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On the Habitability of Europa

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It has recently been suggested that tidal and radiogenic heating of Europa has led to formation and maintenance of a liquid water ocean overlain by a thin ice crust (S. W. Squyres, R. T. Reynolds, P. M. Cassen, and S. J. Peale (1983). *Nature* **301,** 225–226). The present work examines the environmental consequences of such a model with regard to the possible existence on Europa of regions that could satisfy the basic requirements for the survival of known organisms. Appropriate temperatures and long-term environmental stability are implied by the ocean model. The presence of necessary biogenic elements is assumed based on the expected origin of the ocean. The availability of biologically useful energy is assumed to be the principal limiting factor for life on Europa. Possible electrical, thermal, and chemical energy sources are discussed. Calculated resurfacing rates for the active crust model are used to estimate the quantity of photosynthetically active radiation that might reach the proposed ocean through crustal fractures. The amount of biomass that this energy could support, based on Antarctic microorganism analogs, is estimated and discussed. Although these calculations cannot determine whether life forms exist or could exist on Europa, they do suggest that there may be regions on Europa, very limited in both space and time, with physical conditions that are within the range of adaptation of life on Earth.

INTRODUCTION

The Voyager flybys of Jupiter produced remarkable images of Europa, one of the four large Galilean satellites. The highest resolution images show a very bright surface transected by a network of long linear features of lower albedo and brownish color (Fig. 1). The features range in size from tens of kilometers in width and thousands of kilometers in length down to the resolution limit of the images (~4 km/line pair). Assuming a silicate density like that of Io, Europa's density of 3.03 g cm^{-3} suggests that it is roughly 6% H_2O by mass.

Recent theoretical work has suggested that a combination of tidal and radiogenic heating on Europa has led to internal dehydration of silicates and formation of a liquid water ocean overlain by a thin crust of ice (Cassen *et al.*, 1979, 1980; Squyres *et al.*, 1983). It is likely that the linear features result from fracturing of the ice crust (Smith *et al.*, 1979). Fracturing may have been caused by crustal stresses due to tidal flexure (Cassen *et al.*, 1979; Helfenstein and Parmentier, 1980) or due to membrane deformation induced by free rotation of the ice shell over Europa's tidal bulge. Liquid water exposed to space by fracturing will boil vigorously, creating a geyser-like cloud of vapor that would recondense over the surface at distances up to hundreds of kilometers from the fracture.

Several direct observations support the hypothesis of a liquid ocean and active resurfacing on Europa (Squyres *et al.*, 1983). First, the surface of Europa is nearly free of craters. Such extensive removal of craters by viscous relaxation requires a thermally insulating surface layer that substantially elevates near-surface temperatures and reduces viscosities. A deposit of condensed frost could provide such a layer due to its very low thermal conductivity. Second, the photometric function of Europa's surface material differs significantly from that of impact ejecta deposits of equal albedo on Ganymede and Callisto, but is consistent with a surface layer of condensed frost

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FIG. 1. A Voyager 2 image of Europa.

(Buratti and Veverka, 1983). Third, the observed distribution of sulfur implanted from the jovian magnetosphere into Europa's icy surface (Lane *et al.*, 1981) may be explained by implantation contemporaneous with deposition of H_2O on the surface. The observed sulfur column density gives a minimum global mean H_2O frost deposition rate of roughly 0.1 μm per year.

Furthermore, calculations of the thermal state of Europa have been performed incorporating heating by radionuclides in Europa's silicate interior and by tidal dissipation in both the interior and in the ice shell. These calculations suggest that a liquid water ocean at least several tens of kilometers deep should be present on top of the silicates, overlain by an ice crust averaging no more than roughly 10 km thick. Such a crust could be much thinner if a significant insulating frost layer is present, and would be expected to have local and regional variations in thickness.

Given the indication of a substantial liquid water ocean on Europa, and the affinity of life forms on Earth for an aqueous environment, it is perhaps appropriate to investigate the possibility of Europa's habitability. In this paper we consider the type of environment that might exist in an ocean on Europa and the suitability of that environment as an abode for life. The description of a hypothetical ecosystem on Europa would entail a knowledge of the environment far beyond anything currently available. It is possible, however, to address the much more limited question of the availability of basic requirements for living systems. These include (1) a proper physical environment (appropriate temperature, pressure, etc.), (2) long-term stability of that environment, (3) necessary biogenic elements, and (4) adequate energy sources.

A liquid water ocean would satisfy condition (1), and the scenario proposed by Squyres *et al.* (1983) would imply the maintenance of an aqueous environment over most of the age of the solar system, satisfying condition (2). The heating and hydrothermal differentiation of an initially homogeneous material of carbonaceous chondritic composition would result in the solution of significant concentrations of biogenically important elements in the ocean. This has occurred in the Earth's oceans, and the assumption is made that condition (3) may be satisfied on Europa as well. We further assume that cycling of these elements by nonbiological processes is sufficient to prevent their depletion. Environmental energy fluxes on Europa are much less than those on Earth, and we examine the consequences of the assumption that energy availability is the limiting factor regarding the suitability of Europa as a habitat for living organisms.

THERMAL ENERGY

The largest contribution to the energy density within a Europan ocean would be the thermal flux from the interior produced by tidal heating, decay of radioactive elements, and release of stored energy from an earlier period of higher heating. This energy is probably not useful for doing biological work, however. The temperature of an ocean heated from beneath will increase with depth, but the low viscosity and efficient thermal convection will make it impossible for the thermal gradient to be significantly steeper than the adiabatic gradient. The adiabatic thermal gradient in water at low pressure is roughly 2.1°K $kbar^{-1}$, or 0.03°K km^{-1} for an ocean on Europa. In order to use this energy to do work with a reasonable thermodynamic efficiency (i.e., in order to be immersed in a significant thermal gradient) it appears that an organism would have to have a length on the order of kilometers. We therefore dismiss thermal gradients within the ocean as a biologically useful energy source.

Only at the upper and lower solid boundaries of the ocean could appreciably higher gradients be found. Above the water–ice interface (at the top of the ocean), the temperatures would quickly fall well below the freezing point of water. At the ocean bottom, however, there is a possibility of available thermal energy for biological systems at liquid water temperatures. On the Earth, the concentration of thermal energy in local high temperature regions at submarine ridge crests has led to large scale hydrothermal activity (Corliss *et al.*, 1979). 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 bacteria that derive their entire energy supply from low temperature oxidation of the geothermically reduced sulfur compounds emitted from the vents (Jannasch and Wirsen, 1979). Photosynthesis provides no biological energy to these small ecosystems, although the oxygen used as an electron receptor in the case of the Earth is originally a product of photosynthesis.

Analogous hydrothermal regions might exist on Europa. The calculated mean heat flux from Europa's silicate interior according to the model of Squyres *et al.* (1983) 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 surface volcanic activity at the present. However, since the Moon's near-surface regions are singularly water free and at substantially lower temperatures, this does not rule out the possibility of hydrothermal activity on Europa. Current data and modeling techniques are wholly insufficient to permit a quantitative assessment of the probability of such activity.

Europa's thermal energy would also be capable of driving currents in an ocean. This would be particularly true if heat flow were concentrated in volcanic regions on the ocean floor. Even without submarine vulcanism, however, the principal heat transport mechanism through an ocean would be thermal convection, and any inhomogeneity in the pattern of heat flow from the ocean floor would lead to large-scale horizontal motions. The distribution of heat production by tidal dissipation is inhomogeneous (Peale and Cassen, 1978), so we expect that an ocean would be well mixed.

SOLAR ENERGY

Next, we consider the external contributions to the energy state of a Europan ocean. The energy flux from charged particles in the jovian magnetosphere is at least one or two orders of magnitude less than the solar constant at Europa (Eviatar *et al.*, 1981), and the depth of penetration of charged particles is much less than that for photons. We therefore ignore charged particles and concentrate on the solar flux. We assume that solar energy will only reach the liquid water where the ice crust has been recently fractured. An important quantity is therefore the annual amount of Europa's surface area over which liquid water is exposed to sunlight by crustal fracturing. This quantity may be estimated using the calculated frost deposition rate of 0.1 μm year^{-1} (Squyres *et al.*, 1983). If liquid water is exposed to the near vacuum at Europa's surface, it will begin to boil, causing rapid freezing due to removal of heat of vaporization (Cassen *et al.*, 1979). The water will initially be near its freezing point, where the heat of vaporization is 2.5×10^{10} erg g^{-1}, 7.6 times the heat of fusion. Evaporation of 1 g of water will therefore remove sufficient heat to freeze 7.6 g of ice. Vaporization will continue in the liquid until a stable ice layer has been formed; that is, a layer thick enough that the pressure at its base exceeds the H_2O vapor pressure (Lingenfelter *et al.*, 1968). The vapor pressure of water at its freezing point is about 6×10^3 dyn cm^{-2}, equal to the pressure at the base of a 50 cm ice layer on Europa. Vaporization of liquid exposed at the surface would therefore cease once enough heat of vaporization has been removed to freeze a layer of ice 50 cm thick. The required energy loss is about 1.5×10^{11} erg cm^{-2}, corresponding to a vapor production of about 6 g for each square centimeter of water exposed in the fracture event. Taking a density for the recondensed frost of roughly 0.1 g cm^{-3}, a minimum global mean deposition rate of 0.1 μm $year^{-1}$ implies a total frost production of at least 3×10^{11} g $year^{-1}$. The total surface area exposed per year would therefore be at least 5×10^{10} cm^2, or 5 km^2.

We now calculate the amount of light that could reach the liquid water as a result of such exposure. We assume here that any liquid water exposed at the surface is in contact with an ocean below, as seems likely due to the fact that the ocean and crust are heated from below. Initial freezing of a stable ice layer would be very rapid; we consider a bubbly ice layer with thickness $x_b = 50$ cm to form very rapidly. After such a layer has formed, freezing would continue by thermal conduction through the ice layer and formation of clear ice at its base. We have performed a numerical solution of the one-dimensional heat conduction equation, with an upper boundary condition of radiative equilibrium (including insolation) and a water–ice phase change at the lower boundary. The result of this calculation, clear ice thickness x_c as a function of time, is shown in Fig. 2. Values used for the thermal properties of ice are thermal diffusivity $k = 10^{-2}$ cm^2 sec^{-1}, and specific heat $c = 3 \times 10^7$ erg g^{-1} $°K^{-1}$.

Using extinction coefficients for the ice, we can calculate the decrease of transmissivity with time due to thickening of the layer. Wavelength dependent extinction coefficients for both clear and bubbly ice are given by Hobbs (1974). The coefficient a_λ is defined by

$$I_\lambda(x) = I_\lambda(0)e^{-a_\lambda x}$$

where I is downward intensity at wavelength λ. Note that the extinction coefficient incorporates both absorption and scattering. For bubbly ice, scattering is much more important than absorption, so that a does not depend strongly on wavelength. Using a wavelength-averaged extinction coefficient of 0.028 cm^{-1}, the intensity at the base of the bubbly ice is 0.25 times the intensity at the surface.

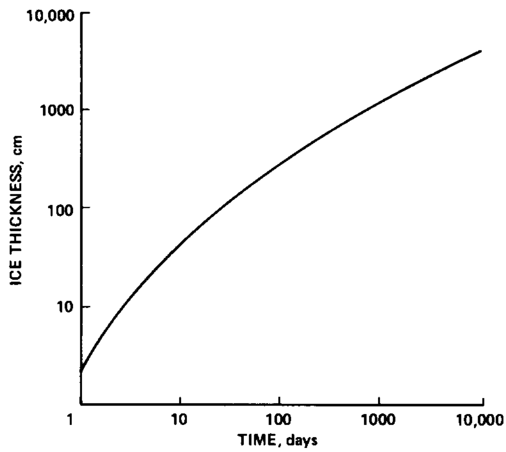

FIG. 2. Calculated thickness x_c of clear ice that forms over a hypothetical fresh exposure of liquid water on Europa, as a function of time. One-dimensional heat conduction is assumed, with radiation and insolation at the surface.

In clear ice, the wavelength dependence of extinction must be considered. Using the growth of a clear ice layer given in Fig. 2 and the appropriate wavelength-dependent extinction coefficients, we calculate the intensity at the base of the ice as a function of time and wavelength. Combining these results with the solar spectrum and integrating over time and over the range of photosynthetically useful radiation (here taken to be 3750–7250 Å), the total energy that would penetrate an ice surface held perpendicular to the sun's rays would be 1.4×10^{12} erg cm^{-2} for one such fracturing event. The total area of 5 km^2 calculated above to be exposed to sunlight per year on Europa must be multiplied by a factor of $\frac{1}{4}$ to account for the fact that energy is intercepted over only Europa's projected disk rather than its full surface area. The total solar energy in the range 3750–7250 Å to reach a Europan ocean is therefore calculated to be $(1.4 \times 10^{12}$ erg $cm^{-2}) \times (\frac{1}{4}) \times (5 \times 10^{10}$ cm^2 $year^{-1}) = 2 \times 10^{22}$ erg $year^{-1}$.

In this simple calculation we have only considered freezing of ice due to one-dimensional heat conduction toward the surface. If the openings in the crust through which light may enter are very much deeper than they are wide, however, significant freezing will take place by conduction away from the fracture walls as well. This effect would result in ice buildup along the walls and would diminish the total amount of sunlight reaching the liquid water. The frequency of resurfacing events on Europa and the thickness of the ice are therefore critical in determining the amount of illumination received. If fracture events are infrequent and expose relatively large areas in each event, the illumination (for the minimum calculated resurfacing rate of 0.1 μm year^{-1}) would be near the value of 2×10^{22} erg year^{-1} calculated above. If events are frequent and result from very narrow fractures, however, the amount of light reaching the water would be less.

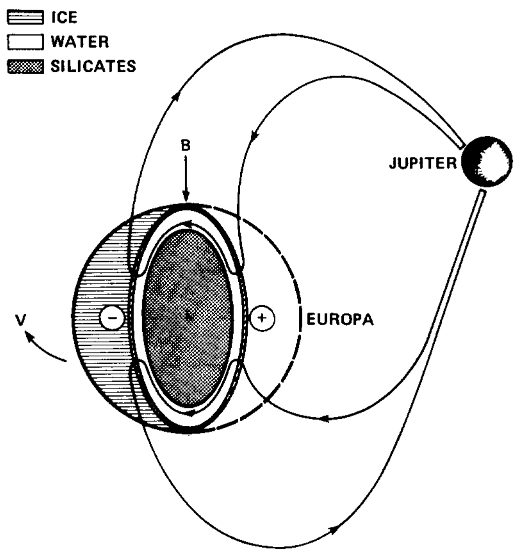

FIG. 3. Schematic view of electric current though a Europan ocean driven by Europa's motion relative to Jupiter's magnetic field.

ELECTRICAL ENERGY

Another possible source of biologically useful energy could result from the motion of Europa through Jupiter's magnetosphere. Motion with respect to the magnetosphere, which corotates with the planet, will cause the sub-Jupiter hemisphere of Europa to become positively charged with respect to the anti-Jupiter hemisphere (Fig. 3). There will therefore be a tendency for a current to flow through Europa from one of these poles to the other (Colburn and Reynolds, 1983). If a liquid water layer is present, current flow will be concentrated there, as the electrical conductivity of silicates at temperatures appropriate for Europa is low enough that the current in the rocky core would be negligible. The magnitude of the current in the water depends on the electrical conductivity of any ice layer through which it must pass, and also on the external circuit through the jovian magnetosphere. We expect water in such an ocean to be rich in salts derived from the interior, so that its electrical conductivity would be quite high ($\sim 1\ \Omega^{-1}$ m^{-1}) and thus not be a limiting factor in determining the strength of the current. The conductivity of ice is substantially lower, however ($\sim 10^{-6}\ \Omega^{-1}$ m^{-1} at 273°K, $\sim 10^{-14}\ \Omega^{-1}$ m^{-1} at 90°K; Auvert, 1973). To estimate an upper limit, we assume that the current is limited only by the resistance of the external circuit, and is as high as that measured for Io, 2×10^6 A (Ness *et al.*, 1979). This situation would exist only when liquid water is actually exposed at the surface at both electrical poles. When liquid is not exposed at both poles, the current is energetically negligible, due to the low electrical conductivity of the ice.

If liquid were permanently exposed at the surface, and suitable electrodes were present (Colburn and Reynolds, 1983), electrolysis caused by this current could annually create as much as 10^{10} g of oxygen at the sub-Jupiter hemisphere, and 1.2×10^9 g of hydrogen at the opposite hemisphere, storing chemical energy at the rate of 2×10^{21} erg year^{-1} for 100% efficiency. The actual energy stored annually, assuming a current of 2×10^6 A whenever liquid is exposed at both poles, would be 2×10^{21} erg multiplied by the fraction of the time that liquid is actually exposed. This fraction may be quite small, as the time required to freeze a layer of bubbly ice by evaporative cooling and thus to effectively halt current flow probably does not exceed 10 min. As in the case of light entering the water through fractures, the magnitude of an electrical energy source would be strongly dependent on the frequency of fracturing events. It could be significant if fracturing events are common. For example, if fracturing takes place each tidal period (3.55 days) and results in a current of 2×10^6 A for 10 min, the annual maximum energy deposition would be 4×10^{18} erg. If fracturing events are large but infrequent, however, the possible energy deposition would be much less. Note that the dependence of the energy deposition on the frequency of fracturing has a sense opposite to that of the solar energy source.

The length of time that solar energy could penetrate through a thin ice layer could be lengthened significantly by an electrical heating process (Colburn and Reynolds, 1983). For a crack exposing liquid water, the maximum available electrical power would not be sufficient to prevent rapid freezing of the initial 50 cm ice layer. Under favorable conditions, however, it could provide enough heating to hinder the subsequent thickening of the layer. For example, if a layer were to be maintained at 273°K, the heat lost by radiation to space would be 300 W m^{-2}, which could be produced by a current of 0.04 A m^{-2} flowing through the ice (with resistance for unit area of 2×10^5 Ω). For the current level assumed, 2×10^6 A, a crack area of 100 km^2 could be maintained, with 90% of the power still available in the rest of the circuit. Such heating would require the simultaneous presence of recent fractures in both electrical hemispheres.

EARTH ANALOGS

Nowhere on Earth do the ecological conditions duplicate those calculated for the Europa model, so there is no known organism ideally suited to inhabit such a niche. However, many of the problems that would be faced by life on Europa have been encountered by life on Earth. It is possible, then, to consider known communities that have properties that would be useful to a successful organism on Europa.

There are a number of environments on Earth in which photosynthesis occurs at extremely low light levels and through significant thicknesses of ice. In lakes in the Antarctic Dry Valleys, many of which remain ice-covered all year, algal mats grow on the lake bottoms (Parker *et al.*, 1980, 1981; Wharton *et al.*, 1982, 1983). Laboratory studies and field observations indicate that these algae photosynthesize at light levels at or below 0.05% L_0, where L_0 is the fraction of the solar constant at photosynthetically active wavelengths (Parker *et al.*, 1981, 1982). Photosynthesis is so vigorous during the austral summer that trapped oxygen bubbles lift the mats up through the water to the base of the ice. For comparison with the Antarctic lakes, Fig. 4 gives the mean wavelength-integrated photosynthetically active radiation that would penetrate a thickening ice layer on Europa, assuming heat loss to the surface only. Under this assumption, light levels would exceed 0.05% L_0 for roughly 4.5 years after a fracturing event, when the ice thickness has reached about 15 m.

Another interesting community with regard to the habitability of Europa is that of the Antarctic sea-ice diatoms. This community was described by Bunt and Wood

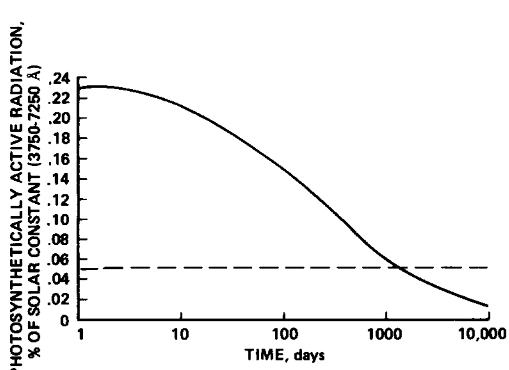

FIG. 4. Maximum amount of photosynthetically active radiation (3750–7250 Å) that could penetrate to an ocean on Europa as a function of time following a fracturing event. Dashed line shows illumination at which algae are capable of photosynthesizing in Antarctic lakes.

(1963) as "the brown coloration commonly visible as bands in sea-ice, especially in the lowermost layers." The coloration is due to diatoms growing below the ice or trapped within the ice. These organisms actively metabolize in an extremely harsh environment, in contact with the liquid water at the ice–seawater interface, where ambient temperatures are below $-1.86°C$ and light levels are reduced to less than 1% of the illumination at the surface (Sullivan and Palmisano, 1981). In addition, the diatoms (like the algal mats) are subject to 6 months of total darkness during the austral winter. Production achieved under these levels is remarkably high (Bunt, 1963) and represents an important contribution to the carbon and energy flows through the subice and benthic ecosystems (Sullivan and Palmisano, 1981). Bunt (1963) concluded that while heterotrophy may occur at a minimal level, the growth of the diatoms results almost entirely from photosynthesis. Sullivan and Palmisano (1981) examined the chlorophyll *a* content of 30 ice cores, and found a mean value of 114 mg m^{-2}. For comparison, the maximum quantity of chlorophyll *a* in the euphotic zone of a freshwater lake is typically 230–310 mg m^{-2} (Wetzel, 1975).

Several physiological adaptations are triggered in the diatoms by the decrease in sunlight indicating onset of polar night: their metabolism is reduced and their heterotrophic potential is increased as much as 60-fold (Sullivan and Palmisano, 1980). Survivorship of winter adapted cells kept in complete darkness at 0°C for 6 months is 0.1 to 10%.

Using the characteristics of sea-ice diatoms, we can estimate a maximum biomass that could be supported by oxygenic photosynthesis in an ocean on Europa. The efficiency of light utilization by phytoplankton in aquatic systems is generally much lower than photosynthetic efficiencies of systems on dry land; nearly all estimates are less than 1% (Wetzel, 1975). At low light intensities adaptations occur which increase efficiencies somewhat. Nonetheless, we conservatively assume an efficiency for conversion of absorbed energy to organic carbon of 0.5%. Since the energy inflow of photosynthetically active radiation as calculated above is at most 2×10^{22} erg $year^{-1}$ (4.8×10^{11} kcal $year^{-1}$) and the energy required to produce carbohydrate (CH_2O) by oxygenic photosynthesis is 112 kcal $mole^{-1}$, we calculate a maximum carbon production at this efficiency of 2.6×10^8 g $year^{-1}$. This assumes that organisms can very rapidly reach a dense population under an exposed fracture, so that all photosynthetically active radiation that reaches the ocean is used for carbohydrate production. The mean carbon content of algae is $53 \pm 5\%$, giving a maximum biomass production rate of 4.8×10^8 g $year^{-1}$. If the survivorships from sea-ice diatoms of 0.1 to 10% after 6 months are used (corresponding to exponential decay times of 26 and 80 days, respectively), an equilibrium density of dormant stages (organisms not exposed to light and therefore not photosynthesizing) may be calculated. Averaged over the surface of Europa, this calculation yields an equilibrium biomass of $1.1 - 3.4 \times 10^{-6}$ g m^{-2}, or a total of $4.6 \times 10^7 - 1.4 \times 10^8$ g.

CONCLUSIONS

It is, of course, not possible to make definite predictions as to whether life actually exists, has existed, or in fact could exist on Europa from the calculations presented here, although such scenarios have been conjectured (e.g., Hoagland, 1980; Clarke, 1982). The calculations do indicate, however, that for a plausible physical model of Europa, the general conditions for the survival of biological organisms could exist, at least in some regions, highly restricted in both space and time. Whether any individual known organism could have all the necessary characteristics to live or flourish in the proposed Europan environment is only conjectural. Based on our understanding of the origin of life on Earth, the evolution of a native Europan organism would appear to require a larger energy source than the photosynthetic one considered above. Again, hydrothermal sources or early periods of higher energy fluxes could be conjectured. It has even been proposed that life on Earth originated at hydrothermal oases (Corliss *et al.*, 1981), but there is no present evidence to support such hypotheses.

This study reemphasizes 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. It also suggests the serious consideration of future missions that could penetrate the surface and perform *in situ* measurements.

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REFERENCES

AUVERT, G. (1973). *Etude des configurations et des transferts de protons dans la glace*. Thesis, L'Universite Scientifique ete Medicale de Grenoble, France.

BUNT, J. S. (1963). Diatoms of Antarctic sea-ice as agents of primary production. *Nature* **199,** 1255–1257.

BUNT, J. S., AND E. J. F. WOOD (1963). Microalgae and Antarctic sea-ice. *Nature* **199,** 1254–1255.

BURATTI, B., AND J. VEVERKA (1983). Voyager photometry of Europa. *Icarus* **55,** 93–110.

CASSEN, P. M., R. T. REYNOLDS, AND S. J. PEALE (1979). Is there liquid water on Europa? *Geophys. Res. Lett.* **6,** 731–734.

CASSEN, P. M., S. J. PEALE, AND R. T. REYNOLDS (1980). Tidal dissipation in Europa: A correction. *Geophys. Res. Lett.* **7,** 987–988.

CLARKE, A. C. (1982). *2010: Odyssey Two*. Ballantine, New York.

COLBURN, D. S., AND R. T. REYNOLDS (1983). Electrolytic currents in Europa. Submitted for publication.

CORLISS, J. B., J. DYMOND, L. I. GORDON, J. M. EDMOND, R. P. VON HERZEN, R. D. BALLARD, K. GREEN, D. WILLIAMS, A. BAINBRIDGE, K. CRANE, AND T. H. VAN ANDEL (1979). Submarine thermal springs on the Galapagos Rift. *Science* **203,** 1073–1083.

CORLISS, J. B., J. A. BAROSS, AND S. E. HOFFMAN (1981). An hypothesis concerning the relationship between submarine hot springs and the origin of life on Earth. *Oceanol. Acta* (*SP*) 59–69.

EVIATAR, A., G. L. SISCOE, T. V. JOHNSON, AND D. L. MATSON (1981). Effects of Io ejecta on Europa. *Icarus* **47,** 75–83.

HELFENSTEIN, P., AND E. M. PARMENTIER (1980). Fractures on Europa: Possible responses of an ice crust to tidal deformation. *Lunar Planet. Sci. Conf. Proc. 11,* 1987–1998.

HOAGLAND, R. C. (1980). The Europa enigma. *Star and Sky* **2,** 16–31.

HOBBS, P. V. (1974). *Ice Physics*. Oxford Univ. Press (Clarendon), Oxford.

JANNASCH, H. W., AND C. O. WIRSEN (1979). Chemosynthetic primary production at East Pacific sea floor spreading centers. *Bioscience* **29,** 592–598.

LANE, A. L., R. M. NELSON, AND D. L. MATSON (1981). Evidence for sulfur implantation in Europa's UV absorption band. *Natuer* **292,** 38–39.

LINGENFELTER, R. E., S. J. PEALE, AND G. SCHUBERT (1968). Lunar rivers. *Science* **161,** 266–269.

NESS, N. F., M. H. ACUNA, R. P. LEPPING, L. F. BURLAGA, K. W. BEHANNON, AND F. M. NEUBAUER (1979). Magnetic field studies at Jupiter by Voyager 1: Preliminary results. *Science* **204,** 982–987.

PARKER, B. C., G. M. SIMMONS, K. G. SEABURG, AND R. A. WHARTON (1980). Ecosystem comparisons of oasis lakes and soils. *Antarct. J. U.S.* **15**(5), 167–170.

PARKER, B. C., G. M. SIMMONS, F. G. LOVE, R. A. WHARTON, AND K. G. SEABURG (1981). Modern stromatolites in Antarctic Dry Valley lakes. *Bioscience* **31,** 655–661.

PEALE, S. J., AND P. M. CASSEN (1978). Contribution of tidal dissipation to lunar thermal history. *Icarus* **36,** 245–269.

SMITH, B. A., AND VOYAGER IMAGING TEAM (1979). The Galilean satellites and Jupiter: Voyager 2 imaging science results. *Science* **206,** 927-950.

SQUYRES, S. W., R. T. REYNOLDS, P. M. CASSEN AND S. J. PEALE (1983). Liquid water and active resurfacing on Europa. *Nature* **301,** 225–226.

SULLIVAN, C. W., AND A. C. PALMISANO (1981). Sea-ice microbial communities in McMurdo Sound. *Antarct. J. U.S.* **16**(5), 126–127.

WETZEL, R. G. (1975). *Limnology*. Saunders, Philadelphia.

WHARTON, R. A., B. C. PARKER, G. M. SIMMONS, K. G. SEABURG, AND F. G. LOVE (1982). Biogenic calcite structures forming in Lake Fryxell, Antarctica. *Nature* **295,** 403–405.

WHARTON, R. A., B. C. PARKER, AND G. M. SIMMONS (1983). Distribution, species composition, and morphology of algal mats in Antarctic dry valley lakes. *Phycologia*, in press.