Astro2020 Science White Paper

Investigating the Solar System's Ocean Worlds with Next-Generation Space Telescopes

Thematic Areas: ☒ Planetary Systems ☐ Star and Planet Formation
☐Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐Stars and Stellar Evolution ☐Resolved Stellar Populations and their Environments
☐Galaxy Evolution ☐Multi-Messenger Astronomy and Astrophysics

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Abstract:

Spurred by discoveries of this past decade and intense scientific and political interest, the search for life on the solar system's ocean worlds has begun. This search must include next-generation space telescopes, which are uniquely capable of observing numerous distant targets at spatial resolutions equivalent to a not-too-distant flyby, for nearly arbitrary amounts of time, unimpeded by the Earth's atmosphere. This white paper describes the specific questions – drawn from the NASA Roadmap to Ocean Worlds – that can be best addressed by future space telescopes. It also identifies key measurements to help plan the design and operation of these assets in order to ensure the best use of their capabilities in the ocean worlds exploration endeavor.

Ocean worlds in the solar system, defined for the purposes of this white paper as bodies with a current local or global liquid ocean (Lunine 2017; Hendrix, Hurford et al. 2019), have become the subject of intense scientific interest in the past decade as possible abodes for life beyond Earth. Ten years ago, there was only strong evidence for subsurface oceans on Jupiter's moons Europa, Ganymede, and Callisto (Khurana et al. 1998; Kivelson et al. 2000, 2002), the H_2O plume on Enceladus (e.g. Porco et al. 2006), and Triton's N_2 plume (Smith et al. 1989). It is now known that Enceladus' plume is sourced from a global ocean (Thomas et al. 2016) at conditions compatible with life (Sekine et al. 2015), providing energy and bioessential element sources (Waite et al. 2017; Postberg et al. 2018). Europa too may be intermittently erupting water to space (Roth et al. 2014; Sparks et al. 2016, 2017; Jia et al., 2018). Titan is now recognized as a world of two oceans: surface light hydrocarbons and subsurface water (Iess et al. 2012). Indirect evidence indicates that Pluto and Saturn's moon Dione too may have a deep ocean (Nimmo et al. 2016; Beuthe et al. 2016), and that the last pockets of briny water may be freezing on Ceres (Neveu and Desch 2015). There may be many more possible ocean worlds in the solar system, yet to be investigated.

The interest has widened from purely scientific to also political, with the U.S. Congress mandating that NASA establish "an Ocean World Exploration Program whose primary goal is to discover extant life on another world" (H. Rept., 2015). In response, the community has developed a NASA Roadmap to Ocean Worlds (Hendrix, Hurford et al. 2019). The Roadmap outlines key science goals as milestones in assessing the potential for ocean worlds to host life (Fig. 1). Ideally, these goals would be addressed by robotic exploration at each ocean world. However, the sheer number of targets (Fig. 2) and necessity for monitoring at practical timescales of days to decades makes complementary telescopic observations essential.

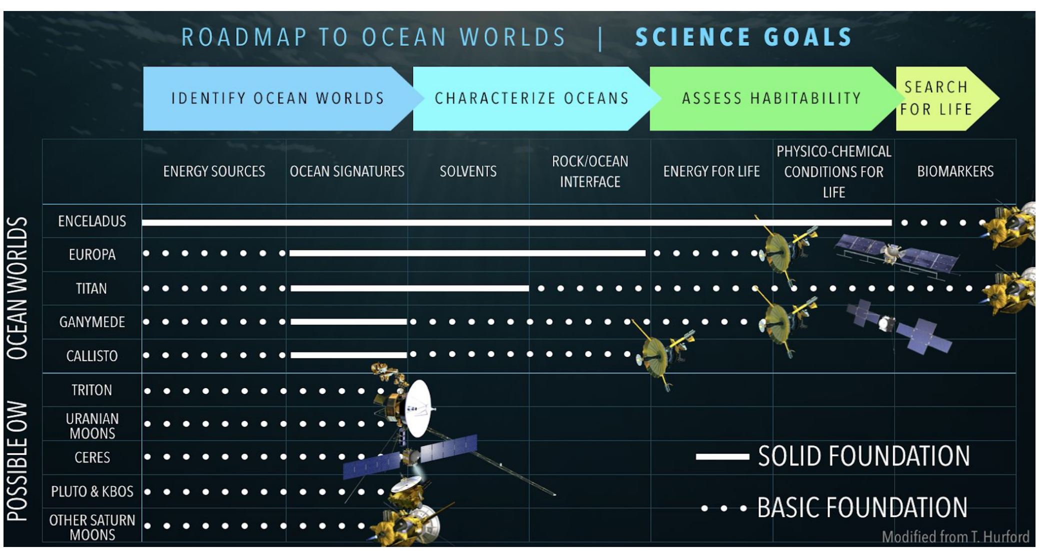

Figure 1. Science goals for ocean world exploration. White lines across roadmap milestones depict the current state of knowledge for each world or class of worlds from past exploration by the Cassini, Galileo, Voyager, Dawn, and New Horizons spacecrafts (from top to bottom). Upcoming missions such as Europa Clipper (NASA) to Europa and JUICE (ESA) to Ganymede will make further progress along this roadmap, but there is a need for a higher cadence of observations of a large number of worlds that requires complementary telescopic observations. Modified from Hendrix, Hurford et al. (2019).

Here, we describe ocean world science uniquely achievable with a next-generation space telescope (labeled  in Fig. 3-4). We exclude the science that could be achieved just as well at a lower cost and risk with 30-m class ground-based observatories with adaptive optics (), but consider the complementarity of remote observations from space with the science that can be achieved in situ at a few select planetary targets with robotic planetary missions ().

Space telescopes are uniquely capable of observing:

(1) a **wide number of solar system targets** (unlike missions to these targets),

(2) in **spectral windows otherwise masked** by atmospheric absorption on the ground, and

(3) for nearly **arbitrary periods of time** if at an appropriate location (e.g. Earth-Sun Lagrange 2 point), uninterrupted by orbital constraints, targets setting below the horizon, or weather.

Relevant large missions under study involve 4- to 15-m diameter mirrors and instruments able to probe UV, near-IR, and far-IR wavelengths to which Earth's atmosphere is opaque (LUVOIR, HabEx, and OST Interim Reports, 2018). Telescopes of this size would provide remarkable spatial resolution on ocean worlds, comparable to a not-too-distant flyby at Ceres, Jupiter, and Saturn, and revealing large-scale surface geology on many Kuiper belt worlds (Fig. 2).

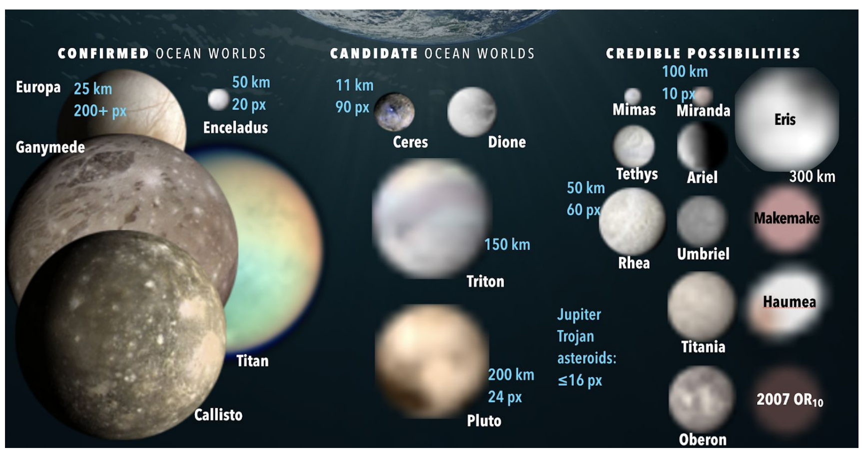

Figure 2. òConfirmedó ocean worlds, òcandidatesó, and òcredible possibilitiesó (Hendrix, Hurford et al. 2019), with Earth limb at top for scale. For each, a spacecraft image (or, for KBOs, a disk of the approximate albedo and color) has been downgraded to the spatial resolution of a 15-m mirror at 500 nm observing from Earth-Sun L2, assuming 2 pixels per resolution element. The spatial resolution is inversely proportional to mirror diameter and directly proportional to wavelength.

What science questions can be addressed with these capabilities? Among many listed under each of the Roadmap to Ocean Worlds four key goals, two questions (both part of Goal I) are particularly amenable to space-based telescopic observations.

1. Is there a sufficient energy source to support a persistent ocean?

The Roadmap's first goal is to identify the ocean worlds of the solar system. This goal, a prerequisite to more detailed investigation by focused missions, necessitates the observation of many dwarf planet and moon targets. This question pertains to the tidal energy available to moons, which depends on the moons' orbital properties that, in turn, change depending in part on the interior properties of the host planet. Measuring these changes constrains the past and current tidal energy available to support an ocean. These can be measured in two ways (Fig. 3):

Measurement 1 ï Doppler imaging of the host planet using techniques derived from asteroseismology (Gaulme et al. 2015) can reveal the structure of its interior (Ice Giants SDT, 2017). In turn, this informs how internal tidal dissipation takes place and therefore its influence on the moons’ orbits and changing tidal energy supply (e.g. Fuller et al. 2016; Lainey et al. 2017). This can require continuous or repeated observations on daily timescales over long time baselines.

Measurement 2 ï Astrometry of the moonsô orbits (semi-major axis, eccentricity, inclination through time) constrains the present and past levels of tidal energy that can be dissipated in the moons given their changing orbital configuration. This requires intermittent measurements at high spatial resolution on timescales as long as possible (Lainey et al. 2017).

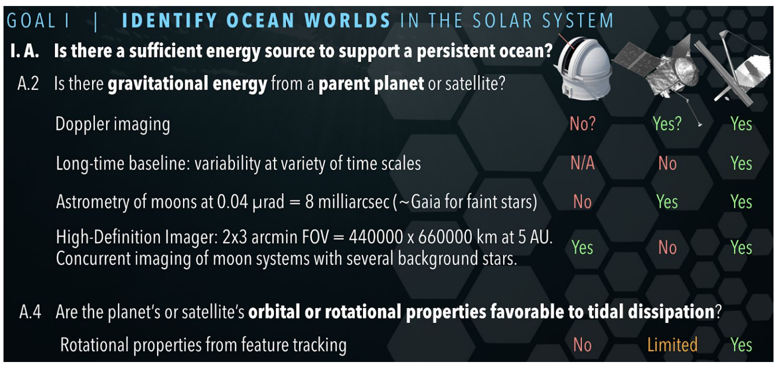

Figure 3. A space-based telescope can constrain the present and past tidal energy supply available to icy moons by (1) observing the host giant planet over a variety of timescales to constrain its interior (internal dissipation) and (2) monitoring the moons’ orbital evolution by astrometry.

2. Are signatures of ongoing geological activity (or current liquids) detected?

Such signatures have been instrumental in observing Enceladus’ plume and Titan’s surface seas, shaping exploration strategies for Europa’s potential plumes, and putting Triton, Pluto, and Ceres on the ocean worlds roadmap. Among the possible signatures listed in Fig. 4, two are ideal for searches using space telescopes:

Figure 4. Space telescopes are uniquely able to survey plume / exospheric signatures of geologic activity / current liquids, and optimal for tracking surface features to constrain the interior. Observations constrained to low phase angles prevent forward scattering/glint. Compositions, except for spectral windows only accessible from space, are better or more cheaply determined with ground-based ELTs with adaptive optics.

Measurement 3 ï Plume and atmospheric/exospheric activity can be monitored at high spatial resolution (Fig. 5), without the interference of Earth's atmosphere, over a variety of timescales. Enceladus has been continuously erupting for more than a decade, but Europa's potential plumes are intermittent or vary enough as to evade most detection attempts. UV emission features (Roth et al. 2014) offer the best spatial resolution and can constrain to first order the plume composition. Absorption of the continuum of a transited host planet could work too (Sparks et al. 2016, 2017), although at high spatial resolution the background may be highly variable. Vibrational (IR) features too may be amenable to observation, but at comparatively lower spatial resolution. Plumes on distant Triton and Kuiper belt worlds would be unresolved (Fig. 2), but global atmospheric changes can be monitored by taking advantage of punctual, short occultations (e.g. Elliot et al. 1998).

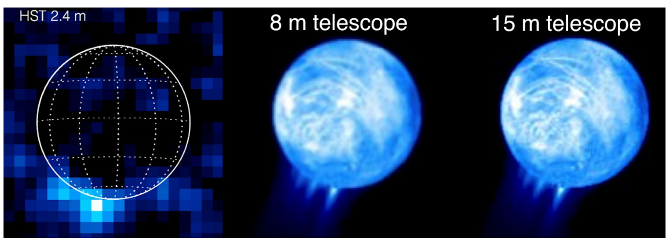

Figure 5. Left: detection of H emission in the far-UV near Europaîs limb attributed to a water vapor plume; HST (2.4-m mirror)/STIS data (Roth et al. 2014). Center & right: simulated far-UV plume observations with 8-m and 15-m telescopes (although plumes are expected to be more umbrella-shaped like Ioîs; Spencer et al. 2007; Berg et al. 2016). Spatial resolution for Uranian moons with a 15-m mirror is comparable to HST resolution at Jupiter. Images from R. Juanola-Parramon (center) and G. Ballester (right).

Measurement 4 ï Surface feature tracking can constrain the interior of moons from their rotational (non-synchronous rotation, polar wander) or libration properties (Thomas et al. 2016). For distant Kuiper belt objects, it can complement light curves in determining rotation periods and spin poles to constrain e.g. the moments of inertia (degree of interior differentiation), key inputs to geophysical evolution models (e.g. Castillo-Rogez & McCord, 2010). Feature tracking requires high spatial resolution and pointing over daily timescales.

Goals II and III of the Roadmap pertain to the ocean characterization and its energy and bioessential element supply. They are better served by in situ planetary missions or ground-based remote sensing, except for the detection of compositional features in spectral ranges not accessible by either, due to limited payloads or atmospheric interference (e.g. Bauer et al. 2010 for Triton; Hendrix et al. 2016 for Ceres).

Goal IV pertains to the direct search for features of life. Target indicators amenable to remote detection include (Neveu et al. 2018):

- isotopic fractionations indicative of metabolism in an atmosphere or plume (more appropriate for targeted in situ sampling in the case of solar system objects),
- the co-location of oxidant and reductant species (see Goals II-III above),
- spectral signatures of pigments (unlikely for subsurface biospheres), and
- spectral signatures of amino acid, nucleobase, and lipid building blocks (difficult; Herbst & van Dishoek 2009).

Beyond features of life, telescopic observations can provide contextual information to facilitate the interpretation of these features, such as information on the intermittency of plumes to support plume measurements carried out with an in situ mission.

In the next decades, it is likely that robotic planetary missions addressing each of the Roadmap's goals will fly. Among numerous concepts at various stages of maturity, some seek to explore the ice giants' moon systems (Ice Giants SDT, 2017), investigate the habitability of Titan (Turtle et al. 2018), and search for life by landing on Europa's surface (Hand et al. 2017) or sampling Enceladus' plume with sophisticated chemical sensors (Lunine et al. 2015; Eigenbrode et al. 2018). However, limited flight opportunities make a concerted campaign conceivable for only the most promising targets (e.g. Sherwood 2016). With the unique ability to observe and monitor numerous targets over a wide range of timescales unimpeded by the Earth's atmosphere, next-generation space telescopes can support, complement, and add to the groundbreaking scientific return expected from the exploration of the solar system's ocean worlds.

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