Pioneering Outer Planet Ocean Exploration at Europa and Beyond.

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Introduction: A mission to explore Jupiter's moon, Europa, has been enthusiastically supported by both of the last two Planetary Decadal Surveys. Europa is one of the most astrobiologically interesting worlds in the solar system, and future exploration of Europa will serve as a model for exploration of other ocean worlds. Europa is a challenging target, orbiting close enough to Jupiter to be continuously bathed in damaging radiation and dynamically taxing due to the constant influence of Jupiter's gravity. Here we describe the pioneering NASA mission to Europa [1] and envisage the future of planetary ocean exploration and search for life missions that it will enable.

A new age of space exploration: Use of NASA's Space Launch System would allow direct transit of the Europa Multiple Flyby Mission to Europa in only ~ three years [2]. This innovation creates the possibility for exploration of the outer solar system with a cadence comparable to the two-year window for launches to Mars that has been exploited in recent decades to rapidly advance our understanding of the red planet and its habitability. Follow-on missions will be able to take advantage of the experience of the Europa mission to address the challenges of operation in the distant space environment and particularly the strong radiation near Jupiter, as well as leveraging improvements in data transmission bandwidth (laser communication), position knowledge (deep space atomic clock), biosignature investigations, and radiation-hardened electronics.

Motivation: Based on multiple consistent lines of evidence provided by the Galileo mission at Jupiter, a compelling case was made for the existence of a liquid ocean at Europa [3], beneath the famously beautiful cracked icy surface. The most definitive evidence comes from measurements of magnetic field data near the moon; humanity has a long history of making and interpreting magnetic field data, going back to at least the original ocean faring clippers, and these measurements represent a gold standard in remote sensing. The Galileo magnetometer measured an induced magnetic field at Europa consistent with a 100-km-thick layer of a conducting material with a density around 1000 kg m^{-3} [4, 5]. Liquid salty water is the only geologically plausible material.

Gravity measurements are consistent with a layer of water that is between 80–170 km thick [3, 4] (although existing gravity measurements cannot unambiguously confirm a liquid ocean). The ocean is overlain by an ice shell, which, based on analyses of crater morphology and other landforms is expected to be between 3 and 30 km thick [6–9].

Among icy worlds, Europa is potentially the most energetic and shares common features with other ocean worlds (but not found on Earth)—in particular a geologically flexed and fractured ice covering that may be undergoing solid-state convection [10] and a deep global ocean with unknown circulation [11]. Understanding the workings of Europa's ice, ocean, and deeper interior will inform exploration of other ocean worlds.

Pioneering exploration of solar system ocean worlds: Initial mission concepts for a dedicated Europa spacecraft that would precess to a circular orbit around the moon were found to be expensive and short lived [12]. The currently planned Europa Multiple-Flyby Mission would provide an innovative solution that allows for multiple flybys of the moon via numerous targeted flybys as well as providing important context on the local environment that Europa is immersed in during its orbit of Jupiter.

The planned Europa Multiple-Flyby Mission would follow up on the Galileo mission to provide a full orbital survey of the magnetic field perturbation, perform global mapping, and sound the subsurface to unambiguously characterize ocean depth and salinity. Compositional and geophysical instruments are expected to further characterize Europa from orbit, and the long-baseline mission will enable assessment of ocean dynamics and variability as well as any plume activity, which has been suggestively observed by HST [13]. The comprehensive instrument suite and numerous close flybys would provide needed mapping of Europa's surface and subsurface in preparation for future landed missions.

Future exploration of Europa: Completion of the robust reconnaissance provided by the current Europa Mission would enable characterization of potential landing sites based on composition, recent activity, subsurface structure (for example shallow water), terrain roughness and stability, optimizing the potential for the detection of life, as well as ensuring mission safety by assessing surface properties (such as roughness and slope) that are currently unknown at the scale needed by a landing system.

Having identified appropriate landing sites a lander mission equipped to sample the surface and subsurface directly would be the logical next step. The primary focus of a lander mission would likely be astrobiology.

This should be followed by rover-style missions which could travel to multiple interesting surface locations to sample the subsurface and perform visual and compositional analysis of materials that come from Europa's near-surface – informed by results from the lander such a mission would aim to search directly for life on a planetary body.

Notional future missions would hopefully include more capable landers, rovers, and lead eventually to a submersible or melt probe that would directly sample the subsurface liquid ocean layer and areas of shallow water.

Results from life detection searches on Europa will be compared with the results of characterization of habitable environments and the search for life on Mars. Environments for life, past or present, on ocean worlds provide one endmember in the characterization of potential past life on Mars. Such comparisons are necessary for informing future astrobiological exploration.

Enabling technologies: Enabling technology for future missions include long-distance rovers capable of traversing multiple kilometers of uneven, icy terrain as well as devices which are able to descend into cracks or plume vents to access subsurface melt lenses and other near surface liquid water regions.

Advancements are also needed in the design of life search instruments. An integrated strategy should be developed to include multiple instruments and complementary techniques. The "Ladder of Life" initiative [14] helps us identify the path from habitability to biosignatures to life and should be used to direct investment. Future techniques may include chemical analysis as well as direct imaging. Investment to incubate innovative technology development will be needed.

The ultimate goal of Europa exploration would likely be a cryobot or autonomous underwater vehicle, which would melt or drill through the surface ice layer to access the ocean directly. Such a probe could enable observations of potential Europa life in situ, in arguably the most habitable environment in the solar system for an extant ecosystem beyond the earth. While such a mission might be beyond the 2050 time horizon for the current study, the precursor missions described here pioneer exploration of alien oceans, continuing humanity's search for life beyond Earth.

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