Possibility of life on Europa

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Abstract. Europa is one of most promising places in our solar system where life may flourish. Observations from several space missions suggest that Europa has an active interior maintained by the tidal stresses from Jupiter and other Jovian moons. The active interior could sustain a liquid ocean under the Europan ice crust and provide enough energy for organic evolution. Life as we understand it requires three basic ingredients: liquid water, energy and organic compounds. This paper presents the case that Europa may possess all of the ingredients to sustain life.

1. Introduction

One of the oldest and the most profound questions that faces humanity is: Does life flourish outside of planet Earth? Over the past decades, Europa's potential to sustain life has made it one of the most promising places in our solar system to address this question.

In 1610, Galileo Galilei pointed his telescope at Jupiter and discovered "four stars that wander around Jupiter as does the moon around Earth." The "stars" Galileo referred to are the four largest Jovian moons: Io, Europa, Ganymede and Callisto. The Galilean moons, as they are called, dethroned the Earth as the centre of the Universe and favoured Copernicus's heliocentric theory.

The space exploration of the Jovian system began in the 70's with the Pioneer and Voyager fly-bys, followed by the Galileo spacecraft in the 90's. The first close look at Europa was imaged by Voyager 2 on July 9, 1979 (Fig. 1). It revealed a strangely smooth world of large criss-crossing linear features and dark mottled terrains. Europa is the smoothest object in the solar system with no geological feature exceeding one kilometer in height. The surface of Europa is one of the brightest in our solar system. Spectroscopy confirmed that the bright surface is water ice.

Europa is the smallest of the four Galilean moons and the second closest to Jupiter. It is roughly the same size as the Earth's moon. The gravity data from the Galileo space mission revealed that the structure and composition of Europa is curiously similar to that of planet Earth (Fig. 2), but could not discern if liquid water is present in the ice crust (Anderson et al. 1997). Europa has an average density of $3.04 g\ cm^{-3}$, and is composed of a rocky interior with an iron core and an outer crust of water approximately 150 kilometres thick (Beatty et al. 1998). The key question is: Does Europa have a subsurface liquid ocean? If a 150 kilometer deep ocean existed below a 15 kilometer thick ice crust, it would be ten times deeper than any ocean on Earth and would contain twice as much water as Earth's oceans and rivers combined.

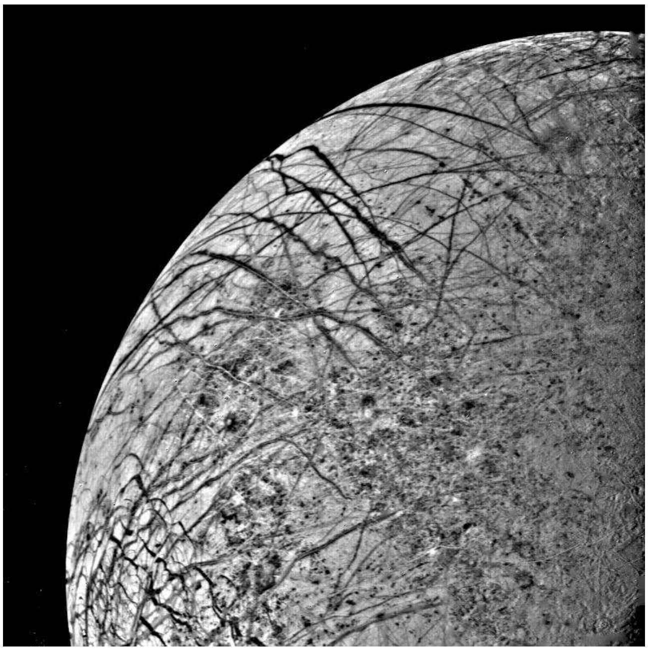

Fig. 1. The first close look at Europa imaged by Voyager 2 on July 9, 1979. It revealed large criss-crossing linear features and dark mottled terrains. (NASA/JPL-Caltech)

Galileo's near-infrared mapping spectrometer revealed that the spectral bands of water ice are skewed and asymmetrical. This indicates the presence of an impurity in the ice such as salt. Magnesium sulfate has been suggested as the salt component of the Europan ice crust, as opposed to sodium chloride in Earth's oceans (McCord et al. 1998). Other possible contaminants may be sulfur and iron, which have been suggested to contribute to the reddish colour in the mottled terrains.

Life as we understand it requires three basic ingredients: liquid water, energy and organic compounds. The studies from the past few decades have revealed that where there is liquid water on Earth, virtually no matter what the physi-

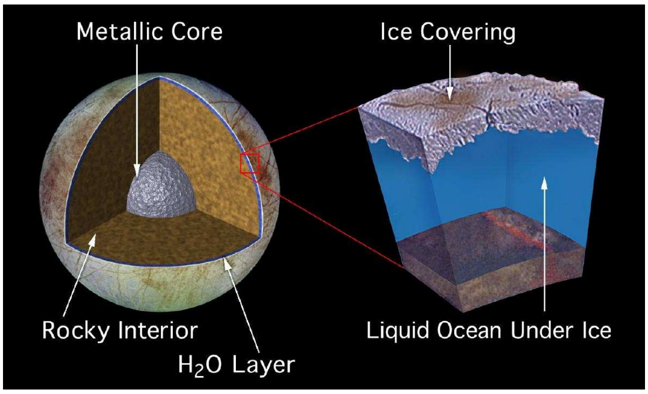

Fig. 2. A possible subsurface structure of Europa. Europa is composed of a rocky interior with an iron core and an outer crust of water approximately 150 kilometres thick. Can the subsurface of Europa hold *liquid* water? (NASA/JPL-Caltech)

cal conditions, there is life (Rothschild & Mancinelli 1998). Investigating the existence of a large liquid body on Europa is a key step toward confirming Europa's potential to sustain life. The next section outlines some of the implications of an Europan subsurface ocean. Possible energy sources and the availability of compounds to enable organic evolution are also discussed in the following sections.

2. Implications of a subsurface ocean

Earth is the only known place in the solar system where large bodies of liquid water are located near solid surfaces. Earth is also the only known place that sustains life. Liquid water is an essential ingredient for life. Tidal stresses from Jupiter could maintain an active Europan interior, which could in turn maintain liquid water beneath the ice crust. Observations of the surface features and the perturbation in the Jovian magnetic field provide possible evidence of a subsurface ocean.

2.1. Tidal heating

Io, Europa and Ganymede are in synchronized orbits around their parent planet Jupiter. The three-body resonance was formed less than 500 million years ago and is the result of dissipative tides in Jupiter and Io (Yoder 1979). Ganymede orbits Jupiter once while Europa orbits twice and Io orbits four times. The massive Jupiter and the synchronized orbits of its companions create diurnal global stresses in Europa.

The effects of the tidal stresses are clearly evident in Io, the closet moon to Jupiter. The tidal heating raises the temperature of the interior to melting and drives the continuous volcanic eruptions on the moon.

In Europa, the heat generated in tidal flex from Jupiter is less intense than that of Io. The non-spherical gravitational field measured from the shift in frequencies of the signals transmitted from the Galileo spacecraft provided quantitative evidence of the tidal distortion (Pappalardo et al. 1999). Tidal stress is the dominant source of internal heat energy, if Europa still has an active interior. The heat generated in tidal stresses could maintain a subsurface ocean and provide enough energy for organic evolution.

2.2. Non-synchronous rotation

Most of the natural satellites in the solar system are in synchronous rotation, always showing the same face to their parent planets. Non-synchronous rotation could be caused by an eccentric orbit and a near circularly symmetric mass distribution about the spin axis (Greenberg et al. 2000). However, the effect of orbit eccentricity could be negated by asymmetry in the mass distribution to retain synchronous rotation. In the case of the Earth-Moon system, the satellite's eccentric orbit and the frozen-in mass asymmetry produce synchronous rotation for the Moon. In such a case, the tidal torque is countered by the torque of the planet acting on the mass distribution of the satellite, thus maintaining synchroneity.

In the case of Europa, a small forced eccentricity is driven by the three-body resonance. Gravity data from the Galileo mission suggest that there may be a permanent asymmetry in Europa's interior mass distribution (Geissler et al. 1998), which may be enough to counter the tidal torque. In that case, the detection of non-synchronous rotation could be attributed to the decoupling of the surface ice crust and the interior. Evidence of decoupling implies the existence of liquid water or ductile ice between the surface and the interior.

Europa's rotation rate, measured using surface features as references, is indistinguishable from that of synchronous rotation, but places a minimum value of 12,000 years on the rotation rate of Europa with respect to Jupiter. Geological evidence, such as changes in the orientations of linear features with age, suggests that there has been substantial rotation in the recent past (Geissler et al. 1998).

Non-synchronous rotation cannot be treated as an independent proof of a subsurface ocean, but merely as an implication. The other possible causes of non-synchronous rotation mentioned above may cause ambiguity in the interpretation.

2.3. Perturbation of Jovian magnetic field

Perhaps one of the strongest cases for a subsurface Europan ocean came from the measurements of the magnetometer on board the Galileo spacecraft. The Jovian moons are immersed in the powerful magnetic field of Jupiter. The magnetometer measured the perturbation of that field around Europa. The perturbation may be caused by the intrinsic field of Europa, but the magnetic axis would have to be tilted at an unusually steep angle with respect to the rotation axis, which makes the scenario unlikely.

An alternative interpretation is that the perturbation is the dipole fields of Europa induced by the temporal variations of the Jovian magnetic field (Kivelson et al. 2000; Zimmer et al. 2000). Armed with this hypothesis, researchers used a simple shell model to investigate the electrical structure of Europa (Fig. 3). A conductive layer of thickness h and conductivity σ is insulated by the interior and the outer shell of thickness d. The conductivities of the Europan rocky interior and icy shell

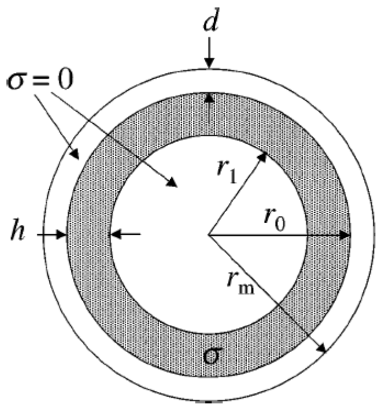

Fig. 3. A model of the electrical structure of Europa. The conductivity of the Europan rocky interior and icy shell are approximated to be zero. The conductivity of the conducting shell was found to be as high as that of seawater. (Zimmer et al. 2000)

Fig. 4. Impact crater Pwyll imaged by the Galileo spacecraft. The crater is about 26 kilometres across. The darker materials are the debris from the impact. The central peak is approximately 600 meters above the crater floor, and the crater walls rise only 300 meters. (NASA/JPL-Caltech)

are approximated to be zero. The distance r_1 and r_0 denote the inner and outer radius of the conducting shell, and r_m is the radius of the moon.

The model agrees with the observation if the conducting shell has a conductivity as high as that of seawater. The agreement is a powerful indication that a global subsurface ocean exists and is at least a few kilometres thick (Zimmer et al. 2000).

2.4. Surface features

The images taken by the Galileo Europa Mission permitted detailed studies of the surface features that were not possible from the Voyager images (Carr et al. 1998). The images revealed a smooth surface with few large impact craters and widespread features resembling liquid filled openings, implying a global and mobile subsurface layer.

There are two types of terrains on Europa's icy crust. The mottled terrains are darker in colour and consist of mainly small hills and areas that have been disrupted locally. The other type of terrain consists of large smooth plains criss-crossed with a large number of linear features, some extending for thousands of kilometres.

All the surface features point to a geologically young surface, suggesting that there are geological events currently working to smooth the surface or at least in the relatively recent past. These features are evidence that liquid or at least partially liquid water exists at shallow depths below the surface of Europa in several different places.

2.4.1. Impact craters

As asteroids are too few in number, it is primarily comets that crash into Jupiter and its satellites. Few large craters were found on the surface of Europa, again implying a geologically young surface. From the estimate of the comet impact flux on Europa Shoemaker (2000), the surface age was deduced to be $\sim 10^7$ years.

The impact craters on Europa do not have the characteristic bowl shapes of craters found elsewhere in the solar system. A typical Europan crater consists of a central peak in a smooth patch and surrounded by concentric rings, much like a frozen record of a rock thrown in a pond. The central peak usually stands higher than the concentric crater walls. This is unusual compared to a typical crater found elsewhere. The soft ice, possibly warmed by the subsurface material, is unable to maintain the walls of the crater.

An example of this is the impact crater Pwyll. Its image taken by the Galileo spacecraft is included in Fig. 4. The crater is about 26 kilometres across and has material excavated from several kilometres below the surface. The darker debris from the impact is apparent from Fig. 4 and is scattered over a large part of the moon. This implies a recently formed crater of about 10-100 million years of age. The impact excavated previously buried material that is darker than the surface. The central peak is approximately 600 meters above the crater floor, and the crater walls rise only 300 meters. The crater floor is smooth and dark.

The fact that these craters differ from the norm of solar system craters formed in cold and stiff material could be explained by a warm Europan subsurface. The soft material beneath the ice shell is warm enough such that, upon impact, it is able to fill in and smooth the crater basin and collapse the crater walls. This is a strong implication that Europa still has an active interior and may have a subsurface ocean beneath the ice shell.

It is worth noting that a more recent paper by Schenk (2002) places a constraint of shell thickness at a minimum of 19 kilometres thick. If this thickness is the true global thickness of the Europan ice crust, it may pose difficulties for the exchange of organic material between the surface and the putative subsurface ocean.

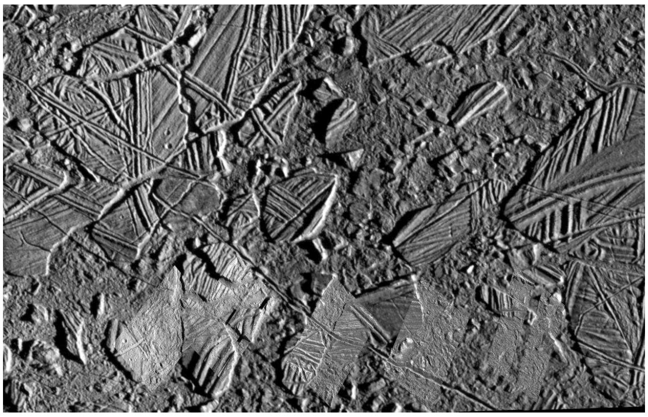

Fig. 5. Conamara Chaos region imaged by the Galileo spacecraft. (NASA/JPL-Caltech)

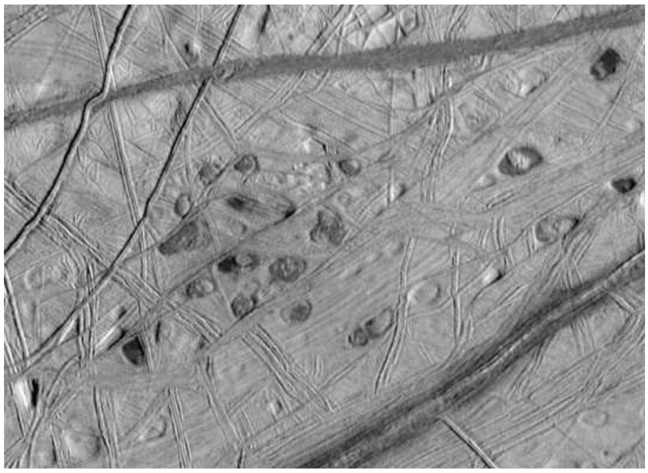

Fig. 6. Examples of circular features named lenticulae, imaged by the Galileo spacecraft in 1998. Each is about 10 kilometres across. (NASA/JPL-Caltech)

2.4.2. Chaos regions

The chaos regions on Europa are thought to be sites of local melt through, and could be an indication of liquid water beneath the ice crust. The chaos regions are wide ranging in size, location and age (Greenberg et al. 1999).

Pre-existing surface features often survive the formation of chaos. The boundaries of chaos regions are not controlled by pre-existing cracks. This fact confirms that the formation process of chaos is a thermal one and not mechanical.

One example of such a surface feature is named the Conamara Chaos and is shown in Fig. 5. The chaos region is littered with fractured, rotated and tilted blocks of ice in an apparently random pattern. Upon closer examination, researchers were able to fit the ice blocks back to the original arrangement, much like a jigsaw puzzle (Greenberg et al. 1999). The fractured ice blocks appear to be sliding on ice or floating on fluid. The movement and rotation of the blocks suggest that the region has a mobile and warm base. In the images examined by Greenberg et al. (1999), at least 18

Small circular features called lenticulae are thought of as small chaos regions (Fig. 6). The formation of lenticulae is believed to be the result of the rising blocks of warm ice and sinking cold ice. Tidal flexing heats the base of the ice shell where the ice is near its melting point. The warm ice at the base of the shell becomes less dense than the cold ice on top and attempts to rise. For a thick enough ice shell, the buoyancy force can overcome the viscous resistance. The rising ice block punches the surface and creates a dome-shaped feature on the landscape. Models suggest that the thickness of the ice shell must be at least 10 kilometres for the creation of lenticulae to be possible (Pappalardo et al. 1999).

2.4.3. Tectonic features

Wedge regions are areas on the surface where the icy crusts have been completely pulled apart. An example of a wedge region is shown in Fig. 7. It is believed that wedge regions are formed by moving ice plates driven by tidal deformation, much like plate tectonic activities on Earth driven by its internal heat energy. The parallel grooves inside the wedge region bear resemblance to new crusts formed at mid-ocean ridges on the Earth's sea floor. The older material is white in colour and is located on the right half of Fig. 7. The bottom left corner shows new and dark material that fills the crack, replacing the older material. The source of supply for the new material may be a subsurface ocean.

Fig. 7. An example of a wedge region, imaged by the Galileo spacecraft in 1998. The area of the image covers approximately 10 square kilometres. (NASA/JPL-Caltech)

Parallel linear ridges are also examples of tectonic surface features. They are believed to be massive fracture lines caused by periodic tidal stresses on the outer shell (Greenberg et al. 1998). Fig. 8 shows some criss-crossing parallel ridges. The brighter ridges lie on top of the darker ones and are younger. The valley between the bright parallel ridges is filled with dark material. There is also evidence of smoothing from the flow of subsurface material at the bottom right corner.

The width of a ridge ranges from a few to 20 kilometres. A ridge can extend to 1,000 kilometres long! Like the wedge region, ridges show evidence of subsurface material welling up

Fig. 8. An example of parallel ridges, imaged by the Galileo spacecraft in 1998. The ridges span approximately 2 kilometres in width. (NASA/JPL-Caltech)

to replace the older surface. The formation of ridges and wedge regions suggests a dynamic interior and a possible warm subsurface ocean.

3. Organic material

The second ingredient for life is organic compounds that sustain organic evolution. Impact delivery has been shown to be a possible source of organic compounds on early Earth. Impact shocks also help jump start organic synthesis (Chyba & Sagan 1992). Comet impacts could also be a source of organic materials for Europa in the same fashion (Pierazzo & Chyba 2000).

Hubble Space Telescope identified the presence of a tenuous atmosphere of molecular oxygen (Hall et al. 1995), but may have little biological significance. The Galileo mapping spectrometer instrument detected combinations of oxygen, carbon, sulfur, hydrogen and nitrogen on the surfaces of Callisto and Ganymede. The instrument also detected tholin, a pre-biotic organic molecule that is needed for organic evolution (McCord et al. 1997). It is likely that similar compounds also exist on Europa. The interaction of charged particles and water ice may also be able produce organic molecules (Chyba 2000).

4. Sources of energy

The final basic ingredient of life is energy. Energy is needed to initiate an origin event and more energy is needed to subsequently sustain organic evolution. Possible sources of the energy required are described in the following sections.

4.1. Energy to initiate an origin event

Sufficient energy is required to jump start organic evolution. Europa lies well outside the conventional notion of the habitable zone in the solar system, where the energy from the sun provides enough energy to sustain life. Solar heating is then ruled out as a possible source. Also, Europa has no significant atmosphere, thus electrical energy produced by lighting is not a possible source.

The main source of energy comes from tidal heating and radioactive decay. The known available energy on Europa is less than that of Mars and Earth. Whether the energy is enough to initiate an origin event is unknown (Hiscox 2000).

4.2. Energy to sustain organic evolution

The hydrothermal energy on Europa is derived from the tidal flexing by Jupiter. Hydrothermal vents may exists on Europa's ocean floor and create local hot spots for chemosynthetic life forms, providing sources of energy and nutrients (see Section 5).

A radiation-driven microbial ecosystem in the ice crust of Europa was suggested by Chyba (2000). Charged particles are accelerated in Jupiter's powerful magnetosphere and bombard Europa. The charged particles then could interact with ice to produce organic and oxidant molecules. The organic materials need to reach the subsurface ocean to begin evolution. Melt through regions, such as the Conamara Chaos could be the means of transporting the organics to the ocean. Chyba (2000) has shown that such a system sustained by radiation energy is possible.

Although photosynthesis is ruled out as a possible energy source for an Europan ocean under an ice shell tens of kilometres thick, it is a possible energy source for the sunlit regions at the shallow depths of the ice shell. Gaidos & Nimmo (2000) proposed one such potential habitat for photosynthetic organisms. The lateral motions of adjacent ice crusts create tectonic geological features. The mechanical energy from the motions may be enough to cause a significant rise in local temperature and reduction in the viscosity of ice. This process could eventually lead to the creation of transient liquid water or brine pockets within the reach of sunlight. This theory makes photosynthesis another possible source of energy of Europan life.

5. Similar extreme conditions on Earth

In the past few decades scientists have come to a realization that where there is liquid water on Earth, life exists. They have found that this is true in virtually any extreme condition. Extremes in temperature, radiation, pressure, dessication, salinity, and pH have all been overcome by life forms on Earth in the presence of liquid water (Rothschild & Mancinelli 1998).

Europa lies well outside of the conventional notion of the habitable zone in the Solar System. However, with the revelation that life thrives in the most extreme environments on Earth, the possibility that life could be sustained in similar environments on Europa becomes greater. Two examples of extreme environments of Earth are discussed here: Lake Vostok and the hydrothermal vent community in the Gulf of Mexico.

5.1. Lake Vostok

Perhaps the environment on Earth most analogous to Europa's putative ocean is Lake Vostok in east Antarctica. Its liquid water body spans 10,000 square kilometres and lies beneath approximately four kilometres of slow moving glacial ice.

The thick glacial ice precludes photosynthetic processes to take place in Lake Vostok, which makes the lake an ideal model for determining how a potential biosphere might survive in a subsurface Europan ocean.

It is thought that subglacial lakes may have one of the lowest stocks of viable organisms on earth. However, hotspots of geothermal activity, which maintain the liquid body, could provide local sources of energy and temperatures more favourable to growth. Such environmental conditions would be comparable to those surrounding deep sea hydrothermal vents.

Scientists have yet to tap into the lake itself, but a project has been initiated to do just that. Not only will Lake Vostok provide insight into life sustaining processes in the extreme conditions of the subglacial lake, but it will also provide scientists with a useful earth-based analogue and a test-bed for technology to assist in the design of unmanned planetary missions to Europa (Bell & Karl 1998).

A team of international scientists and engineers began drilling the ice sheet above Lake Vostok in 1989 to obtain a detailed record of the past climate on Earth. In the upper ice layers, colonies of bacteria have been found which survive the long and cold winters using a form of hibernation. During the summer, tiny dust particles act as solar energy collectors and use the sunlight to melt small quantities of liquid water. Throughout most of the ice cores, even to depths of 2400m, viable micro-organisms were present (Abyzov 1998).

The glacier above Lake Vostok may be analogous to pockets of salty brine that might exist in the shallow depth of the Europan ice shell. The results from Lake Vostok support the possibility of a viable photosynthetic community on Europa.

5.2. Gulf of Mexico

Possible metabolic processes in a chemosynthetic ecology have been suggested for Europa and they include methanogenesis, sulfur reduction and iron oxide reduction. Heterotrophic life forms could then be supported by the carbon and energy sources resulting from the excreted byproducts and decaying material from chemotrophic organisms (Kargel et al. 2000).

One location on Earth that may provide a similar life sustaining environment is in the Gulf of Mexico continental slope. There, sea-floor gas vents, oil seeps, gas hydrates, and subsurface oil and gas fields are present. This extreme, low-temperature environment supports complex chemosynthetic communities that derive energy from reduced carbon and methane without the need for energy from the sun (Sassen et al. 1999).

If Europa still has an active interior, thermodynamic disequilibria capable of supplying nutrients and energy to sustain a viable ecosystem, comparable to that in the Gulf of Mexico, may exist on Europa. Excreted byproducts and decaying material from the vent community could serve as the bases for a broader ecosystem by supplying carbon and energy sources (Kargel et al. 2000).

The conditions in the putative Europan ocean are poorly constrained, thus the Gulf of Mexico hydrothermal vent community can only provide a partial analogue to Europa's subsurface ocean.

6. Future space missions to Europa

Several important space missions shaped our current understanding of the icy moon. Voyager flew by Europa in 1979 revealing its bright and smooth icy surface. Pioneer 10 and 11 confirmed that Europa is immersed in the powerful magnetospheric radiation from Jupiter. The Galileo spacecraft reached the Jovian system in December of 1995 and sent back images and scientific data of unprecedented precision.

The Europa Orbiter was scheduled to be launched in 2003. Despite its budget increase in 2002, NASA cancelled the Europa Orbiter mission, citing excessive cost growth. The next proposed mission to Europa is the Jupiter Icy Moons Orbiter (JIMO). It is an ambitious plan to orbit three of the Galilean satellites, Callisto, Ganymede and Europa, and is scheduled to be launched after 2012.

The goals of future space missions to Europa should include: obtaining definitive proof of the existence of a subsurface Europan ocean, determining the depth and nature of such an ocean, and possibly acquiring and analyzing samples from the surface ice and even the subsurface liquid water. Possible ways to further confirm the existence of a subsurface ocean include: measuring the amount of tidal bulges and probing the subsurface structure with radar.

7. Conclusion

Life as we understand it requires three basic ingredients: liquid water, energy and organic compounds. Studies have shown promise for all three ingredients to coexist on Europa. Even if all three ingredients are present on Europa, however, it is not for certain that life exists on the moon.

Future missions are needed to confirm the existence of the ocean and obtain samples from the Europan ice shell. If life is discovered on Europa, it would prove that the Earth is not the only body that supports life and may not be a unique occurrence in the Universe. It would also help us unravel the mystery of the origin of life.

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