Subsurface oceans in the outer solar system: the search for life

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29 November 2011

Abstract:

The search for life in the solar system took a dramatic turn with the Voyager I & II missions to the outer solar system: expecting to find dead, frozen worlds, astronomers instead discovered rich, exciting worlds of liquid oceans, thick atmospheres, and dramatic activity. Research since that time has laid out as many as a dozen worlds that could harbor liquid water. This paper explores our investigation of similar extreme environments on Earth that can pave the way for our exploration of these water worlds. We will also examine a number of the leading candidates for subsurface oceans in detail including Europa, Enceladus and Titan, and examine their causes, properties, and prospects for exploration.

I. Introduction

One of the most basic questions we can ask about ourselves and our place in the universe is “Are we alone?” It is a question whose answer tells us as much about ourselves as it does our place in the universe. Are we unique? Does life arise easily or is the probability for life extremely small? Is all life like us, made from carbon and water, and live in a similar environment to Earth? We can only begin asking questions with what we know, and so we begin with ourselves. What are we like and what do we need to survive?

One possible answer to that question is that life like us needs liquid water. This is a plausible enough suggestion. The primordial soup from which life on Earth sprang was mostly water and organic molecules, organic molecules that are present in the cold gas clouds from which solar systems spring. However, not every world has liquid water. The origins of life on Earth grew from single-celled organisms into complex creatures in the ancient oceans. A planet with a similar environment might also bring forth life, maybe even complex life (3). When we began sending spacecraft into the solar system, we looked to the planets first to see if any of them might contain open water as the Earth does.

Before the 1960s, land-based telescopes could see nothing of the surface of Venus, obscured as it was by thick clouds, and Mars was alive in the popular imagination with the stories of Percival Lowell who argued he could see *canali* that were the signs of a dying intelligent civilization. Because Venus was closer to the Sun, it was thought perhaps the surface was a lush, jungle world covered with prehistoric animals, but hopes for a lush Venus were dashed by Mariner and Venera spacecraft: 900°F surface temperatures are so hot as to strip hydrogen off of water molecules. There was no lush jungle here, just a seething, hell house created by a runaway greenhouse effect. Mariner and Viking likewise dashed hopes for complex life on Mars with images of a barren landscape of craters and temperatures so frigid even carbon dioxide freezes out of the atmosphere. Initial soil tests on Mars were inconclusive for life, and it was initially believed that Mars was as barren as the Moon. If we couldn't find life on our sister worlds, those with the best chance to be Earthlike, where else could we look?[1]

When the Voyager missions arrived at Jupiter, they revealed the moon Io with its sulfur volcanoes. They also found frozen Europa with its cracked and craterless plains. At Saturn, they found Titan shrouded with a methane haze, a molecule with a short atmospheric lifetime (11). The outer solar system had been expected to be nothing but dead worlds, frozen and boring, and utterly inhospitable to life. This was not what Voyager found, and speculation immediately began about what kinds of life could exist in such places. Speculation centered around whether Europa might have an ocean beneath its icy surface.

At about the same time, back on Earth, scientists began to discover that life was even more diverse than we had previously imagined. Extremophiles were discovered in volcanic vents at the bottom of the ocean subsisting on chemical energy in the total absence of sunlight. They were found in the Antarctic ice sheet (8), and in sulfur pools in Yellowstone living in environments we were had previously thought would be instantly lethal. If life could exist in these inhospitable places on Earth, why not in a europan

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[1] It's true that in recent decades, this bleak picture for Martian life has been softened somewhat. The kinds of life we might find there, however, are influenced by the same story of extremophiles on Earth in the discussion that follows, only the model of which extremophiles to look at closely is a bit different.

ocean, or a lake of liquid methane on Titan? Efforts were made to catalogue these life forms and the environments they inhabited so that comparisons could be made to known conditions on Mars, on the moons of the gas giants, and other now potentially viable environments for life. Life that subsisted on permafrost might be capable of surviving near the Martian surface. Life that lived on sulfur might be able exist in the sulfur lakes on Io. Organisms that survived in the darkness in the depths of the ocean on chemical energy might be able to survive in volcanic vents at the bottom of Europa's ocean (32). Analysis of extremophilic life reopened the door to look for life in environments we would never have previously considered to be viable, and exploded the number of candidate environments to investigate. Subsurface oceans are only one such environment.

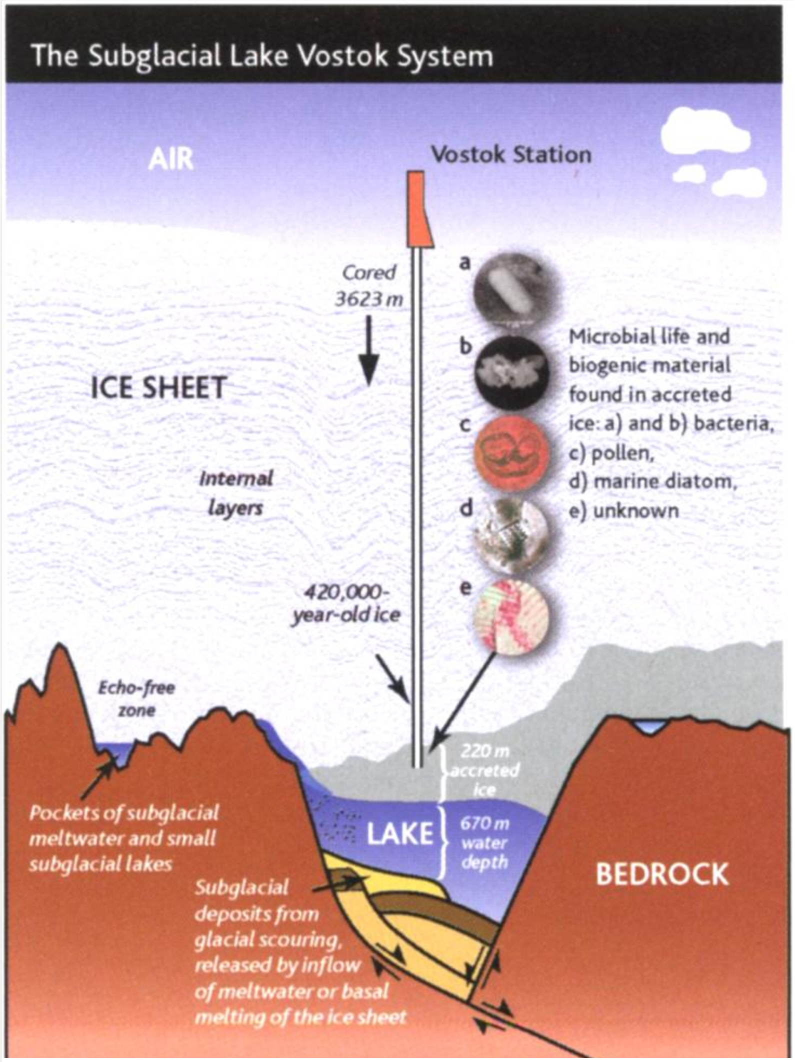


Figure 1. Graphic shows the drilling at Lake Vostok. Alongside the main drilling column are shown bacteria taken from the ice samples along the bore hole. Samples from the ice right above the lake contained bacteria previously unknown. Drilling will resume this (Antarctic) summer. Image from (25).

While the prospects for life on one of the distant moons in the outer solar system are tantalizing, there is much preliminary work to be done here on Earth before we can explore these ecosystems. Some of this preliminary work is being done in the Antarctic. Deep beneath the ice are more than 145 known subglacial lakes (25). The Russians have been planning to drill into Lake Vostok, the largest of these subglacial lakes, since 1970, in part because they can only drill about six weeks per year before even jet fuel freezes. As of February 2011, they were 30 meters from the roof of the lake, but had to stop for the frigid Antarctic winter. The project has come under fire from many sides because of the continued risk of contamination to the lake environment from bacteria living in the kerosene used to keep the drill from freezing (1). If the goal is to sample lifeforms that have been trapped under the Antarctic ice sheet and isolated for 10-14 million years from the rest of the biosphere, contaminating it with bacteria brought down with the drill is problematic for several reasons. While we can document the lifeforms in the kerosene so that they can be distinguished from new lifeforms found in the lake water, we also wish to prevent the lake from being contaminated by an invasive species that takes over the lake and kills all the new life forms we've just discovered. While it is possible surface lifeforms could just die, which result we will get is unpredictable given our current level of knowledge. Ideally, then, we'd like to eliminate the contaminating bacteria before breaking through into the lake to avoid these complications. Studies of the kerosene fluid used have detected such surface bacteria, despite efforts to sterilize the drill bit (1).

Contamination with surface bacteria is also problematic if one is to see this effort as a test run for drilling into subsurface oceans in the outer solar system. Bacteria have been shown capable of surviving in the vacuum of space for years, and in high radiation environments like those around Jupiter, so without adequate sterilization procedures here on Earth, the possibility for delivery live bacteria to Europa would be quite real (10). In addition, Lake Vostok is approximately 4 km deep, approximately the same depth, as will be discussed below, as the europan surface ice, but drilling has been stopped and restarted on a number of occasions because of broken drill bits (54). On a mission to drill into the ice of Europa, replacement drill bits will be extremely hard to come by, so some method of drilling will have to be developed, such as a hot water drill, that doesn't have this problem (46). Across the continent, American scientists are drilling into a smaller subglacial lake, Lake Ellsworth, but as they are proceeding more cautiously, they could be decades behind the Russians (57), and decades more before the techniques these two teams are developing could be transported to a remote probe on Europa.

Though the Russians are being criticized for their apparent haste and, some would argue, carelessness, they, however, argue that because the lake is under pressure, the risk of contamination from the kerosene or any of the drill components is negligible (25); the water from the lake once it has penetrated the bottom of the ice cap will flow back into the drill hole and freeze, where the fresh ice can be sampled without introducing contaminants into the lake. Experts question this claim because their method is untested and given that the water in the lake is both under high pressure and contains a higher than normal content of nitrogen and oxygen gas dissolved in the water (8). They fear the lake could explode like a shaken soda bottle and completely degas, destroying the environment (54)

All of our experience to date with extremophiles on Earth, and the unknown bacteria extracted from the ice above Lake Vostok suggest that if life can form, it can survive in these extreme environments. We do not, however, yet know the limits of the extreme environments in which life can survive, or even under what conditions it can form. Under some scenarios for the origins of life, subsurface oceans are the most similar to the primitive conditions on Earth and so hold our best hope for testing our theories.

II. Contributions to Liquid Water Oceans

A number of factors can contribute to heating of liquid water on a small body and which can help to create and preserve a liquid water environment. Once a body has a liquid layer, it will undergo convection to help dissipate heat; however, the icy layer exposed to the colder temperatures on the surface (38K for Triton to 100K for Europa) will radiate heat mostly through conduction which is a slower

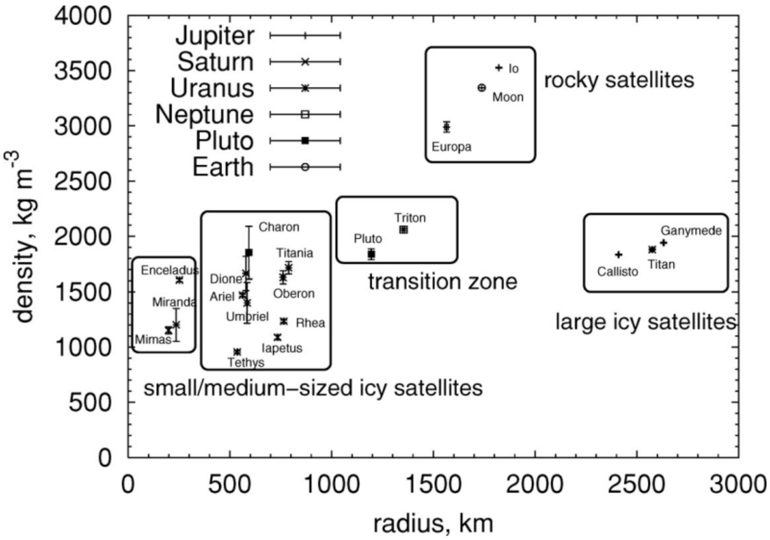


Figure 2. . Radius-density relation for satellites and dwarf planets. Image from (40).

process and so will help the ocean retain enough heat to remain liquid (34). Below, we consider several of the factors that allow the oceans to form and retain a liquid state. While there is some speculation about whether life can exist in environments with other liquids than water, like methane, the interest in subsurface oceans focuses on liquid water environments since this is the kind of life we know.

2.1 Radiogenic Heating

Voyager I & II images of Europa first tipped us off that there might be oceans in the outer solar system. Its young, relatively uncratered surface leads one naturally to ask, how many other bodies might likewise have liquid water oceans? Figure 2 shows the radius-density relation of some of the larger satellites in the outer solar system, together with some dwarf planets. The graph shows how the bodies cluster together. The graph suggests that except in the presence of exceptional conditions, if one body in the group has a subsurface ocean, all may. The radius-density relation is important because it describes how much rocky material (and thus radioactive elements) is present in the body relative to its size. Denser bodies have more radioactivity, and thus a larger internal heat source (40). Indeed, while Eris is not plotted on this graph, as its size relative to its mass decreases, the likelihood it has an internal ocean increases because its density increases inversely proportional to its size, its mass being fixed by dynamical considerations with its moon Dysnomia.

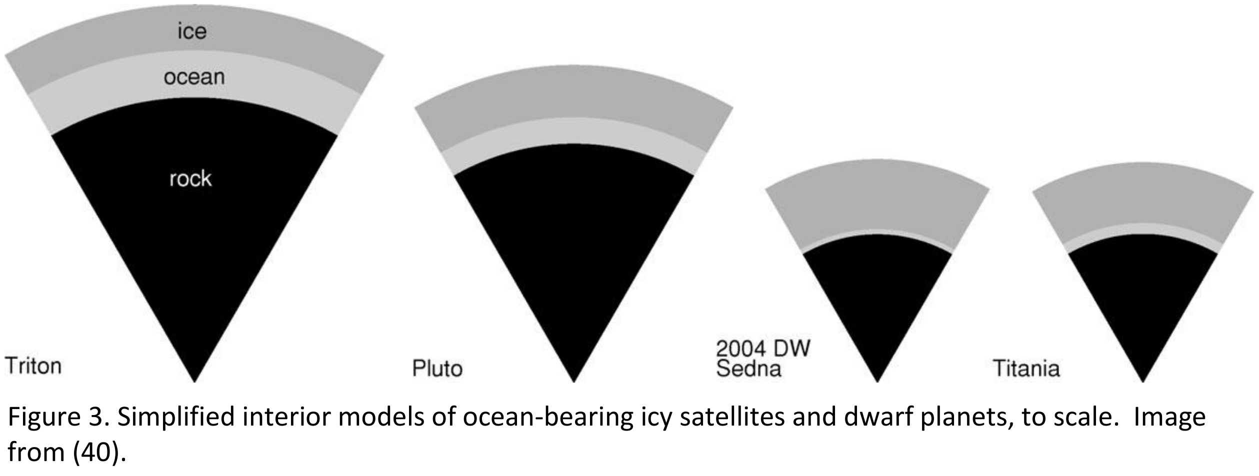
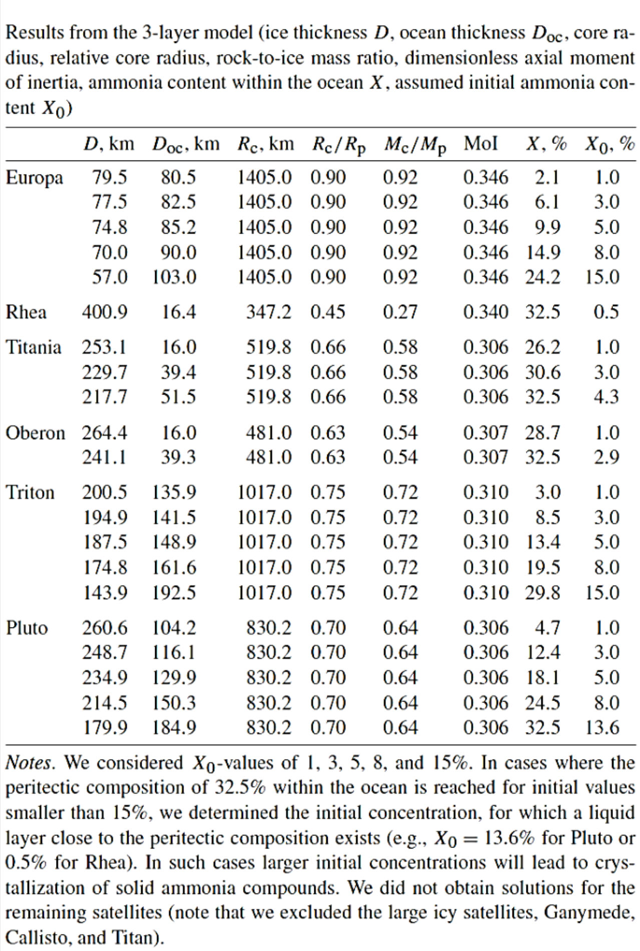


Figure 3. Simplified interior models of ocean-bearing icy satellites and dwarf planets, to scale. Image from (40).

A simplified internal model of the interiors of these icy satellites is shown in Figure 3. The smaller the rocky interior, the thicker the ice shell and the shallower the possible liquid ocean could be. A body like Triton, with 70% of its mass in the rocky core, could maintain a substantial liquid ocean, even one of pure water (40, 22).

2.2 Additives

Table 1. . Taken from (24)



Results from the 3-layer model (ice thickness D, ocean thickness D_{oc}, core radius, relative core radius, rock-to-ice mass ratio, dimensionless axial moment of inertia, ammonia content within the ocean X, assumed initial ammonia content X_0)

	D, km	D_{oc}, km	R_c, km	R_c/R_p	M_c/M_p	MoI	X, %	X_0, %
Europa	79.5	80.5	1405.0	0.90	0.92	0.346	2.1	1.0
	77.5	82.5	1405.0	0.90	0.92	0.346	6.1	3.0
	74.8	85.2	1405.0	0.90	0.92	0.346	9.9	5.0
	70.0	90.0	1405.0	0.90	0.92	0.346	14.9	8.0
	57.0	103.0	1405.0	0.90	0.92	0.346	24.2	15.0
Rhea	400.9	16.4	347.2	0.45	0.27	0.340	32.5	0.5
Titania	253.1	16.0	519.8	0.66	0.58	0.306	26.2	1.0
	229.7	39.4	519.8	0.66	0.58	0.306	30.6	3.0
	217.7	51.5	519.8	0.66	0.58	0.306	32.5	4.3
Oberon	264.4	16.0	481.0	0.63	0.54	0.307	28.7	1.0
	241.1	39.3	481.0	0.63	0.54	0.307	32.5	2.9
Triton	200.5	135.9	1017.0	0.75	0.72	0.310	3.0	1.0
	194.9	141.5	1017.0	0.75	0.72	0.310	8.5	3.0
	187.5	148.9	1017.0	0.75	0.72	0.310	13.4	5.0
	174.8	161.6	1017.0	0.75	0.72	0.310	19.5	8.0
	143.9	192.5	1017.0	0.75	0.72	0.310	29.8	15.0
Pluto	260.6	104.2	830.2	0.70	0.64	0.306	4.7	1.0
	248.7	116.1	830.2	0.70	0.64	0.306	12.4	3.0
	234.9	129.9	830.2	0.70	0.64	0.306	18.1	5.0
	214.5	150.3	830.2	0.70	0.64	0.306	24.5	8.0
	179.9	184.9	830.2	0.70	0.64	0.306	32.5	13.6

Notes. We considered X_0-values of 1, 3, 5, 8, and 15%. In cases where the peritectic composition of 32.5% within the ocean is reached for initial values smaller than 15%, we determined the initial concentration, for which a liquid layer close to the peritectic composition exists (e.g., $X_0 = 13.6\%$ for Pluto or 0.5% for Rhea). In such cases larger initial concentrations will lead to crystallization of solid ammonia compounds. We did not obtain solutions for the remaining satellites (note that we excluded the large icy satellites, Ganymede, Callisto, and Titan).

In addition to internal radioactivity, subsurface oceans can be maintained by the introduction of ammonia (NH_3) or salts to a water mixture. While water freezes at atmospheric pressure at 273K, ammonia acts as antifreeze, and can maintain an ocean in a liquid state down to 176K. Salts dissolved in water have higher freezing temperatures than ammonia-water solutions, but still serve to drop the freezing point from pure water and can increase the depth and duration of existing liquid layers (7). Table 1 shows calculations of the depth of a liquid ocean and ice cap for six icy satellites (and Pluto). The exact ratio of ammonia to water in the solar nebula is not known, so calculations were made for a number of initial ratios, from 1% to 15%. Those conditions that produced liquid oceans are shown in the table. The figures in the table only take into account radiogenic heating and ammonia concentration. Tides or other heat sources discussed below are not included in these figures yet a substantial number of them could contain liquid water layers (22). Not included in this list is Ganymede or Callisto, both of which are also candidates for water layers (12, 44).

2.3 Tidal Heating

A third factor that can help maintain a liquid ocean is tidal heating. Tidal heating comes from calculating the differential forces of gravity on a body in different parts of its orbit. Most moons are locked in synchronous rotation and so only face one side toward their parent body. Because of this, tidal differences are due to the eccentricity of their orbits as the moon moves first closer to, and then further away from, the center of gravity of the system. Larger eccentricities lead to greater differences and so larger tidal forces. The more circularized an orbit is, the smaller those differences will be. Eccentric orbits create gravitational differentials as a moon (even one in synchronous rotation with its parent) orbits. It experiences more gravity as it reaches periapsis (closest approach, perijove if we are talking about Europa)[2], and less gravity at apoapsis (apojove for Europa). The tidal forces can be approximated by Equation 1, where R is the distance to the center of the parent mass, G is the gravitational constant, M is the mass of the parent object, Δr is the difference between the apoapsis and periapsis (characteristics of the orbit, not the body), and r̂ is the radial direction.

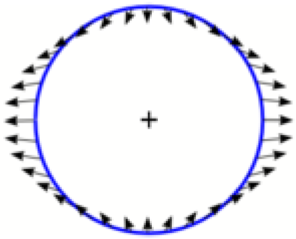


Figure 4. Tidal forces on a satellite are outward in the direction of the parent body, and inward perpendicular to the direction of the center of mass of the system. Changes in the strength or direction of the field can cause frictional heating in the interior.

$$\overrightarrow{a_{tidal}} \approx \frac{2GM}{R^3}\Delta r\hat{r} \tag{1}$$

This tug and pull as the distance from the parent body changes creates friction in the body and the energy is dissipated as heat. If the tidal forces are strong enough, the body can melt completely. Once the body is melted, the energy normally goes into circularizing the moon's orbit, cutting off the tidal heating (34).

Other forces in the system can act to prevent the orbit from circularizing, even once melting is complete. Laplace resonance occurs when two or more moons in a system interact with each other gravitationally until they fall into orbits that are whole number

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[2] When one orbits the Sun periapsis is also called perihelion, for the Earth, it's perigee. Likewise apoapsis for bodies orbiting the Sun is aphelion, and for orbiting the Earth, apogee. Each planet has its own special term, but these are the general, geometric ones.

integer ratios of each other, such as 2:1 or 3:2. Such resonances will provide an additional gravitational kick during each orbit, and increasing the eccentricity even as tidal energy seeks to circularize it. If multiples bodies participate in the resonance, the additional tidal heating can be enormous and long-lasting (21).

A third contribution to tidal forces can come from other factors influencing the gravitational quadrupole moment induced when a moon orbits a highly oblate body in an inclined orbit, the greater the inclination, the greater the effect. As the moon orbits, if it stays in or near the plane of the ecliptic, the column of mass between the moon and the center of mass of the system remains uniform, but if the orbit is highly inclined, the column of mass decreases, and the mass at the equator is now pulling in a slightly different direction. This effect tends to fall off rapidly, but for moons of planets with large mass, a small radius, rapid spin or high inclination, the effects can be significant (6). While objects that formed with their parent planet are typically quite close to the plane of the planet's equator, some objects, like Triton, are captured satellites and have an extremely high obliquity.

Once a body has a liquid ocean, the effects of tidal forces can be strengthened. Thin surface layers above a liquid layer flex more readily than a solid sphere and can create more tidal heating (9). In addition, the decoupling of the surface from the core can generate frictional forces that slow down the rotation of the core and keep it just out of synchrony with the rotation. The core will then slowly be flexed in different directions over time rather than, in synchronous rotation, always having the tidal forced point in one direction (23).

2.4 Detection of Subsurface Oceans

Short of drilling below the surface to find the ocean, we can determine to relatively high probability if these objects have oceans from a number of external clues.

Young surfaces are perhaps the easiest way to detect a subsurface ocean. If the ocean is close enough to the surface, impact craters will be obliterated by the upwelling of ice into the craters, and all signs of the impact will be erased. The dearth of large impact craters on Europa was the first clue that something remarkable was happening beneath the surface. Of course, depending on the temperature of the surface, young surfaces need not be heralds of water ice. The surface of Titan is littered with methane lakes, and Triton has a combination of nitrogen ice and methane ice on the surface. Other factors can, therefore, be at work. Determination of the presence of water ice will be necessary through spectroscopy or other means (38).

Cryovolcanic activity may be witnessed or tell-tale signs of it may be noted in topography (29). Even if the surface is not very young, remnants of less active features may still be present (12). Brightly-coloured impact crater rays may signal the presence of relatively new ice. Volcanic structures that expel water “magma” onto the surface or other active geologic activity such as geysers may be detected (31, 17).

Gravitational effects can be measured with careful monitoring of the surface (24). Tides create changes in the surface and internal rotation rates as previously noted. Direct observation of the way the gravitational field of a body changes, and the rising and falling of the surface under tidal flexing can help determine six tidal Love numbers. These parameters solve six differential equations used to determine the behaviour of differentiated planetary models. These equation were first derived to model the interior of the Earth, but they have now been used to model the interiors of moons thought to have subsurface oceans acting like the mantle does in the Earth (23).

Liquid layers in moons, like liquid layers on the Earth, can generate their own electrical and magnetic fields (15). Of course, iron is much more effective than water, so the detection of such fields requires sensitive instruments. However, most of the moons thought to have subsurface oceans orbit planets with large and dynamic magnetic fields, thus making anomalies in those fields signs of moving charges in the liquid layer. Bodies without such a liquid layer will not modify the field at all.

Below, we will consider how these factors work to create subsurface oceans in specific bodies. We will consider three in detail: Europa, Enceladus, and Titan.

III. Europa

Europa is the second of the Galilean satellites[3] in distance from Jupiter situated between Io and Ganymede, but the smallest of the four in size. The Voyager spacecraft found the europan surface to be covered in ice with a high albedo and very few craters.

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[3] The Galilean satellites are Jupiter’s four largest moons discovered by Galileo: Io, Europa, Ganymede and Callisto.

Its mean radius is 1569 km, and has a tenuous atmosphere of oxygen. It orbits Jupiter in about 3.5 Earth days.

Europa, as shown in Figure 2, is surprisingly similar in composition to Io and the Earth's Moon, but its surface features look nothing like either. Io is a body of multiple presently-active volcanoes of sulfur, while the Moon is a dead world. Europa is believed to have a liquid ocean under its icy surface. The natural question to ask is how is this possible?

Having formed further away from the sun than our Moon did, Europa has a larger portion of its mass composed of ices. It is believed to have a small iron core, surrounded by mostly rocky material, and a layer of ices at the surface (22). As shown in Table 1, Europa has enough rocky material to produce radiogenic heat to maintain an ocean of an ammonia-water mixture, overtopped by a thick icy crust (24). However, the young age of the surface indicates that the crust layer may be much thinner than predicted by this model alone (15).

An interesting feature of the three closest Galilean satellites is that they are in Laplace resonance with each other. Ganymede orbits once for every two times Europa orbits Jupiter, and Europa in turn orbits once for every twice Io orbits Jupiter. The resulting 1:2:4 resonance gives the satellites an extra gravitational kick on a regular basis, preventing their orbits from fully circularizing. This residual eccentricity keeps the tides strong enough to provide the energy needed to melt the interior of Io in a particularly violent fashion, and to keep a subsurface ocean on Europa from freezing even without the need for the antifreeze effects of ammonia. The Laplace resonance is not completely stable and evolves with time, oscillating between freezing periods and runaway heating periods. Europa's ice thickness is now estimated to be between 3 and 70 km thick, but now appears to be in a cooling phase (21). The 3 km depths are comparable to the depth of the Antarctic ice sheet above Lake Vostok (54).

Further evidence for a liquid layer inside Europa comes from measurements from the Galileo mission including the detection of a deviation in Jupiter's magnetic field around Europa (15). These measurements strongly suggest a liquid ocean, and that the ocean is saline enough to conduct electricity. The data suggests a best fit to the europan ice shell at 4 km thickness, and a near-saturated saline level. However, because of the temperature and other properties of the europan ocean, the level of salinity would only be slightly more saline than a freshwater lake on Earth, and considerably less saline than Earth's oceans (16). The water would be potable by humans if salinity was the only consideration.

As heat escapes from the europan core and rocky interior, it is likely to form volcanic vents at the bottom of the liquid water layer (53). Deep beneath the ice, life forms would be protected from Jupiter's radiation environment. Without sunlight, it was once thought impossible for life to exist in such a place, but with the discovery of life forms living near black smokers along volcanic vents at the bottom of the Earth's oceans living on chemical energy alone, Europa might be the best place in the solar system to find life similar to what we find on Earth.

Because the data for Europa is the best known, it can teach us the most about the kinds of forces that may have to be considered to account for what we know. While tidal forcing driven by the Laplace resonance is the most common way to explain the heating of the subsurface ocean, another theory of tidal forcing driven by the obliquity of the orbit has also been proposed. It is suggested that even Europa's relatively small obliquity can set up Rossby waves in the ocean capable of dissipating more energy than the tidal forces from the Laplace resonance (50).

Europa, because it is the closest of the subsurface oceans, and with one of the thinnest ice shells, it is the most likely to be visited by spacecraft first. Orbital missions are being proposed by NASA in conjunction with the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) to spend nine months orbiting Europa. Their goal would be to study the ocean from orbit, and better understand the geology of the ice shell. They would also try to characterize sites for future landers that might penetrate the ice and sample the ocean (4). This mission is currently planned for launch in 2020. A mission called Juno is currently on its way to Jupiter, but it is not intended to focus extensively on Europa.

IV. Enceladus

Enceladus is only about a third the size of Europa, and it orbits Saturn within its faint E ring. Indeed, observations suggest that Enceladus itself is the source of the material in the E ring (33), from the plumes of water ice detected escaping from the South Pole (17, 28).

The small size of Enceladus makes it an unlikely candidate for a liquid ocean. The rocky core does not provide enough heat to maintain a liquid layer, even with the addition of ammonia, for any significant period of time, and it should long ago have frozen solid (37). It is therefore not surprising that calculations indicate that the subsurface ocean on Enceladus cannot be in a steady state (36). It releases more heat than current tidal forces or radiogenic heating appear to be able to sustain. If a subsurface ocean exists around the whole moon, it may be rapidly in the process of freezing. Estimates suggest that it may survive only ~30 My under present conditions. Variations in its eccentricity and other orbital characteristics may lead to periods of freezing and melting. Because the heat anomaly appears only under the South Pole, there are a number of unknowns related to its formation. Chief

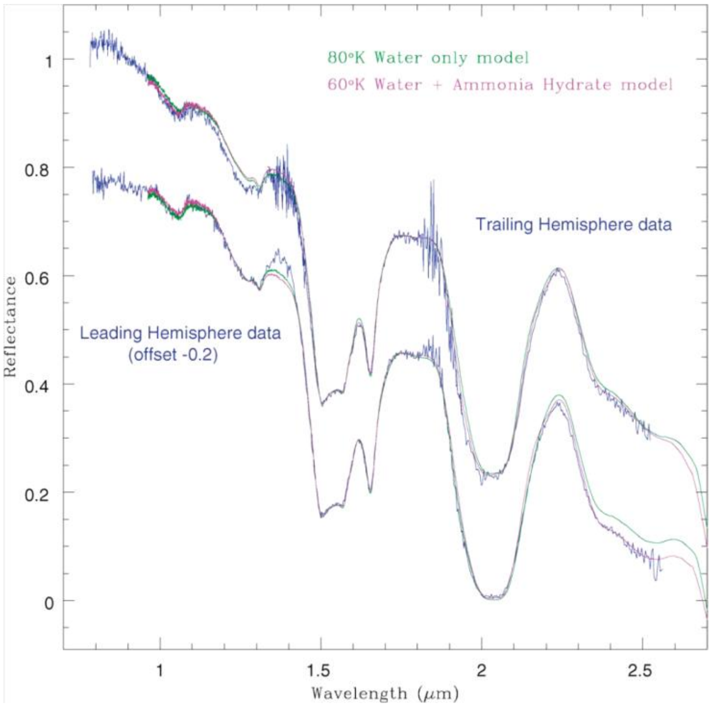

Figure 5. Spectral data from ice plumes at Enceladus' south pole. Absorption lines almost perfectly match pure water ice lines, with minor contributions from ammonia ice. Image from (36).

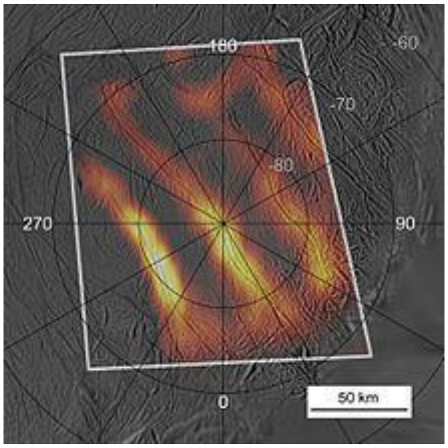

Figure 5. Image from Cassini of the South Pole of Enceladus where heat anomalies have been imaged in infrared. (NASA)

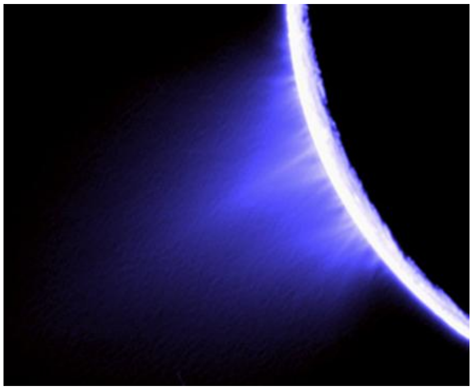

Figure 6. An image of the plumes of water vapor being ejected from the south pole of Enceladus as captured by Cassini. (NASA)

among the questions that need to be answered is if this is a remnant of a global ocean, or the result of a large impact (45, 49).

Peculiar to Enceladus is the fact that the majority of the escaping heat and water plumes emanate from the South Polar region. The region on the surface of the moon is dominated by terrain called “tiger stripes” that appear to be the source of the plumes.[4] Infrared cameras can detect a noticeable heat anomaly beneath this region (35).

One possible explanation for this anomaly is diapirism. Diapirs are bubbles of material that form under a solid surface when a less dense material finds itself underneath a denser material. The less dense material is pushed aside by the denser material under the weight of gravity and the less dense material is forced upward. Salt diapirs are common in some parts of the Earth because of this process. What is being proposed for Enceladus is similar, but the material being forced to the surface is heated water. This is thought to explain the relatively small size of the heat anomaly (47).

Direct detection of liquid water on Enceladus is easier than on Europa, since Enceladus is expelling material from its interior into space. Enceladus is currently squirting jets of material into the E Ring around Saturn and both the ring and the jets of material can be sampled spectroscopically for signs of water. Figure 7 shows a spectrograph in the infrared showing the absorption bands from water ice at 80K. The match is quite close for both the leading and trailing edges of the geyser material; however, a slightly better match on the leading hemisphere can be made with the addition of some ammonia hydrate (55). The ammonia is significant because it is the antifreeze agent believed to be at work in subsurface oceans (other than Europa) that keep the liquid layer from freezing. The presence of ammonia hydrate may indicate the presence of ammonia in the water mixture, but this data cannot tell us the exact concentrations.

There are currently no missions planned for Enceladus, but the dramatic water geysers have moved the moon up to the top of some lists for prospects for the search for life. The advantage of easy access to the ocean water is clearly one of the considerations to be made, since sampling material from the jets will be easier than

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[4] “Tiger stripes” are dark regions on the surface on Enceladus that line the cracks on the surface from whence the water geysers are erupting. The cracks form long, roughly linear features on the surface suggestive of the stripes on a tiger’s back.

drilling through several kilometers of ice. However, since the long-term stability of an ocean on Enceladus is highly questionable (32), the prospects for life do not seem to be as high as that for Europa, whose warmer and more stable oceans would have time to evolve. If life gets going rapidly and ubiquitously if the conditions are right, Enceladus could still tell us a great deal about how easily life gets started, or how hard.

V. Titan

Another moon of Saturn also has the possibility for a subsurface ocean, one that was not suspected of having one when we first got a close look at it through the Voyager cameras.

Titan is the largest moon of Saturn, and since Voyager, was shrouded in mystery because the surface was covered with a thick orange haze. It is the only moon in the solar system with a thick atmosphere, and it is able to retain it because of its frigid temperatures, 94K on the surface, and relatively large size. The atmosphere is mostly nitrogen with a pressure of approximately 1.5 times that of Earth sea level. The haze is formed by complex hydrocarbons that appear to rain onto the surface and form lakes (39).

The Cassini probe currently in orbit around Saturn has allowed for the calculation of the tidal Love numbers for Titan. These indicate that the core and the surface are decoupled from one another, and the core is rotating more slowly than the surface (29) causing the moon to fall out of synchrony with its orbital period. This effect would not be possible if the interior were solid ice.

Another piece of evidence that leads to the conclusion that Titan has a subsurface ocean is the detection of an electrical field (48). The manifestation is different than with Europa suggesting that properties of the oceans may be somewhat different.

Cassini has made numerous mapping runs of the Titan surface since depositing its Huygens probe through the atmosphere. Features that look like volcanic features have been imaged, suggesting that water “magma” may be ejected onto the surface from time to time much as lava is on Earth (29, 31).

Despite the indications of a subsurface ocean, Titan does not have sufficient tidal or radiogenic heating to account for the existence of a pure water ocean. It is therefore believed that ammonia must be a significant component of the ocean to keep it liquid at the kinds of temperatures that would be required (43).

Titan remains a destination for future science missions. Sampling material on the surface near one of these cryovolcanic features could provide evidence for life in the interior, if it exists, without the need to drill. A mission to return probes to Titan are being considered, but they are currently battling the proposed Europa mission for funding.

VI. Policy

NASA currently has several missions underway to examine worlds with subsurface oceans, though most are not targeted at this specific environment, and others in the works which will be. Current missions include the ongoing Cassini mission in orbit of Saturn that continues to monitor the surfaces of Titan and Enceladus. On its way to Pluto is the New Horizons mission, expected to arrive at Pluto in 2015. While Pluto was not on our list of well-established subsurface oceans, there is good reason to believe it may have one. Triton, which itself is a captured Kuiper Belt object is likely to have a subsurface ocean even without the antifreeze properties of ammonia (24). Pluto is of a similar size and composition, so study of this object could provide us with information both Pluto, but also about Triton and Eris as well. In addition, Juno was launched in 2011 to Jupiter, and while its primary mission is not to study Europa, new information about the surface is likely. With developments regarding Europa's chaos terrain recently being released, that they may harbor lakes in the interior of the ice layer, it's likely that these regions will be targeted for additional images if possible.

The search for life is part of a fundamental question that humans ask of themselves and the universe we live in. The answer to that question is not, however, at the top of everyone's priority list. It is a difficult argument to make to people who are unemployed that we should spend billions of dollars drilling into Europa in fifteen years. However, much of the technology that needs to be developed can be argued for on more than just the basis of pure research. Advanced drilling technologies can have implications for the search for methane hydrates on the ocean floor, for example. The life forms living in the subsurface Antarctic lakes are biologically related to other Earth species; they may have mutated in interesting ways that can be exploited for medical or bioengineering purposes. For example, what keeps them from freezing? Each one of the 145 isolated Antarctic lakes has a different population of isolated organisms, and any one of them could yield something practically useful. The Antarctic is so inhospitable most of the year, the kinds of remote technology, and dealing with such temperatures, are exactly the kinds of technologies needed to plan a mission to sample Europa's ocean. The cost to drill into Lake Ellsworth is estimated at a mere $20 million (57). Moreover, our concerns about not contaminating these lakes carry over directly to eliminating contamination on any future europan mission. For now, however, drilling all the way into the water layer is probably beyond our capabilities, but sampling the surface ice may give us information about the ocean if the ice layer is convective, as expected. (2, 14)

The next planned mission to Europa is scheduled for liftoff in 2020 and is expected to cost $2.7 billion for the proposed life of the mission, compared with $1.39 billion for the Galileo mission, according to NASA. However, the cost for the mission will be spread between NASA and ESA, and includes an orbiter for Ganymede as well (4). Ganymede is also expected to have a subsurface ocean, under a much deeper layer of ice than Europa. Studying it may give us information about other deep, interior oceans that can be found on Titan, Triton, and Pluto (12, 41).

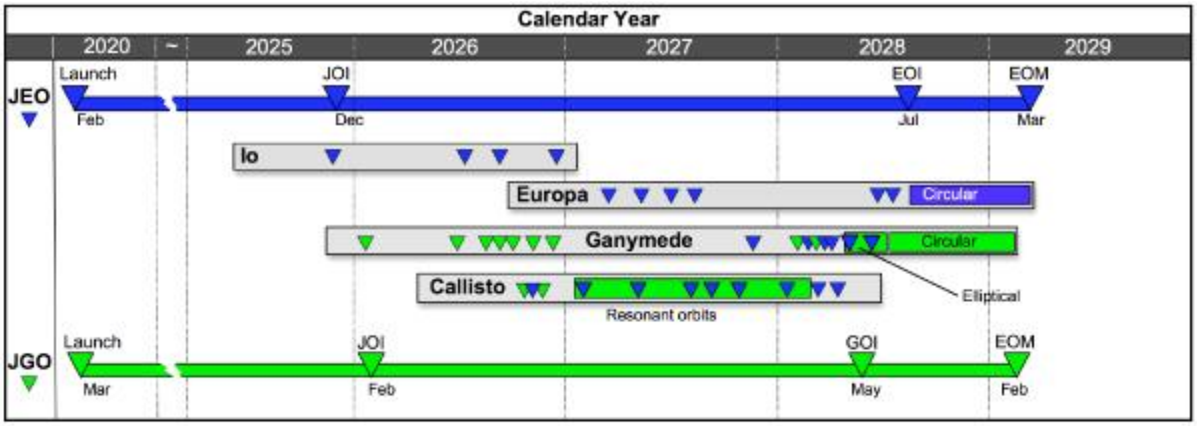

Figure 6. The proposed timeline for NASA's Jupiter Europa Orbiter and the Jupiter Ganymede Orbiter that together compose the Europa Jupiter System Mission. (NASA)

Addition to the direct benefits of examining alien life, any information we gain from these missions about the properties of life in general could provide us with information on designing artificial organisms.

VII. Conclusion

We have only touched on the worlds that may harbor subsurface oceans and their prospects for life. In addition to Europa, Enceladus and Titan, Triton, Ganymede and other large moons and dwarf planets are likely to have large subsurface oceans (22, 37, 44). These are more difficult to reach, either because of the distance to the objects, or because of the thickness of the surface ice layer. With so many worlds having this kind of environment, the solar system could be teeming with primitive organisms (or even more advanced organisms), and the prospects for life in the universe go up considerably.

In addition, we also have to look at the exoplanets we are finding around other stars and consider not only the planets themselves as possible environments for life, but also their larger moons. The “habitable zone” looks quite narrow if we are looking for places for humans to live. While subsurface oceans may not be our first choice for home, but life may not be so picky.

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