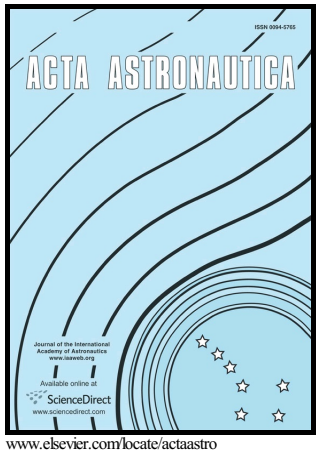

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Ocean Worlds Exploration

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Abstract

Ocean worlds is the label given to objects in the solar system that host stable, globe-girdling bodies of liquid water—"oceans". Of these, the Earth is the only one to support its oceans on the surface, making it a model for habitable planets around other stars but not for habitable worlds elsewhere in the solar system. Elsewhere in the solar system, three objects—Jupiter's moon Europa, and Saturn's moons Enceladus and Titan—have subsurface oceans whose existence has been detected or inferred by two independent spacecraft techniques. A host of other bodies in the outer solar system are inferred by a single type of observation or by theoretical modeling to have subsurface oceans. This paper focusses on the three best-documented water oceans beyond Earth: those within Europa, Titan and Enceladus. Of these, Europa's is closest to the surface (less than 10 km and possibly less than 1 km in places), and hence potentially best suited for eventual direct exploration. Enceladus' ocean is deeper—5-40 km below its surface—but fractures beneath the south pole of this moon allow ice and gas from the ocean to escape to space where it has been sampled by mass spectrometers aboard the Cassini Saturn Orbiter. Titan's ocean is the deepest—perhaps 50-100 km—and no evidence for plumes or ice volcanism exist on the surface. In terms of the search for evidence of life within these oceans, the plume of ice and gas emanating from Enceladus makes this the moon of choice for a fast-track program to search for life. If plumes exist on Europa—yet to be confirmed—or places can be located where ocean water is extruded onto the surface, then the search for life on this lunar-sized body can also be accomplished quickly by the standards of outer solar system exploration.

Keywords: planetary exploration, moons, Saturn, Jupiter, exobiology

1. Introduction: The meaning of "Ocean Worlds"

The post-Renaissance perception of the solar system's planets (and our Moon) as abodes for life was driven first in the West by the Copernican concept that Earth is not unique in any astronomical sense and then by 20th century science fiction aided by marginal and sometimes misinterpreted telescopic observations [1], [2]. This perception has largely been dashed by the past half-century of increasingly detailed astronomical observations and growing sophistication of planetary exploration. In particular, Mars has been largely relegated to a long-past abode of life, with speculations of remnant microbial organisms eking out an existence today deep within its rocky crust [3].

Exploration of the rocky and icy moons of the giant planets beginning in 1979 with Voyagers 1 and 2 at Jupiter changed this perception of a geologically and biologically inactive solar system by showing that such bodies—previously imagined to be cold, dead and geologically uninteresting—possess diverse levels of geological activity up to and including Io, the most volcanically active world in the solar system [4]. What was not understood until 1979 was the importance of tidal heating—the transformation of potential energy of an eccentric orbit into frictional heating within the body—in the multi-moon systems of the giant planets [5].

Subsequent discoveries by the Voyagers 1 and 2 in the 1980's[6], the Galileo Jupiter Orbiter in the 1990's [7], the Cassini Saturn Orbiter over the past 12 years and its Huygens Probe which landed on Titan in 2005 [8], the New Horizons Pluto flyby in 2015 [9], and the Dawn rendezvous with the asteroid Ceres [10] have provided evidence for liquid water oceans beneath the surfaces of multiple bodies in the solar system—from Mars, to the asteroid belt and the vast realm beyond. In a few cases the evidence comes from multiple observations of diverse types, in others a single measurement, and in many cases only theoretical assertions can be made. But in at least one instance (Saturn's moon Enceladus), there is strong evidence that ocean material has been directly sampled by mass spectrometry in a plume of gas and ice emanating from fractures in the south polar region of that moon.

The planetary science community and NASA itself have therefore begun to recognize the existence of a class of objects—"Ocean Worlds"—which are solar system bodies that definitely, provisionally, or potentially host globe-girdling layers of liquid water within their interiors. Since liquid water is essential for life as we know it—life composed of various organic acids, sugars, and similar molecules—the presence of liquid water within a body makes it a candidate in the search for life.

The present paper will summarize the evidence for oceans within each of the bodies currently included in the ocean worlds list as used by many planetary scientists, then focus on three objects--Jupiter's Europa, Saturn's Enceladus and Titan—where the evidence is strongest. It will describe what we know about these oceans and how we know it, and then move on to the prospects for determining more about their suitability for life ("habitability")