occurrence rate of ocean habits, and question OW2 emphasizes the importance of understanding ocean worlds as complex systems. Unfortunately, there are no current missions that address OW1; however, several missions have been proposed or studied that address this question, including the Uranus Orbiter and Probe, which was the highest priority Flagship Class mission identified by the OWL Decadal.

Potential missions that support OW1 (identify ocean worlds) include:

- Uranus Orbiter and Probe (*OWL highest priority Flagship*) [Simon et al., 2020]
- Neptune/Triton orbiter or flyby, or Triton Ocean Worlds Surveyor (*Included in NF7*) [Rymer et al. 2020; Hansen-Koharcheck et al. 2020]
- Ceres Sample Return (*Included in NF5*) [Castillo-Rogez et al., 2020]
- Calypso [Martin, E. S., Bottke W. F., et al., 2020]
- Pluto System and Kuiper Belt [Howett et al., 2020]

Because of the breadth of OW2, numerous current, proposed or studied missions address aspects of the question. The current missions that address OW2 include the following.

- Juno [Bolton et al., 2017]
- Europa Clipper [Vance et al., 2023]
- Dragonfly (in development) [Barnes et al., 2021]
- Lucy [Levison et al., 2021]
- JUICE [Grasset et al., 2013]

Potential missions that support OW2 include, but are not limited to the following.

- Uranus Orbiter and Probe (*OWL highest priority Flagship*) [Simon et al., 2020]
- Enceladus Orbilander [MacKenzie et al., 2022]
- Enceladus Multiple Flyby (*Included in NF5*) [Davila et al., 2020]
- Neptune/Triton orbiter or flyby, or Triton Ocean Worlds Surveyor (*Included in NF7*) [Rymer et al. 2020; Hansen-Koharcheck et al. 2020]
- Ceres Sample Return (NF5) [Castillo-Rogez et al. 2020]
- Centaur Orbiter and Lander (CORAL) (NF5) [Telus et al., 2020]
- Comet Surface Sample Return (*Included in NF5*)
- Europa Lander [Hand et al., 2022]

- Saturn Probe (*Included in NF5*)
- Titan Orbiter and Probe* [Hayes et al., 2020]
- Ocean World Subsurface Access mission [Oleson et al., 2019]

*Previously included in OWL NF5 or NF6 but recommended for removal by the Committee on Astrobiology and Planetary Science (CAPS) [NASM 2025]

Critically, the missions required to address each question identified by the OWWG tend to differ in scale. Questions OW3 and OW4 (habitability and the search for life) typically require large class missions. These include Europa Clipper (Flagship), JUICE (ESA L-class), Enceladus Orbilander (formulated as Flagship), Europa Lander (formulated as Flagship), and subsurface access ocean world missions (Flagship, e.g. Oleson et al., 2019). Many aspects of questions OW1 and OW2 can be addressed by missions in the New Frontiers class (Neptune/Triton orbiter, Ceres Sample Return, CORAL, Comet Sample Return) or even Discovery class. Questions OW1 and OW2 can also be partly addressed by missions focused on system science, such as the Uranus Orbiter and Probe mission. Thus, progress on answering each question can be made across NASA's existing mission line.

On UOP

As currently formulated, the Uranus Orbiter and Probe (UOP) mission does not address the highest priority OW science goals. Although the *stated* mission goal is "Exploring Habitability", the associated questions are [Simon et al. 2021]

- Did any of Uranus's moons have substantial heat flux or oceans in the past?
- Are any of the moons presently ocean worlds?

These questions are consistent with OWWG priority 2 questions OW1 and OW2, rather than the higher priority questions OW3 (Habitability) and OW4 (life). The UOP mission study identified four additional science objectives, including determining the Uranian satellite's internal structure, composition, surface geology, and exogenic processing, but in the opinion of the OWWG, the question of habitability is not fully addressed. Additional mission design efforts are warranted to investigate whether modifications to the UOP mission architecture, design, or operations could enable UOP to address the highest priority OW goals without substantially increasing mission cost or risk.

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