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Europa: Prospects for an Ocean and Exobiological Implications

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Introduction

As far as we know, Earth is the only planet in our solar system that supports life. It is natural, therefore, that our understanding of life as a planetary phenomenon is based upon Earth-like planets. For example, Mars has received a great deal of attention as a possible former abode for life because its climate appears to have been somewhat more Earth-like in the past. However, there are environments in the solar system where liquid water, commonly believed to be a prerequisite for biological activity, may exist in a distinctly non-Earth-like environment. One such location is Europa, one of the Galilean satellites of Jupiter. The possibility that liquid water exists on Europa presents us with some interesting exobiological implications concerning the potential of the satellite to support life.

An Ocean on Europa?

The images of Europa taken during the Voyager flybys of the Jovian system (chapter frontispiece) show a very bright surface transected by a network of long linear features of lower albedo and brownish color. The features are seen down to the resolution of the images (~4 km/line pair) and are as large as tens of kilometers across with maximum lengths comparable to the radius of Europa (~1500 km). Their geometry indicates that they are probably fractures caused by extensional stresses in Europa's crust. Other linear topographical features include low ridges of unknown origin. Overall, however, the surface of Europa is remarkably level. Only a handful of small impact craters have been positively identified, and it is doubtful that topography anywhere on the satellite exceeds a few hundred meters.

Even the most basic pre-Voyager information about Europa appeared enigmatic. The surface is composed primarily of H_2O and frost, yet the satellite's density clearly indicates that it is predominantly a silicate body. Simple but powerful cosmochemical arguments suggest that all of the Galilean satellites should be composed primarily of silicates and varying amounts of H_2O. Water frost was first positively identified as a major component of Europa's surface in 1972, based on the presence of strong infrared H_2O absorption features in its reflectance spectrum. This finding has been confirmed by later observations, which have led to the conclusion that more than 95% of the spectroscopically detectable material on the surface of Europa is water. Despite the nearly pure water ice surface composition, the density of Europa is known to be 2.97 g cm^{-3}. A density this large indicates a composition dominated by silicates, with only a relatively small admixture of H_2O. If the silicate component of Europa is largely dehydrated and has a density like that of Io (3.57 g cm^{-3}), then Europa is composed of 7 to 8% free H_2O by mass. If, however, the silicates are hydrated, then the density is consistent with a composition including little or no free H_2O.

Three models have been proposed for the internal structure of Europa that are consistent with the satellite's surface composition and density. These are the *thin ice*, *thick ice*, and *ice/ocean* models (fig. 6-1). The thin ice model suggests that the silicates in Europa's interior are largely hydrated and that the surface H_2O ice is a very thin layer (a few km) lying over the hydrated silicates. In the thick ice model, enough internal heat is produced and retained to dehydrate the silicates, driving the H_2O to the surface to form a layer of solid ice on the order of 100 km thick. In the ice/ocean model still more heat is produced and retained, melting much of the ice. The internal structure of Europa in this model consists of a dehydrated silicate interior, an ocean of liquid water on the order of 100 km thick, and a thin (≤10 km) ice layer on the surface.

All of these models are consistent with Europa's density and surface composition and choices among them must be made on the basis of surface morphology and models of Europa's internal thermal evolution.

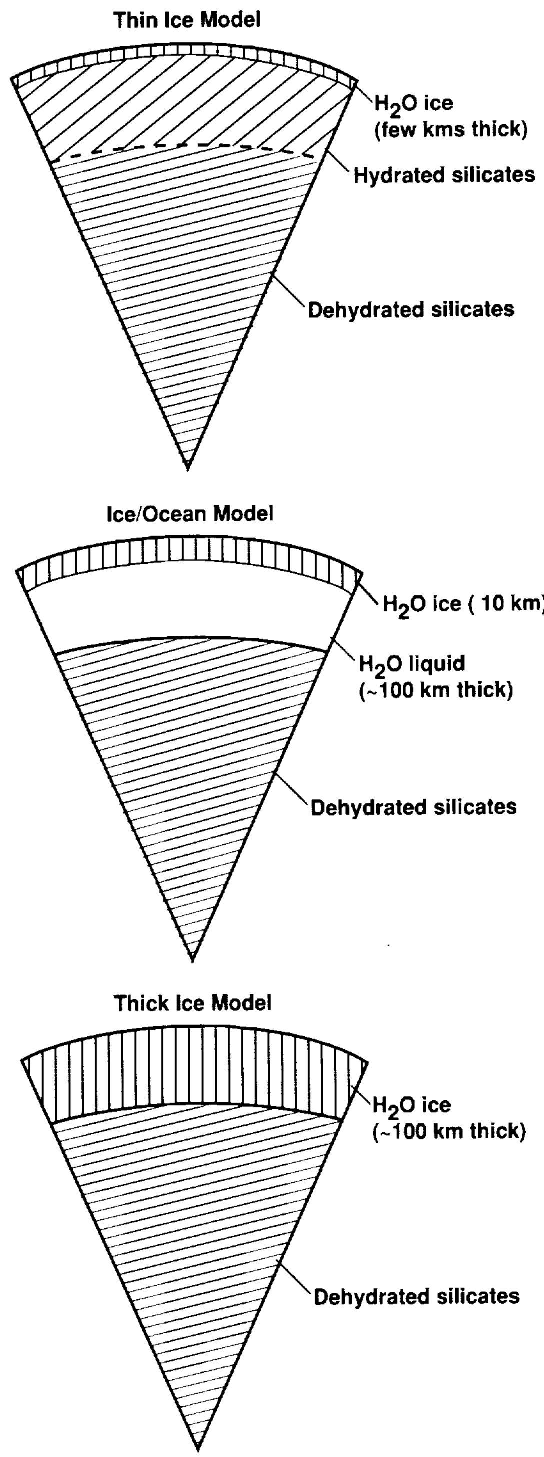

Figure 6-1. Three models proposed for the internal structure of Europa include the thin ice, thick ice, and ice/ocean models.

Thermal Evolution of Europa

The heat source that may maintain liquid water within Europa is the dissipation of tidal energy. Tidal forces arise in a satellite because the gravitational field of the planet varies across the body of the satellite. Regions on the satellite that are nearer the planet feel a stronger attractive force than those that are farther from the planet. The effect of these forces is to distort the satellite's shape. Tidal torques generated by this distortion rapidly fix the satellite's rotation to be synchronous, so that one face always points in the direction of the planet. However, if the orbit is eccentric, the size of the tidal bulge varies with distance from the planet. Hence the satellite is continuously flexed as it proceeds around its orbit. Conservation of angular momentum and energy in this process results in the eccentricity of the orbit being damped, so that the orbit gradually becomes circular unless some process acts to maintain the eccentricity. Hence the tidal heating process is self-limiting and the heating will cease when the circular orbit condition is reached.

However, for many of the satellites of the outer solar system, mutual interactions among the satellites act to maintain non-circular orbits over extended periods. The prime example of this phenomenon is the "Laplace resonance" between Io, Europa, and Ganymede. This resonance results in the continuous forcing of Europa's eccentricity, and thus, the continuous deposition of tidal energy as heat. Physically, the energy dissipated by the tides comes from the orbital energy of the satellite and the rotational energy of the planet.

The mean heat flow for Jupiter's innermost large satellite, Io, has been determined observationally to be ~1500 erg cm^{-2} s^{-1}. This heat flow is driven by tidal dissipation and is reflected in the spectacular volcanic activity observed on the surface of Io by Voyager. However, the tidal dissipation rate is also strongly dependent on the orbit's semi-major axis, a, which is defined as half the length of the longest axis of the orbital ellipse. The tidal dissipation rate decreases as $a^{-15/2}$. So Europa, largely because it is significantly farther from Jupiter than Io, undergoes substantially weaker tidal heating. The crucial question is whether or not the heating is sufficient to maintain liquid water in the satellite's interior.

Europa's Three Models

Consider again the three possible models of Europa's interior discussed above (fig. 6-1). Of these, the thin ice model appears to have the most severe problems. Radiogenic heat is generated by a body as a result of the decay of radioactive isotopes trapped in the interior of the planet or satellite upon formation. When one calculates the magnitude of tidal heating in the silicate portion of Europa it appears that the combined tidal and radiogenic heat flow is sufficient to dehydrate the bulk of the silicates in Europa's interior, thus producing an amount of water or ice at the satellite's surface in excess of that predicted by the thin ice model. More importantly, it has been shown that the thin ice model should lead to long-term retention of large impact craters since rock close beneath the surface would inhibit glacier-like relaxation topography. This result is in strong contrast with Europa's nearly crater-free surface. Choosing between the thick ice and ice/ocean models, however, is more difficult. The critical problem concerns the rate of heat removal by thermal conduction and solid state convection in the ice. According to tidal heating calculations, conduction alone cannot remove heat rapidly enough from Europa to keep most of the ice in a thick outer layer from melting. On the other hand, if solid state convection occurs through the ice, it can remove heat rapidly enough to prevent melting and maintain a solid ice layer. On Earth, flow of glaciers takes place by deformation of ice in the solid state; similar deformation could allow slow convection in Europa's icy crust. However, solid state convection in an outer ice layer can occur only if the layer exceeds some critical thickness, which is about 30 km on Europa.

Therefore, the crux of the dilemma in choosing between the two models lies in the question of whether the tidally generated heat flow ever became low enough to allow the freezing of Europa's entire water mass. If this occurred then Europa has probably lost its heat effectively through time by solid state convection in the ice, avoiding the formation of an ocean. Alternatively, if the heat flow never became small enough to allow the formation of a layer of ice 30 km thick then an ocean should exist. The period of Europa's thermal evolution in which this potential evolutionary bifurcation is believed to have been resolved is the period toward the end of the satellite's accretion. However the outcome of a particular evolutionary model that predicts the conditions of the satellite toward the end of this critical accretion period hinges on the highly uncertain calculation of the tidal heating rate. Very simple calculations suggest that tidal heating rates exceed those that would allow convection and freezing by more than a factor of two. More detailed consideration of the rheology of an ice shell has suggested that tidal heating in such a shell would be smaller than this, and preservation of a liquid layer correspondingly more difficult. On the other hand, consideration of tidal dissipation in an ice layer of varying thickness has led to the suggestion that these variations could lead to enhanced local heating and melting. Based on theoretical arguments alone, then, the presence of a liquid ocean appears plausible but not proven.

If an ocean does exist, fractures that occurred through the entire depth of the ice layer would briefly expose the liquid water below. This possibility is supported by the existence of apparent fractures on the surface of Europa. Fracturing could be caused by tidal stresses or by movement of the shell with respect to the tidal bulge of Europa. Liquid water exposed to the surface by fracturing would boil rapidly, creating a cloud of vapor that would condense and fall as frost over the surface of the satellite (fig. 6-2). An insulating layer of porous frost would reduce the surface conductivity below that of solid ice, thereby lessening the escape of heat which would lead to increased melting and the further reduction of the thickness of the ice shell.

Several lines of observational evidence tentatively support the hypothesis of liquid water below a thin ice shell on Europa as well as active resurfacing of the surface, possibly by release of water through cracks in the ice. First, the lack of craters and the apparent mobility of the crust are most readily explained in this manner. Second, the photometric function of Europa's surface indicates that there is a substantial textural difference between that surface and impact ejecta deposits of similar albedo on Ganymede and Callisto. The photometric properties may be more consistent with a surface layer of condensed frost as opposed to impact ejecta. Third, the SO_2 concentration observed on Europa's surface can be interpreted to be a result of uniform addition of S^- ions from Jupiter's magnetosphere to the surface on which a much larger amount of H_2O is continually deposited. Deposition rates for H_2O of 0.1 $\mu m\ yr^{-1}$ are inferred. Despite these inferences, however, the hypothesis that an ocean of liquid water exists beneath Europa's icy shell remains unproven. Definite conclusions must await further exploration of the satellite.

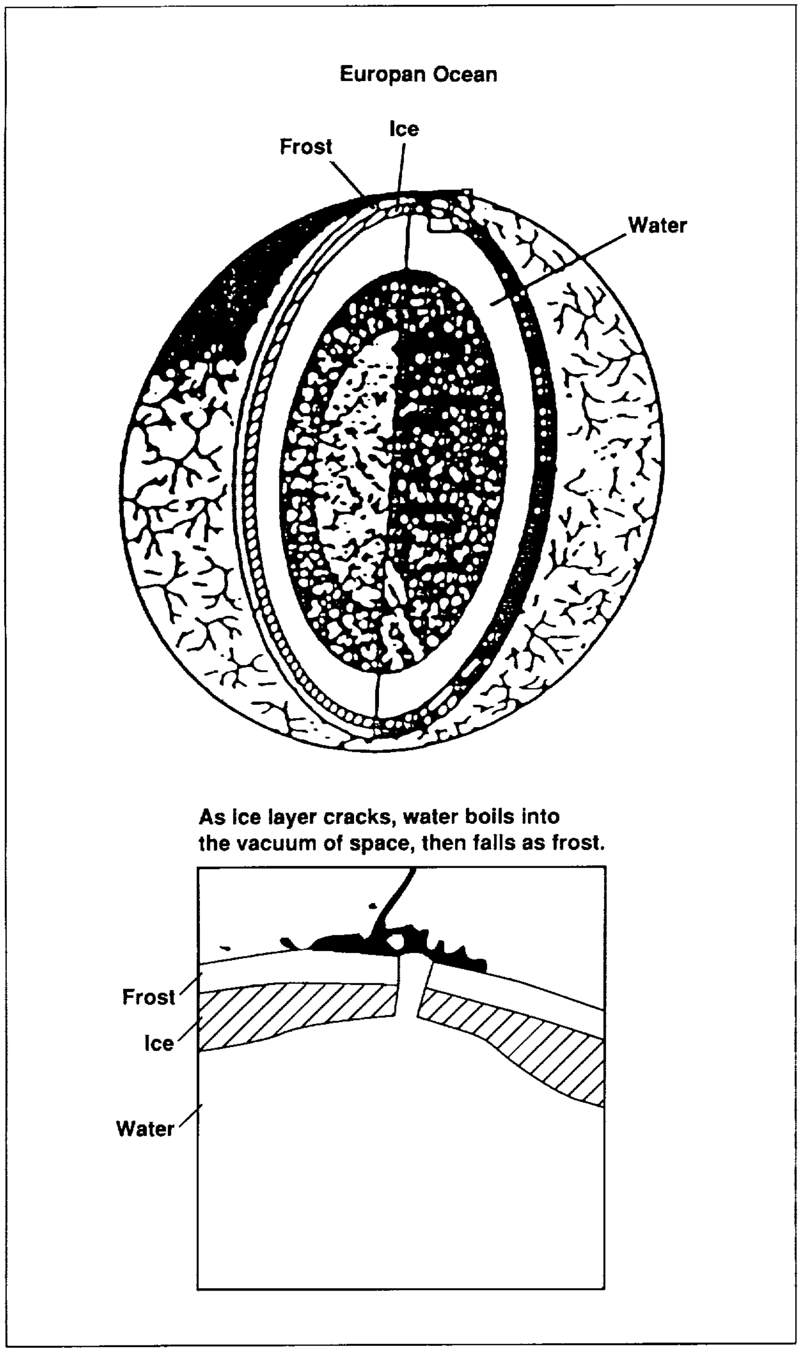

Figure 6-2. Liquid water exposed to the surface by fracturing would boil rapidly, creating a cloud of vapor that would condense and fall as frost over the surface of the satellite.

Exobiological Implications

If an ocean does exist in Europa, what would be the exobiological implications of this fact? We know that in addition to the presence of liquid water and biologically useful sources of energy, the presence of compounds of the biogenic elements (H, C, N, O, S, P) is considered essential for the existence of life in any cosmic body.

Very little is known about the bulk composition of Europa and other Galilean satellites except that they must have been made of matter present in the Jovian nebula, rich in water and other compounds of the biogenic elements, as suggested by studies on the formation and evolution of these satellites. It has been argued that as a result of the substantial luminosity of proto-Jupiter the condensation of ices, such as H_2O, was inhibited at a close distance to the planet, and a sharp chemical gradient was created among the Galilean satellites. Under these circumstances Io would only have retained dehydrated silicates and other minerals, sulfur, and SO_2, whereas increasing amounts of H_2O in the form of ice or water of hydration would have been retained by Europa, Ganymede, and Callisto.

Table 6-1: Density Comparisons between Galilean Satellites and Carbonaceous Chondrites*

Galilean satellites		
Io	Europa	Ganymede
3.57	2.97	1.93
Carbonaceous chondrites		
Type III	Type II	Type I
3.5	2.5-2.9	~2.0

*Density comparisons between carbonaceous chondrites and the Galilean satellites ignore the processes of self compression and ice phase changes that presumably took place on the satellites.

The only direct evidence available about the composition of these satellites is that obtained by spectral measurements on their surfaces. Io's surface is dominated by sulfur and its compounds, particularly condensed sulfur dioxide. The other three satellites have copious amounts of water-ice in their surfaces, about 95% in Europa, 90% in Ganymede and 30 to 90% in Callisto. The non-water ice material on the Galilean satellites appears to be spectroscopically similar to that of carbonaceous chondrite material and to that of minerals containing Fe^{3+}. Carbonaceous chondrites (particularly Wiik Types I and II) are a class of meteorites characterized by their high concentrations of iron-magnesium silicates and of volatile components such as water, sulfur, and carbon in comparison to other meteorite classes.

On the basis of these and other observations a suggestion is advanced, as a working hypothesis, that the Galilean satellites were made of matter similar to that of carbonaceous chondrites but with increased amounts of water and carbon compounds as would be expected from the composition of the Jovian nebula. The suggestion is also consistent with the relative proximity of the Jovian nebula to the outer region of the asteroid belt where most of the dark asteroids exist. Dark asteroids are presumed to be the parent bodies of the carbonaceous chondrites and, in fact, if we compare the Galilean satellites with carbonaceous chondrites, we see an approximate correlation of their densities. The densities of Io (3.57 gm cm^{-3}), Europa (2.97 gm cm^{-3}), and Ganymede (1.93 gm cm^{-3}) are very similar to the densities of Type III (3.5 gm cm^{-3}), II (2.5-2.9 gm cm^{-3}) and I (~2.0 gm cm^{-3}) carbonaceous chondrites, respectively, according to Wiik's classification (table 6-1). The approximate correlation of the densities is appropriate and useful in that it allows the estimation of the composition of Europa using available data. However, it should be pointed out that a direct density comparison between carbonaceous chondrites and the Galilean satellites ignores the processes of self compression and ice phase changes, processes that presumably led to an increase in the densities of the more massive satellites of Jupiter relative to the less massive carbonaceous chondrites, and thus, should be taken only as a demonstration of an approximate relationship.

Table 6-2: Chemical Composition of Carbonaceous Chondrites

	SiO_2	MgO	C	H_2O	S
Type I	22.56	15.21	3.54	20.08	6.20
Type II	27.57	19.18	2.46	13.35	3.25
Type III	33.58	23.75	0.46	0.99	2.27

If we limit our discussion to the case of Europa and compare it with Type II carbonaceous chondrites (CII), we see that in addition to sulfur (3.25%) the CII chondrites contain relatively large amounts of water (13.35%) and carbon compounds (2.46%) (table 6-2). This shows that planetesimals of this composition, which are believed to have been involved in the formation of Europa through collisions with the proto-satellite throughout its early history, would have carried with them more than sufficient amounts of H_2O to have provided the calculated water fraction of Europa which is at least 7% of the mass of the satellite ($M_e = 4.87 \times 10^{25}$ g). But what is more important from an exobiological point of view is that a significant presence of organic compounds in Europa is also suggested by this comparison. What are the natures of the organic compounds? As indicated by the studies done on the Murchison meteorite, one of the best analyzed CII chondrites, a large variety of organic and other carbon compounds are present (table 6-3). The organic matter present is distributed among different compound classes of obvious biological interest, including amino acids, purines, and pyrimidines, which are the building blocks of proteins and nucleic acids, respectively. It should be noted that the relative amount of the soluble organic compound fraction (about 500 ppm in Murchison) would be equivalent to about 0.05% of the mass of the satellite.

Table 6-3: Distribution of Carbon in the Murchison CM2 Meteorite

Species	Abundance
Acid insoluble carbonaceous phase	1.3-1.8%
Carbonate and CO_2	0.1-0.5%
Hydrocarbons	
aliphatic	12-35 ppm
aromatic	15-28 ppm
Acids	
monocarboxylic (C_2-C_8)	~170 ppm
dicarboxylic (C_2-C_9)	not measured
hydroxy (C_2-C_5)	~6 ppm
Amino Acids	10-20 ppm
Alcohols (C_1-C_4)	~6 ppm
Aldehydes (C_2-C_4)	~6 ppm
Ketones (C_3-C_5)	~10 ppm
Ureas	~20 ppm
Amines (C_1-C_4)	~2 ppm
N-heterocycles	
pyridines and quinolines	0.04-0.4 ppm
purines	~1 ppm
pyrimidines	~0.05 ppm
poly-pyrroles	<<1 ppm
Sum:	1.43-2.35%
Total carbon:	2.0-2.5%

We can translate the CII meteorite data into a possible composition of the upper hydrous layers of Europa. Assuming that about 90% of the satellite's water is in the liquid phase (namely 6.3% of the mass of the satellite) the concentration of organic compounds dissolved in such a subsurface ocean would be of the order of 1%. In absolute terms the amounts of total carbon (carbonates plus carbon compounds) in Europa would be 1.2×10^{24} g and that of soluble organic compounds 2.4×10^{22} g. The latter figure is at least four orders of magnitude higher than the total organics in Earth's active biosphere. Moreover, a concentration of 1% organics in water is a sufficient concentration to lead to significant reaction rates for abiotic biochemical synthesis under favorable conditions. Whether these reactions could have led to emergence and evolution of life on Europa is not known and would have depended very much on the conditions of the satellite toward the end of the accretion phase, as discussed earlier.

Considering what may be occurring today on the surface of Europa, possible evidence for the synthesis of organics may be visible on the satellite's surface. The presence of brown colorations on the surface fractures of Europa has led to the speculative suggestion that the colorations present are due to organics produced abiotically on or below the surface of Europa. Organics synthesized below the surface could be brought to the surface as the result of fractures in the ice. However, at this time the results from a number of investigations that in some way model the conditions on Europa have produced only highly speculative implications.

Early Conditions of Europa

What were the early conditions of Europa and how do they compare with those of carbonaceous chondrite parent bodies? The occurrence of an aqueous environment on such a parent body has been proposed before based primarily on the general characteristics of carbonaceous chondrites. A similar model has been used to explain the similarity of the amino acids found in the Murchison meteorite to those obtained from the classic Miller experiments with electrical discharges. Thus it has been suggested that a parent body of about 100 km in radius could have retained a liquid environment for about 200 million years and an atmosphere for at least 10^4 years. If that were the case, such a parent body model would explain the observations mentioned above on the similarities between amino acid compositions of carbonaceous chondrites and those produced under laboratory models of the prebiotic Earth. These environmental conditions would have been much more plausible for Europa because of the much larger mass and radius (1,563 km) of this satellite as well as its relative proximity to Jupiter.

Studies on the evolution of the Jovian system and the Galilean satellites suggest that during its early phase of formation, Europa was immersed in the Jovian nebula for 10^5 to 10^6 years and its atmosphere was probably retained for a significantly longer time. Therefore, during this time, most of Europa's water was probably partially solid and liquid, coexisting with its atmosphere, an atmosphere which should have been reducing in nature and similar to that of Jupiter. Thus, a number of experiments performed in different laboratories on the abiotic synthesis of organic compounds may be relevant to the early Europan conditions. These studies include the work done by several investigators with electrical discharges and different sources of radiation. Interestingly, these experiments are similar to those described earlier which were performed to explain the current existence of colored compounds along the linear markings of Europa.

Additional synthetic chemical reactions could have occurred upon the infall of planetesimals, meteorites, and comets on Europa. The organic compounds present in the satellite or in the infalling bodies would have been subjected to heating and rapid quenching and cooling at the water-surface interface upon collision during the last phase of satellite differentiation. The low temperatures of Europa's hydrous phases would have facilitated the survival and further interaction of the biochemical compounds which were generated in this early stage.

Low-Temperature Abiotic Chemistry

Examples of relevant low-temperature, abiotic reactions are offered by the synthesis of adenine and purines from hydrogen cyanide and by the formation of peptides by condensation of amino acid amides. Hydrogen cyanide is a ubiquitous cosmic precursor of biochemical compounds since it is present in many cosmic bodies, including interstellar clouds, comets, Titan, Jupiter, and Saturn, and must have been present in the Jovian nebula as well. The formation of adenine and other purines from hydrogen cyanide is well known from our earlier work. Adenine is probably present in Halley's comet as shown by data from the spacecraft Vega 1 (U.S.S.R.) mass spectrometer. This important biochemical compound has also been speculated to be present at the bottom of Titan's methane-ethane ocean.

What is less well known is that hydrogen cyanide can produce the precursors of purines in high yields at temperatures of –10°C and lower from dilute solutions (0.001 M) of HCN. Upon further cooling and formation of the water-ice, the hydrogen cyanide solution is concentrated until it becomes 75% HCN at the eutectic point (–22°C). Thus by freezing, enormous enrichments are possible of reactive chemical species which produce biochemical monomers. A similar situation applies to the condensation of monomers to polymers observed in the conversion of glycinamide, a common precursor of glycine, to polyglycine, a linear molecule containing a number of amino acid residues joined end to end. Glycinamide is also readily obtained from hydrogen cyanide. Furthermore, the model proposed for the replication of polynucleotides also requires relatively low temperatures (0 to 25°C). In fact, a number of investigators consider the low-temperature prebiotic synthesis of biochemical compounds a crucial stage for the origin of life on Earth.

Possibility of the Emergence of Life on Europa

As discussed above, the early history of this Galilean satellite may have been favorable for the capture and *in situ* formation of different organic compounds, including biochemical monomers and polymers. The low-temperature environmental conditions may have also facilitated the preservation and further interaction of labile biochemical polymers.

Whether these processes proceeded to a more advanced stage of development is not known because no experimental work has been done at low temperatures on the protocellular stages of prebiological evolution. A possible difference with the conditions of the primitive Earth may be the absence of processes of cyclic evaporation for a continued period of time under atmospheric pressure. This is hypothesized to have facilitated on our planet the formation of phospholipids and other amphiphilic compounds which presumably gave rise to liposomes that encapsulated catalytic nucleotides. Whether these and other stages of protocellular evolution may or may not have been possible on Europa is not clear. However, recent information obtained on the amphiphilic components of the Murchison meteorite has shown that they have the ability to self-assemble into bilaminar and trilaminar membranes similar in structure to the membranes found in living cells. This is a significant finding that increases the possibilities of formation of membranous structures which could facilitate the appearance of life on Europa.

Table 6-4: Substrates and Energy Available for Metabolic Activity

A. Substrates	Wt %*	Mass
Total carbon (carbonates + C compounds)	2.46%	1.2×10^{24} g
Total sulfur	3.25%	1.6×10^{24} g
Free sulfur (Mighei)	2.39%†	1.2×10^{24} g
Total phosphate (as P_2O_5)	0.27%	1.3×10^{23} g
Soluble phosphates (~10% of total phosphate)	0.027%	1.3×10^{22} g
Soluble organic compounds	~0.05%	2.4×10^{22} g
Soluble nitrogen compounds (Orgueil, CI)	0.01%	4.9×10^{21} g

B. Energy sources for metabolic activity	
Hot suboceanic thermal springs	>100°C
Chemical energy from redox reactions; thermal plumes with unequilibrated chemical systems	e.g., H_2, H_2S, S, reduced organics, SO_2, SO_4, CO_2
Solar radiation	Surface and upper layers

*Wt % are averages for CII carbonaceous chondrites except for soluble nitrogen (CI).
†Wt % is average from Mighei analyses.

Prerequisites for the Habitability of Europa

Leaving aside the unanswered question concerning the possible origin of life on Europa, it is also of interest to determine whether any form of indigenous or terrestrial life may be able to survive and reproduce under the existing conditions of this satellite. The presence of liquid water is one of the major requirements for the existence of life in a cosmic body. As discussed above, Europa may have possessed a significant body of water since its formation and during the course of its geological history so that this first requirement may be fulfilled. Two other necessary requirements are the availability of compounds of biogenic elements (as precursors of biochemical molecules and as substrates for metabolic reactions) and a continuous supply of energy.

As discussed earlier, we have seen that using the carbonaceous chondrite model, about 2.4×10^{22} g of soluble organic compounds may have been present at the time of formation of Europa (tables 6-3 and 6-4). Furthermore, the total amount of organic and inorganic carbon is about 1.2×10^{24} g and some of this carbon (e.g., CO_2) could, in principle, be available to enter into metabolic cycles. As seen in table 6-4, the total value for sulfur (in any form, reduced and oxidized) would be expected to be of the same order of magnitude as that for total carbon.

On the other hand, the availability of the biogenic element nitrogen is not so well known. Based on the amounts of amino acids and heterocyclic nitrogenous compounds in the Murchison meteorite, the values for soluble organic nitrogen are about an order of magnitude lower than those for the dissolved carbon. It should be pointed out, however, that some nitrogen was probably retained in the form of ammonium sulfates, sulfides, or other salts which must have been present in the Jovian nebula. Indeed, Jupiter presumably has large amounts of ammonia and ammonium sulfides, and at least one analysis of the Orgueil meteorite, a CI chondrite, gave a value of 0.098% for ammonium chloride. If a similar percentage had been present in Europa it would correspond to about 4.9×10^{21} g for the whole satellite. Therefore, the total amount of soluble nitrogen on early Europa may have been somewhat lower than that of dissolved carbon (2.4×10^{22} g).

The other, extremely important biogenic element is phosphorus, which has been found in the form of PN in interstellar clouds, phosphine in Jupiter, and phosphates in interplanetary dust particles and meteorites. More specifically, phosphorus is also present in the three types of carbonaceous chondrites. The average amount of phosphate measured as P_2O_5 in the CII meteorites is 0.27%. The corresponding total amount for Europa would be 1.3×10^{23} g (table 6-4). This biogenic element exists in the above meteorites primarily as insoluble and partially soluble calcium phosphate minerals. It is also present in the form of phosphides. Upon solubilization of the inorganic phosphates they would be suitable for participation in the abiotic synthesis of key biochemical compounds, such as nucleic acids and important metabolic substrates. Because they are in the form of chloro- or hydroxyl apatite as well as CaMgH phosphates and possibly as sodium phosphates, only a small percent of these phosphates would need to be solubilized (e.g., ~10%) for the amount of the phosphate anion to reach the value of 1.3×10^{22} g which is more than 50% of the amount of dissolved carbon.

In summary, using the carbonaceous chondrite model, the amounts of reactive carbon, nitrogen, and phosphate compounds available as precursors or metabolic sources for the synthesis of biochemical compounds would range from 4.9×10^{21} to 2.4×10^{22} g. Even assuming that only 10% of these compounds reached the Europan ocean, the subsequent amounts of these elements present in the ocean would be in the range of 10^{20} to 10^{21} g, values which are two to three orders of magnitude larger than the total terrestrial biomass (10^{18} g).

Energy Sources for Biosynthesis and Metabolic Activity

Assuming Europa's ocean exists, there are primarily two major energy sources in the aqueous layers of Europa which could be utilized biologically for the synthesis of biochemical compounds and for different metabolic reactions.

The first is the dissipation of tidal energy in the form of heat, which presumably maintains a significant fraction of the water on Europa as liquid. In Io, the dissipation of tidal energy does not occur in a very uniform manner, but rather in discrete zones or spots, as shown by the more than 100 sulfur volcanoes on its surface. At a much lower scale the transfer of heat from the core of Europa to the bottom liquid water layers of its ocean may also occur in localized places. The existence of these non-uniform areas of heat transfer in Europa are at present only speculative, however, assuming they exist, they could be analogs of terrestrial deep oceanic thermal vents. On the

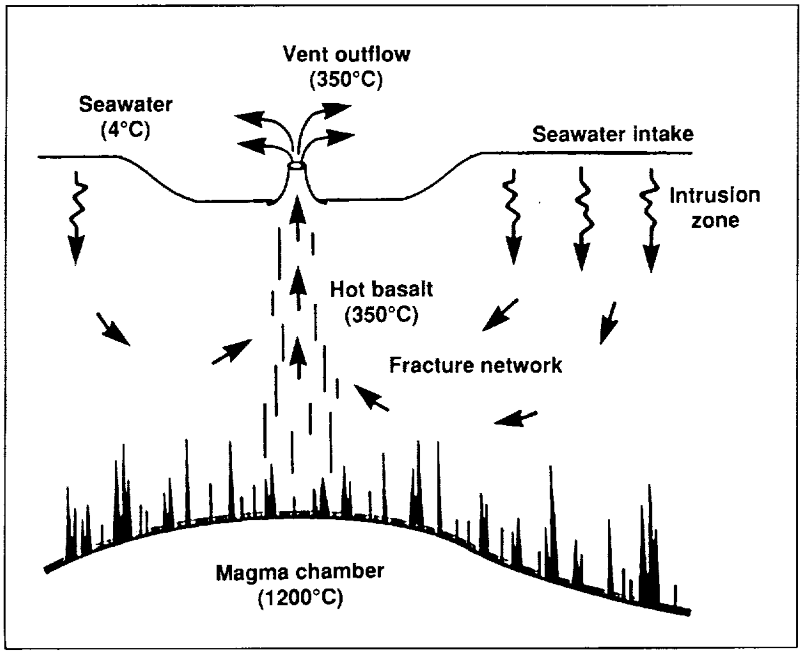

Figure 6-3. On Earth, the concentration of thermal energy in local high-temperature regions at submarine crests has led to large-scale hydrothermal activity. Reactions between sea water and hot basalt beneath the ocean floor produce solutions that ascend to the seafloor and emerge as hot springs whose sulfur and hydrogen compounds sustain chemosynthetic or chemolithotrophic bacteria.

Earth, the concentration of thermal energy in local high-temperature regions at submarine crests has led to large-scale hydrothermal activity (fig. 6-3). Reactions between sea water and hot basalt beneath the ocean floor take place at temperatures in excess of 300°C. The resulting solutions ascend to the sea floor where they emerge as hot springs that sustain oases of life. At the base of the food chain in these oases are chemosynthetic or chemolithotrophic bacteria that derive their entire energy supply from the reaction of geothermally produced sulfur and hydrogen compounds released from the vents.

Analogous hydrothermal regions conceivably could exist on the bottom of Europa's ocean. The calculated mean heat flux from Europa's silicate interior is less than a third of the mean heat flow of the Earth. In fact, it is only some 50% higher than that of the Moon, which is not observed to have any volcanic activity at the present. However, since the Moon's near-surface regions are virtually water-free this does not rule out the possibility of hydrothermal activity on Europa. Current data and modeling techniques are insufficient to provide a quantitative assessment of the probability of such activity.

The existence of sulfur on Europa, as suggested by the carbonaceous chondrite model, offers an additional similarity between terrestrial and theoretical Europan oceanic vents. It is of interest to note in this respect that due to the unequilibrated nature of the matter in these meteorites, and also probably in the Jovian nebula, several of the different states of oxidation of the sulfur compounds may coexist simultaneously, e.g., from the most reduced sulfides to the most oxidized sulfates. This would establish an adequate chemical redox potential ideally suited for utilization in metabolic reactions early in the satellite's development.

The latter infers the plausibility of the existence, at some time during Europa's past or present history, of a microbial ecosystem analogous to those that exist presently near terrestrial submarine geothermal vents.

The second form of energy that could be utilized biologically is the solar radiation which reaches the icy surface of the satellite. Assuming that solar energy would reach liquid water only where the ice crust had recently been fractured, it is straightforward to predict the maximum amount of light that could reach the Europan ocean. Calculations show that the light levels in the water would be extremely low, even immediately after a fracturing event. However, for up to 4.5 years after a fracturing event they could remain higher than the levels at which photosynthesis occurs in primitive microbial mats in perennially ice-covered lakes in the Dry Valleys of Antarctica. So, if such fracturing does indeed occur, very limited local environments may exist for extremely short periods of time that are within the range of adaptation of simple Earth organisms.

Two very important caveats should be added to this discussion of solar energy input. First, the scenario presented here represents a strict upper limit in that it does not consider loss of thermal energy to the walls of a fracture. If a fracture is narrow relative to the thickness of the forming ice cover, heat loss to the walls will cause freezing that may be substantially more rapid than we calculate. Second, we do not know the frequency with which fracturing events occur, or indeed if they take place at all. Using the most liberal estimates of fracturing, based on an inferred resurfacing rate by recondensing frost, we obtain a maximum total fracture area of approximately 5 km^2/yr, which is an exceedingly small fraction of the total surface area of the satellite.

Habitability of Europa by Anaerobic Life

On the basis of discussion so far, the three most important requirements for the maintenance of life (i.e., liquid water, sources of energy and organic compounds) could conceivably have existed on Europa during all of its geological history. Therefore, it may be appropriate to consider ecosystems on Earth that can be used as analogs to a putative Europan biota. Since no significant amounts of molecular oxygen appeared in the Earth's atmosphere until about 2 billion years ago, it would be reasonable to assume that any Europan biota would have to be essentially anaerobic and prokaryotic. In the lines that follow, some of the anaerobic microorganisms which could probably survive and grow in a Europan habitat are considered.

Photosynthetic organisms can take inorganic carbon in the form of CO_2 and fix or assimilate it into a usable organic form such as carbohydrates. Organisms with this ability are considered autotrophs or "self-feeders." Conversely, organisms ranging from humans to microorganisms that cannot fix inorganic carbon and thus are forced to consume organic carbon in the form of preformed biochemical compounds are called heterotrophs. Today's heterotrophs accomplish this by consuming plants and animals; however, at the onset of biotic history it is believed that primitive organisms survived by consuming the abiotically formed organic molecules present in the "Oparin broth." These organisms, believed to be the first organisms on Earth, had neither autotrophic nor photosynthetic capabilities. Only when these early cells began to exhaust the oceanic supply of nutrients did a need arise for autotrophic capability and eventually the ability to use light as an energy source to fix carbon. Therefore, the first anaerobic microorganisms were probably ancestors of the early heterotrophic prokaryotes that later developed autotrophic capabilities. Some of the fermentative *Clostridium* species have been suggested as such early heterotrophs. These organisms derive their energy by the anaerobic fermentation of many different organic compounds. Some of the sulfate-reducing bacteria which are strict anaerobes are also known to be capable of fermentative growth in the absence of sulfate. However, since *Clostridium* and sulfate reducers are highly evolved eubacteria, they cannot be considered as the earliest heterotrophic ancestors.

The study of phylogenetic trees determined from 16S rRNA sequence comparisons has led to the establishment of three major taxonomic groupings or fundamental cellular kingdoms, namely, eukaryotes, eubacteria, and archaebacteria. The universal ancestor was probably different from any of these three groups of organisms. However, some of the archaebacteria, particularly, the extreme thermophiles (e.g., *Thermoproteus, Pyrodictium, Sulfolobus, Desulfurococcus*), sit relatively close to the intersection of the three primary phylogenetic lines. Therefore these extreme thermophilic archaebacteria may more closely resemble some of the most ancient prokaryotes. In fact, some of them are fermentative anaerobes that have the ability to use sulfur, instead of oxygen, in their respiratory mode of metabolism.

The extreme thermophiles live at high temperatures (up to 110°C) and are very versatile microorganisms. For instance, the *Thermoproteus* species can grow in a strictly chemolithoautotrophic manner by deriving energy from the oxidation of inorganic compounds such as H_2 by means of sulfur instead of oxygen and utilizing CO_2 as its sole carbon source. Alternatively, they can grow by sulfur respiration of different organic substrates. The products of their fermentation during heterotrophic growth are CO_2 and H_2S. Instead of sulfur, malate can serve as a terminal electron acceptor. Thus the same organisms can be fermenters (heterotrophs) or chemolithotrophs (autotrophs), depending on the environmental conditions. These organisms represent possible bridges between fermentative metabolism and sulfur-dependent autotrophism or chemolithoautotrophism.

The importance of sulfur in ancient organisms has also been emphasized. Using several different methods of analysis of rRNA sequences, it has been found that sulfur metabolism is primitive for 98% of the possible phylo-genetic trees. These sulfur metabolizers (e.g., *Thermoproteus tenax*) have been classified as some of the most ancient microorganisms. Indeed, specimens of three extreme thermophilic archaebacteria (with morphologies similar to *Thermoproteus, Thermofilum,* and *Pyrodictium*) have been isolated using the *Alvin* submersible from the inside of a hydrothermal vent (at 130°C nominal temperatures) located at the Juan de Fuca Ridge in the Pacific Ocean about 500 km west of Seattle. The *Pyrodictium* gen. nov., is a new genus of submarine sulfur-reducing archaebacteria which grows optimally at 105°C.

In conclusion it appears that the earliest heterotrophic and autotrophic ancestors could have inhabited geothermal sulfur springs on the primitive Earth. Furthermore, one could not rule out the possibility of the existence around Europan deep oceanic vents of bacterial ecosystems similar to those existing around the Earth's deep-sea hot springs. Table 6-5 indicates the basic reactions characteristic of these heterotrophic and autotrophic microorganisms.

Table 6-5: Anaerobic Habitability of Europa by Archaebacteria—Energy-Yielding Metabolic Reactions

Metabolism	Reactions yielding energy and biosynthetic products (B.P.)	Example(s)
A. Thermophilic archaebacteria		
Heterotrophic:		
Fermentation	Yeast extract $\rightarrow CO_2$ + B.P.	*Staphylothermus marinus*
Sulfur respiration	Organics* + S $\rightarrow H_2S + CO_2$ + B.P. *(sugars, alcohols , formate, acetate)	*Thermoproteus tenax* (1) *Desulfurococcus mobilis*
Autotrophic:		
Sulfur reduction (S/H autotrophy)	$CO_2 + H_2$ + S $\rightarrow H_2S$ + B.P. (CO_2 assimilation via reductive TCA cycle)	*Pyrodictium occultum* *Thermoproteus neutrophilus Sulfolobus ambivalens* (2)
B. Methanogenic archaebacteria (3)		
Heterotrophic:		
Fermentation	Organics* + $H_2 \rightarrow CH_4$ + B.P. *(CH_3OH, CH_3NH_2, formate, acetate)	Many methanomicrobiales
Autotrophic:		
CO_2 reduction by H_2 (4)	$CO_2 + H_2 \rightarrow CH_4$ + B.P.	All methanobacteriales and methanococcales

(1) Facultative autotrophs.
(2) May also grow aerobically oxidizing S° to SO_4.
(3) They also reduce S° to H_2S.
(4) Some use Fe° instead of H_2 as the only source of electrons.

Table 6-6: Habitability of Europa by Photosynthetic Eubacteria—Energy-yielding Metabolic Reactions

Metabolism	Reactions yielding energy and biosynthetic products (B.P.)	Example(s)
A. Green non-sulfur bacteria		
Typical anaerobic photoheterotrophs (1)	Organics $\xrightarrow{\text{light}}$ Biosynthetic Products Also facultative photoautotroph (fixes CO_2) and aerobic chemoheterotroph	*Chloroflexus aurantiacus*
B. Green sulfur bacteria (anoxygenic)		
Stricly anaerobic photo-autotrophs (1, 2)	$CO_2 + 2H_2S \xrightarrow[\text{P(I)}]{\text{light}} (CH_2O) + S_2 + H_2O$ CO_2 assimilation via reductive TCA cycle.	*Clorobium limicola*
C. Cyanobacteria (oxygenic and facultative anoxygenic)		
Typical oxygenic photo-autotrophs (3,4)	$CO_2 + H_2O \xrightarrow[\text{P(I \& II)}]{\text{light}} (CH_2O) + O_2$ All have Calvin-Benson cycle	*Oscillatoria*
Facultative anoxygenic H_2S photoautotrophs (4)	$CO_2 + 2H_2S \xrightarrow[\text{P(I)}]{\text{light}} (CH_2O) + S_2 + H_2O$ Similar to green sulfur bacteria	*Oscillatoria limnetica* (5)

(1) Similar to plant photosystem I: uses bacteriochlorophylls (Bchls) ferrodoxins (iron-sulfur proteins) and NADP carriers.
(2) They can photoassimilate acetate but only if H_2S and CO_2 are simultaneously present. CO_2 and acetate are assimilated by reversal of the tricarboxylic cycle (reductive TCA).
(3) They may survive aerobically in the dark at the expense of the dissimilation of glycogen to glucose and the oxidative pentose phosphate cycle. They have no functional TCA cycle.
(4) Similar to plant photosystems I and II: use chlorophyll a.
(5) *Oscillatoria limnetica* is a halophilic cyanobacteria capable of anaerobic, sulfide-dependent photoassimilation of CO_2. Sulfide inhibits photosystem II and induces an enzyme that allows sulfide to donate electrons to photosystem I. Elemental sulfur accumulates extracellularly. In the dark ATP can be generated from stored polyglucose reserves by either of two means: anaerobic respiration using the accumulated elemental sulfur as the electron acceptor; or a homolactic fermentation. This metabolism is similar to that of green sulfur bacteria and is widely distributed among non-heterocystous filamentous cyanobacteria.

It is believed that as early heterotrophic life on Earth established itself, the accompanying continuous decrease of fermentable substrates acted as a further evolutionary pressure toward autotrophy. Another closely related group of autotrophic anaerobes that do not require the use of light are the methanogenic archaebacteria which may also resemble some of the most ancient microorganisms on Earth. They obtain their energy and biochemical substrates simultaneously from the reduction of CO_2, by hydrogen, or other reduced compounds. The methanogens are also able to reduce elemental sulfur to H_2S by means of H_2 and obtain energy from this process similar to the extreme thermophiles. Representatives of the above two groups of archaebacteria, the anaerobic sulfur chemolithotrophs and the methanogens, have been isolated from the bottom layers of the Black Sea. Therefore organisms such as these could in theory be able to survive in the bottom layers of a Europan ocean. From a terrestrial evolutionary point of view, the picture that emerges by comparing the energy metabolisms of the sulfur thermophiles and the methanogens as well as their 16S rRNA sequences and their relative positions in the phylogenetic tree is that the ancestral archaebacterium was in essence an extreme sulfur-dependent thermophile which eventually gave rise to the methanogenic archaebacteria. Although the evolutionary connection of the thermophilic and methanogenic archaebacteria with the anoxygenic green sulfur phototrophic eubacteria is certainly more distant, there are also some similarities in their energy metabolisms which indicate an evolutionary relationship. Compare tables 6-5 and 6-6.

On the Earth the role of bacteria involved in the sulfur cycle was also very important during the subsequent phases of evolution. In fact, they are supposed to have been the originators of anoxygenic photosynthesis carried out by green sulfur bacteria in anaerobic environments. The earliest phototrophic bacteria used H_2S as a reductant (table 6-6.). They performed only one light conversion reaction, mediated by bacteriochlorophyll (photosystem I), and had a simple electron transport chain that included ferredoxins and cytochromes. They fixed CO_2 via a reductive tricarboxylic acid cycle. The electron donor for photosynthesis was H_2S, which was oxidized to extracellular elemental sulfur. These green photosynthetic bacteria, represented by extant Chlorobiaceae, are the strict anaerobes presumed to be the ancestors of blue-green bacteria or cyanobacteria. On the basis of 16S rRNA sequence analysis, a possibly more primitive group of phototrophic eubacteria is the green non-sulfur bacteria (anaerobic photoheterotrophs) which utilize organic compounds in a fermentation mode by using light energy for the generation of proton gradients and electron transport (table 6-6.).

Habitability by Aerobic Life

The photosynthetic cyanobacteria are characterized by having two photosytems (I and II) and using H_2O as a reductant instead of H_2S. The photosynthetic process of cyanobacteria is very similar to that of higher plants. They produce oxygen and are aerobic prokaryotes. Considering the limited amount of light available on Europa, the development of the anoxygenic photosynthesizers similar to those mentioned in the previous section would probably be somewhat limited if not altogether unlikely. It is therefore very difficult to answer the question of whether the envisaged putative Europan biological evolution would have subsequently led to the emergence of oxygenic photosynthetic microorganisms.

On the Earth, even though the presence of substantial amounts of oxygen in the atmosphere did not prevail until 2 billion years ago, the cyanobacteria may have appeared much earlier as indicated by some of the affinities of the microfossils found in Africa and Australia, the latter being 3.5 billion years old. It is possible however that the organisms represented by these microfossils had not yet developed the capability to utilize H_2O as a reductant and were still utilizing in its place the H_2S that their presumed ancestors, the green sulfur photosynthetic bacteria, had been using earlier. Indeed, some species of cyanobacteria, such as *Phormidium frigidum* which is found in ice-covered Antarctic lakes and *Oscillatoria limnetica* which is found in hypersaline lakes, are adaptable to extreme environments and can live under anoxic conditions. Furthermore, the latter eubacterium, *O. limnetica*, can perform anoxygenic photosynthesis at the expense of hydrogen sulfide as a hydrogen donor.

Even though it is highly speculative, it is possible that such an evolutionary transition from anoxygenic photosynthesizers to oxygenic photosynthesizers could have taken place on Europa. If this step did in fact occur, the upper part of the Europan ocean would have subsequently contained oxygen gas from the molecular oxygen released by the cyanobacteria. The partial saturation of the ocean waters could in turn bring important changes in the oceanic life, such as the possibility of establishing ecologically cooperative associations with anaerobic organisms living at lower levels of the Europan ocean as it happens in ice-covered Antarctic lakes. The above discussion on the habitability of Europa by photosynthetic microorganisms is summarized in table 6-6.

The low-temperature habitats of Earth's oceans and lakes maintain a host of aerobic and anaerobic ecosystems which provide an ideal starting point when one attempts to create a model for a speculative Europan biota. The ecosystems formed by the microbes that live under the ice in the cold waters of the Arctic and Antarctic oceans are of particular interest. The microorganisms inhabiting the perennially ice-covered Antarctic lakes have been extensively studied. The structural features and dynamics of these lakes have been described as a general model for Martian paleolakes. By changing the scale dramatically they could also be used as models for the subsurface ocean of ice-covered Europa.

The ecosystem of the Antarctic lakes is characterized by ecologically cooperative associations between several species of pennate diatoms, heterotrophic bacteria which occur abundantly throughout much of the benthic regions of these lakes, and microbial mats composed primarily of blue-green bacteria, specifically the cyanobacteria *Phormidium frigidum* and *Lyngbya martensiana*. These microbial mats are precipitating calcite and trapping and binding sediment, forming alternating laminae of organic and inorganic matter. A common feature of many of these benthic mats is their development into modern, cold water stromatolites. Because of the unique nature of these lakes, where the habitats vary chemically from fresh water to saline and from oxic to anoxic conditions, these stromatolites have been suggested as analogs of those that once inhabited deep water Precambrian systems. One of the more interesting features of the microorganisms living in the Antarctic lakes is not only their adaptation to the cold temperatures but their ability to live adaptatively in either aerobic or anaerobic conditions. Therefore, a speculative suggestion is that these organisms might possibly be able to survive and grow, to a limited extent, in a Europan ocean.

Conclusions

The observed abundance of H_2O in the satellites of the outer solar system could support the development of life as we know it if the liquid state can be maintained. We believe this could be the case of Europa as shown by the data from the Voyager flybys of Jupiter and the studies made on this satellite by two of us as well as other investigators.

We have presented a physical and chemical model for the possible habitability of Europa based upon studies of the evolution of the Galilean satellites and a comparison of these satellites with the chemical composition of carbonaceous chondrites. We conclude that Europa has amounts of reactive organic or inorganic compounds of the order of 10^{21} g or better, as shown in table 6-4. These compounds, being made of the different biogenic elements (H, C, N, O, S, P), are sufficient to provide the essential biochemical molecules for the emergence of life. In addition to water and biochemical molecules there are energy sources available on Europa, such as sunlight near the surface, and, more importantly, submarine hot springs at the floor of the Europan ocean, which, like the volcanoes on Io's surface and the terrestrial suboceanic vents, contain substantial amounts of sulfur and sulfur compounds.

Since energy and the necessary biochemicals may have been present, life could have emerged on Europa if the early conditions of this satellite would have been favorable. Whether such a process took place or not, the Europan environment could have provided, and may provide today, the necessary conditions for the survival and growth of many of the anaerobic microorganisms which thrive in terrestrial deep oceanic vents. Among the prokaryotic microorganisms capable of surviving and growing on the bottom sediment layers of Europa's ocean are the sulfur-dependent thermophilic archaebacteria and their evolutionary descendants, the methanogenic archaebacteria.

We also conclude, as other investigators have, that tidally heated habitable zones could possibly exist, with even more favorable conditions than Europa, around giant planets in planetary systems beyond the solar system.

These studies emphasize the importance of the Galileo Jupiter Orbiter Mission for closer observations of Europa. Observations that could be performed by Galileo include monitoring of Europa to look for the vapor and frost cloud that could result from a fracturing event, and high resolution imaging of the surface to elucidate the processes involved in forming the linear features as well as the variations in their albedo and coloration. Furthermore, radar sounding could be used to detect if liquid water is present. It is also suggested that serious consideration should be given to future missions using landing spacecraft that could penetrate the surface and perform *in situ* surface and subsurface measurements on Europa.

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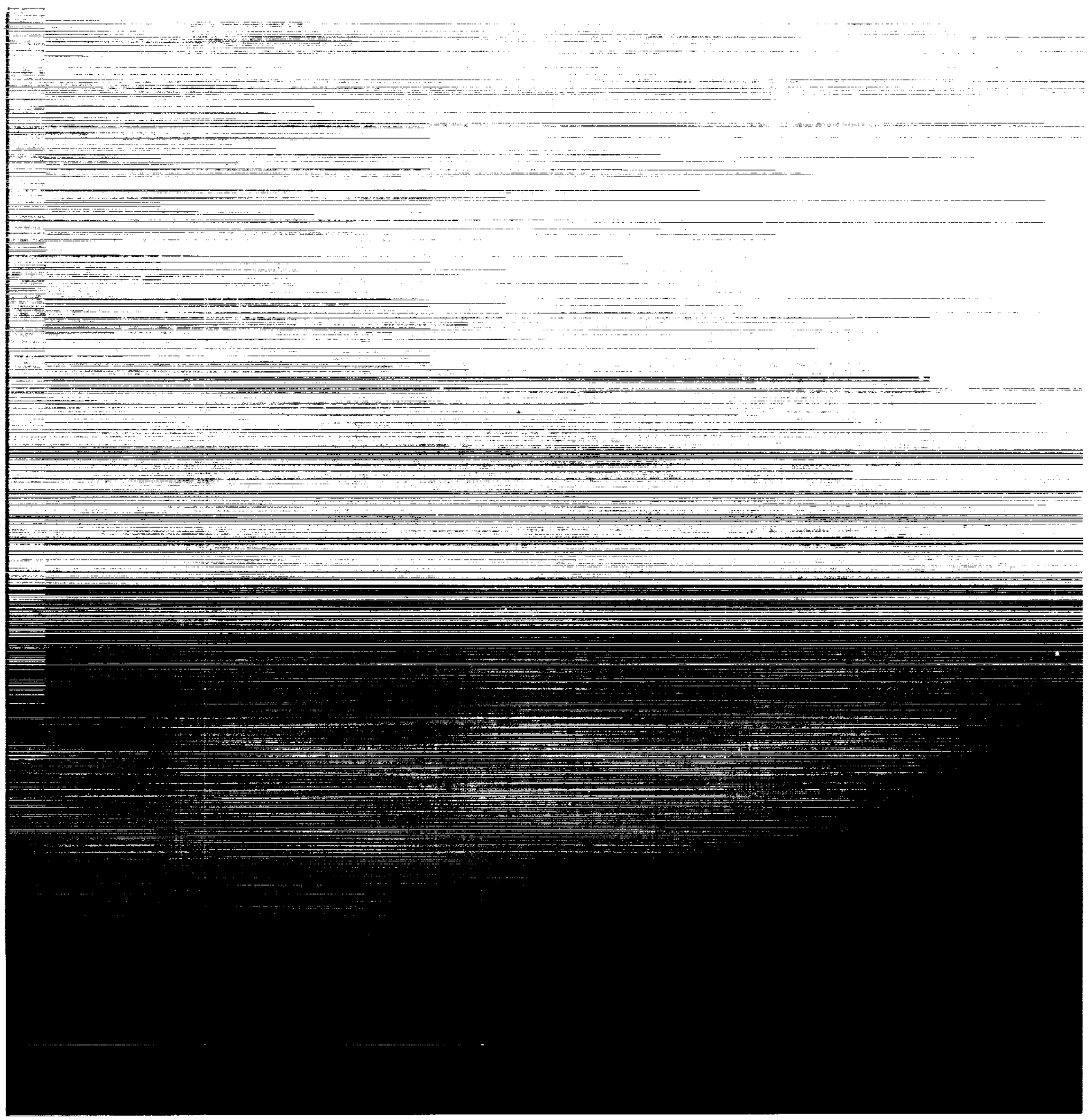

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