EUROPA AS AN ABODE OF LIFE

Invited Paper

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Abstract. Life as we know it on Earth depends on liquid water, a suite of 'biogenic' elements (most famously carbon) and a useful source of free energy. Here we review Europa's suitability for life from the perspective of these three requirements. It is likely, though not yet certain, that Europa harbors a subsurface ocean of liquid water whose volume is about twice that of Earth's oceans. Little is known about Europa's inventory of carbon, nitrogen, and other biogenic elements, but lower bounds on these can be placed by considering the role of cometary delivery over Europa's history. Sources of free energy are challenging for a world covered with an ice layer kilometers thick, but it is possible that hydrothermal activity and/or organics and oxidants provided by the action of radiation chemistry at Europa's surface and subsequent mixing into Europa's ocean could provide the electron donors and acceptors needed to power a Europan ecosystem. It is not premature to draw lessons from the search for life on Mars with the Viking spacecraft for planning exobiological missions to Europa.

Keywords: astrobiology, Europa, exobiology, Jupiter, oceans, radiation

1. Introduction

Life as we know it on Earth depends on liquid water, a suite of 'biogenic' elements (most famously carbon, but others as well) and a useful source of free energy. It is likely, though not yet certain, that Jupiter's moon Europa harbors a subsurface ocean of liquid water whose volume is about twice that of Earth's oceans (Pappalardo *et al.*, 1999; Stevenson, 2000b). Little is known about Europa's inventory of carbon, nitrogen, and other biogenic elements, but lower bounds on these can be placed by considering the role of cometary delivery over Europa's history (Pierazzo and Chyba, 2001). Sources of free energy may be challenging for a world covered with an ice layer kilometers thick (Reynolds *et al.*, 1983; Gaidos *et al.*, 1999), but it is possible that hydrothermal activity (McCollom, 1999) and/or organics and oxidants provided by the action of radiation chemistry at Europa's surface (Chyba, 2000a, b; Gaidos *et al.*, 1999; Chyba and Phillips, 2001; Cooper *et al.*, 2001) and subsequent mixing into Europa's ocean could provide the electron donors and acceptors needed to power a Europan ecosystem. Here we examine Europa's suitability for life from the perspective of these three requirements, and discuss some early thoughts on the challenges facing a search for life on Europa via a spacecraft lander.

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2. Europa Overview

Europa, the second of the four Galilean satellites in its distance from Jupiter, is an ice-covered body with a radius of 1560 km, about the same size as Earth's Moon (1738 km). Europa is locked in a tidal resonance with its neighboring satellites, volcanic Io on the inside and large Ganymede on the outside. Like each of the Galilean moons, Europa is spin-locked to Jupiter, rotating about its pole with a period identical to its orbital period of 3.6 Earth days. The resonance keeps the satellites from perfect circular orbits, inducing a forced eccentricity that varies their distances from Jupiter and results in tidal flexing and internal dissipation of energy. This heating is most intense at Io, due to its proximity to the giant planet Jupiter, and results in constant volcanic activity on that small moon. A substantial amount of heat is dissipated within Europa's core, mantle, and ice shell as well (Cassen *et al*., 1979, 1980; Ojakangas and Stevenson, 1989). Gravity measurements made by the Galileo spacecraft (Anderson *et al*., 1998) show that Europa is an internally differentiated rocky body with about 100 km of material of density $\sim$1000 kg m^{-3} at its surface, virtually certainly water in either solid or liquid phase. If this water were predominantly liquid, it would be more than double the volume of all of Earth's oceans combined. Europa's surface varies in temperature from about 50 K near the poles to as much as 120 K at the equator (Ojakangas and Stevenson, 1989; Spencer *et al*., 1999). Its tenuous atmosphere, due mostly to oxygen sputtered from its surface ice (Hall *et al*., 1995; Sieger *et al*., 1998), is in fact a near-vacuum. Liquid water exposed at Europa's surface would rapidly boil and freeze; once freezing progressed to about half a meter the pressure of this ice cap would exceed the vapor pressure of the underlying water and boiling would cease (Reynolds *et al*., 1983).

Several lines of evidence have been suggested for the presence of liquid water beneath the icy surface of Europa (Pappalardo *et al*., 1999; Stevenson, 2000b). These include theoretical studies, spectroscopic measurements, observations of Europa's geology, and magnetic field measurements.

2.1. Theoretical evidence for liquid water

Europa's surface was known to contain water ice from ground-based spectroscopic measurements (e.g. Pilcher *et al*., 1972) even before the Voyager spacecraft arrived at Jupiter in the late 1970's. Models of satellite accretion (Stevenson *et al*., 1986) suggest that Europa probably consists of silicates, metals, and water, and most models begin with chondritic abundances (e.g. Kargel, 1991; Kargel *et al*., 2000). Early thermal models (Lewis, 1971; Consolmagno and Lewis, 1976) using conductive cooling and radiogenic heating predicted the possibility of a liquid water layer beneath a frozen ice crust on Europa. Later models (Reynolds and Cassen, 1979; Cassen *et al*., 1982) showed that such a configuration was unstable due to convection as the ice thickened, and the ice layer would freeze solid only about

100 Myr after formation. However, when tidal dissipation was added as a heat source (Cassen *et al.*, 1979, 1980), the possibility remained that there could be a balance between tidal heating, radiogenic heating, and conductive and convective (McKinnon, 1999) cooling that could allow a portion of the subsurface water layer to remain liquid over geologic time.

Current models have failed to resolve this issue completely (Ojakangas and Stevenson, 1989; McKinnon, 1999), mostly because the rheology of ice is poorly known at the temperature of Europa and at the long frequencies (corresponding to the 3.6 day orbital period) associated with tidal flexing (Durham *et al.*, 1997). Also unknown is the exact composition of Europa's ice: the addition of small amounts of other volatiles such as ammonia or salts to the water could dramatically change the viscosity of the ice (Deschamps and Sotin, 1998; McCord *et al.*, 1999). Another important factor is the physical state of the ice, including its grain size and degree of fracturing, which could affect its strength. Thus, theoretical models of tidal heating and deformation suggest that liquid water could have been or currently be present beneath the icy surface of Europa – most models predict that the bulk of the 100 km water layer is currently liquid but cannot definitively resolve the issue by themselves.

Gravity measurements of Europa's moment of inertia, based on radio Doppler data from the Galileo spacecraft's close flybys of Europa, suggest that Europa is completely differentiated. The most likely configuration includes an Fe or Fe-S central core, an anhydrous rocky mantle, and a surface layer of material with a density of around 1000 kg m^{-3} that is between 80 and 170 km thick (Anderson *et al.*, 1998). The most likely thickness of the outer layer is about 100 km. The only cosmochemically plausible material with this density is water, but the gravity data cannot distinguish between liquid water and solid ice due to the small density contrast between the two. Thus, gravity models can only state that Europa has a surface layer of about 100 km of some combination of solid water ice and/or liquid water. One hundred km of ice on Europa's surface would represent about 7% of Europa's total mass, roughly corresponding to the percentage of water in carbonaceous chondrite meteorities (Kargel *et al.*, 2000). Many outer solar system objects are even more water-rich; comets, for example, are 40–50% water ice by mass (Delsemme, 2000), as are Jupiter's moons Ganymede and Callisto (Lewis, 1971). Higher-order gravity terms could be measured by an orbiting spacecraft such as the planned Europa Orbiter (NASA, 1999; Johnson *et al.*, 1999), and may be able to resolve Europa's internal structure with greater detail.

2.2. Voyager and Galileo images of Europa's surface

Before the Voyager spacecraft flybys of Europa in the late 1970's, little was known about Europa's surface except for its anomalously high albedo and the spectroscopic suggestion of the presence of water. Images of Europa taken by Voyager revealed a surface covered with crack-like features, and very few impact craters (Smith *et al.*, 1979; Malin and Pieri, 1986). The lack of craters was surprising,

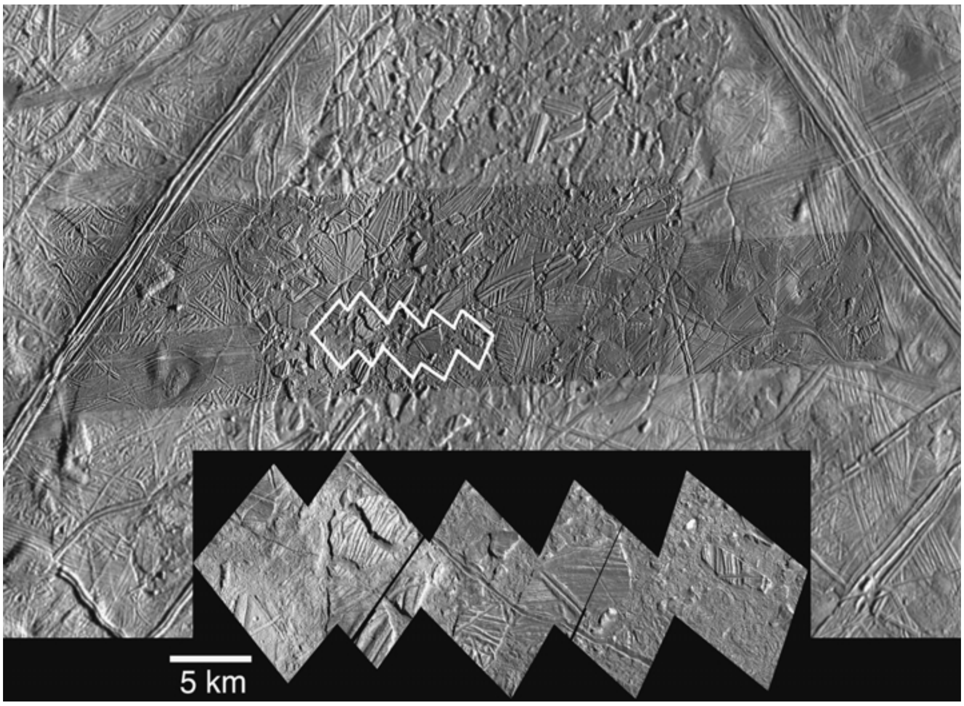

Figure 1. This image shows Galileo observations of chaotic terrain at three different resolutions. Blocks of crust with pre-existing linear ridges appear to have been disrupted, rotating and translating in a hummocky 'matrix' before arriving at their current locations. Models differ as to whether this motion was a result of liquid water near the surface or purely solid-state processes.

since all bodies in the Solar System are regularly hit by debris. This results in a pock-marked surface like that of the Moon unless geologic activity takes place to remove craters from the surface. The relative lack of craters on Europa means that the surface is young, perhaps as young as tens of millions of years (Zahnle *et al*., 1998, 1999; Levison *et al*., 2000; Zahnle, 2001). A young surface requires geologic activity, which is more likely in the presence of liquid water. However, a search for signs of geologic activity on Europa's surface between the Voyager and Galileo observations, over a 20-year period, has shown no detectable changes (Phillips *et al*., 2000).

Images of Europa's surface taken by the Galileo spacecraft have shown surface features which are consistent with the presence of liquid water beneath Europa's surface, but again do not prove it (Figures 1 and 2). Compositional data from Galileo's Near-Infrared Mapping Spectrometer (NIMS) instrument shows that hydrated salts (see Section 3) with very similar compositions are present in various locations on the surface. These salts could be evaporites from a globally mixed water layer, but their presence does not require an ocean. Galileo images show that Europa's surface is primarily covered by a vast set of interconnecting cracks

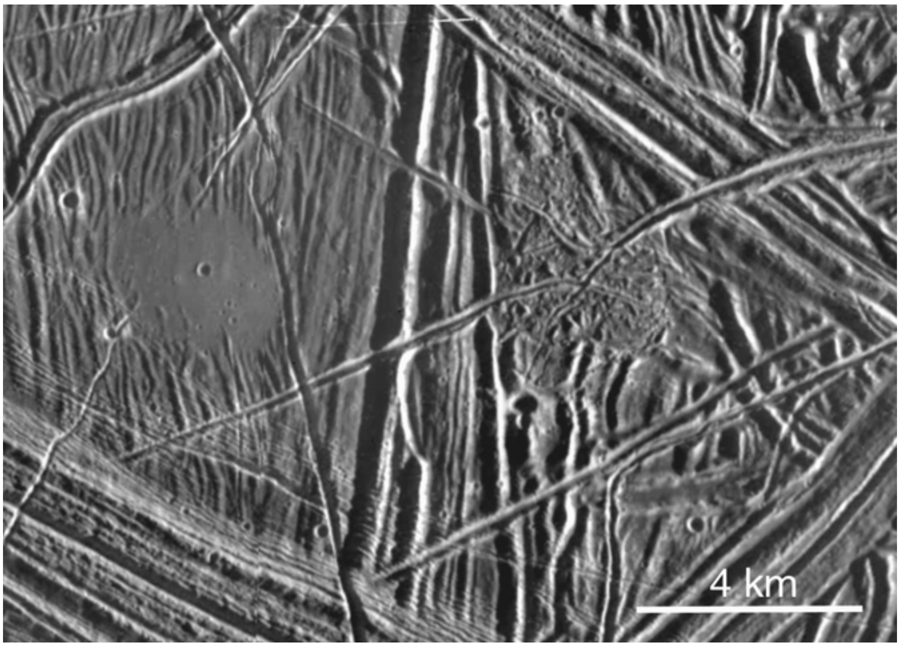

Figure 2. Galileo image of a small region of Europa's surface that seems to have been 'flooded' with smooth material, perhaps liquid water. This smooth material embays the pre-existing ridged plains, and is the best evidence for small-scale cryovolcanic activity seen to date on Europa.

and ridges. Also present are areas of disrupted 'chaotic terrain', where the surface appears to have been broken up into coherent iceberg-like blocks that seem to have 'rafted' into new positions (Figure 1; Carr *et al*., 1998; Greenberg *et al*., 1999). Such areas can be reconstructed by fitting the preexisting features on the blocks back together (Spaun *et al*., 1998). Other features of interest on Europa's surface include regions that could possibly be low viscosity surface flows (Figure 2; Greeley *et al*., 1998), and impact craters that are anomalously shallow (Moore *et al*., 1998).

Many models have been proposed for the formation of the variety of features visible in Galileo images of Europa's surface. There is currently no consensus among these often contradictory views of Europa's geophysics. For example, the morphology of Europa's impact craters suggests that they formed within a solid target, but their shallow depths are suggestive of post-formation viscoelastic relaxation (Moore *et al*., 1998). Such models suggest that most craters on Europa formed in a 5–15 km thick brittle surface layer, overlying a lower-viscosity subsurface layer. This subsurface material, however, could either be liquid water or warm, low-viscosity ice. Cryovolcanic surface flows are intriguing, but there are few known regions where the morphology is suggestive of flows (Fagents *et al*., 2000; see Figure 2 for one example). There is also a buoyancy problem in their formation: it is difficult for liquid water to reach the surface, since it is denser than ice.

Models of ridge formation range from cryovolcanism to tidal squeezing to linear diapirs to compression and plastic deformation (Pappalardo *et al.*, 1999). These models vary in requirements from a very thin crust overlying liquid water (the tidal squeezing model) to completely solid-state models with a thin brittle crust on top of a lower-viscosity, warm ice layer (diapirism or compression). For instance, cycloidal ridges have been shown (Hoppa *et al.*, 1999) to correspond in orientation and location to cracking of the surface in response to the changing diurnal tidal stresses. This model requires the existence of a global ocean to obtain sufficient tidal stresses to crack the ice. Clearly, the various proposed models are contradictory, and have very different implications for Europa's subsurface structure and the location or existence of a subsurface water layer.

Chaotic terrain was first seen as a 'smoking gun' for the presence of liquid water beneath Europa's surface (Figure 1; Carr *et al.*, 1998), but subsequent models have been proposed which could form disrupted areas through solid-state ice diapirism (Pappalardo *et al.*, 1998). At the liquid end of the spectrum, regions of chaotic terrain are seen as areas of localized heat flow where the ice layer melted all the way to the surface. In this model, the blocks are buoyant remnants of the preexisting icy crust that move about in a slushy matrix, both translating and tilting. Eventually the matrix freezes solid, ending the blocks' motion and preserving their final positions. This model requires localized heating of the crust, but it may be difficult to concentrate the heating. Moreover, Stevenson (2000a) has argued that the viscosity of warm ice is so low that such a melt-through event would in fact be impossible; the adjacent ice would flow so quickly than any growing melt-through region would be rapidly filled in. The solid-state formation model suggests that ice rises to the surface in a diapir, eventually disrupting the brittle surface. Partial melting could occur due to positive tidal heating feedback during the ascent (McKinnon, 1999; Pappalardo *et al.*, 1998).

2.3. EUROPA'S INDUCED MAGNETIC FIELD

Perhaps the most convincing current evidence for an ocean of liquid water beneath Europa's surface comes from magnetic field results. Recent evidence from Galileo's magnetometer (Kivelson *et al.*, 2000; Zimmer *et al.*, 2000) shows that Europa has an induced magnetic field, which varies in direction and strength in response to Europa's position within Jupiter's strong magnetic field. The strength and response of the induced field at Europa require a near-surface, global conducting layer. The most likely layer that meets these requirements is a global layer of salty water, with a salinity similar to that of Earth's oceans. The data cannot be explained by localized pockets of salty water, and require a nearly complete spherical shell. The thickness of the water layer would need to be greater than about 10 km. The induced field cannot be the result of a frozen ice layer, even if it has pockets of briny water, since ions in solid ice would not be mobile enough (Stevenson, 2000b). It is possible that a type of conducting layer other than a global salty ocean could account for the induced magnetic field, but the salty ocean explanation appears the most plausible.

2.4. DIRECT DETECTION OF AN OCEAN

The previous arguments for the presence of an ocean of liquid water beneath Europa's surface are indirect in nature. Direct evidence of an ocean on Europa requires a spacecraft orbiting Europa with a dedicated instrument suite. The proposed Europa Orbiter spacecraft, currently being planned by NASA (NASA, 1999; Johnson *et al*., 1999), would meet these requirements. A decisive measurement could be made by a laser altimeter that would measure the tidal deformation of Europa's surface. The tidal bulge of Europa will flex by about 1 m for a solid ice shell, vs. as much as 30 m for tens of kilometers of ice over a liquid water layer. Thus, an orbiting laser should be able to track Europa's deformation in real time and determine whether or not an ocean is present. An orbiting spacecraft would also allow the measurement of the higher-order elements of Europa's gravity field and perform an analogous measurement by responding to the varying gravity field responding to the tidally deforming bulge. In fact laser altimetry and gravity measurements will be importantly synergistic (Moore and Schubert, 2000). More precise gravity measurements should also provide more information about the satellite's internal structure.

Another instrument proposed for the Europa Orbiter spacecraft is a radar sounder, which should reveal details of internal structure and might even be able to detect the ice-water interface, depending on the state of the ice (Squyres, 1989; Chyba *et al*., 1998; Moore, 2000). Such measurements will have to await the arrival of a dedicated spacecraft, however, as they cannot be performed from Earth or with the current instrument suite on the Galileo spacecraft. Should a Europa lander ever fly (Tamppari *et al*., 2000), even a single seismometer should be able to determine the thickness of Europa's ice by taking advantage of Crary waves, seismic waves that propagate in ice layers overlying Earth's ocean that present a simple relationship between their frequency and the ice thickness (Kovach and Chyba, 2001).

3. Evidence for Biogenic Compounds

The second requirement for life as we know it is a suite of appropriate biogenic elements, which include carbon, hydrogen, oxygen, nitrogen, phosphorous, sulfur, and others. We have no direct samples of Europa's surface nor any results from in-situ measurements, and spectral measurements taken from orbit can only sample the top few microns of the surface. Globally, the surface is predominantly water ice, but the Galileo Near-Infrared Mapping Spectrometer (NIMS) instrument has directly detected absorption features on Europa due to SO_2 and H_2O_2. There has also been the indirect detection of hydrated compounds from observations of distorted water bands in the near infrared. These observed asymmetries are suggestive of the presence of materials such as sulfuric acid, magnesium and sodium sulfates, and/or sodium carbonates (McCord *et al.*, 1999; Carlson *et al.*, 1999). Such hydrated salts are consistent with theoretical studies that assume evolution from an initial carbonaceous chondrite composition (Kargel *et al.*, 2000). The locations of these potential salts are mostly along ridges, in craters, or in the matrix of chaotic terrain in between the blocks. The composition of the salts is remarkably consistent from place to place on Europa, suggesting that they come from a globally mixed reservoir. One possible explanation is a global salty water ocean, which reaches the surface in places of recent geologic activity and leaves salts behind. However, the presence of these salts does not unambiguously require a global ocean.

Carbonaceous chondrite meteorites are typically several percent organic by mass, so it is reasonable to expect such compounds on Europa – though an analogy should not be mistaken for evidence. A variety of organic functional groups have been detected on Ganymede and Callisto (such as $C \equiv N$ and C-H), and there are very low signal-to-noise observations of such compounds on Europa (McCord *et al.*, 1998). Carbon dioxide has been observed on Ganymede, Callisto, and Europa; the CO_2 abundance of the latter appears to be about 0.2 wt% (McCord *et al.*, 1998; T. McCord, personal communication.)

Another source of biogenic elements on Europa is cometary impacts. Comets are rich in these elements and could deliver substantial quantities of carbon, nitrogen, and other elements (Pierazzo and Chyba, 2001). While much material would be lost from Europa in expanding impact vapor due to Europa's low escape velocity, a significant fraction of lower velocity comets would be retained.

Integrated over the history of the Solar System, some 10^{12} kg of carbon should have been accumulated by Europa in this way (Pierazzo and Chyba, 2001) – about 0.1% of the carbon present in Earth's total biomass(Whitman *et al.*, 1998). Because Europa lacks an atmosphere, 'soft landings' of interplanetary dust particles (IDPs) or small meteorites, sources that may have been important for the prebiotic organic inventory of early Earth (Chyba and Sagan, 1992) or for the successful transfer of microorganisms between Earth and Mars (Mileikowsky *et al.*, 2000), will not occur on Europa. Delivery of intact organic molecules or viable microorganisms in IDPs or meteorites will therefore be far more difficult in the case of Europa. This, in turn, makes it more likely that if there were to be life on Europa, it would represent a separate origin from that of life on Earth.

4. Sources of Free Energy

Life requires a source of useful free energy in addition to liquid water and biogenic elements. Photosynthesis on Europa is likely to be extremely constrained due to

Europa's thick ice cover (Reynolds *et al.*, 1983). It has been suggested that niches might exist within Europa's ice shell where transient near-surface liquid water environments could permit photosynthesis or other metabolic processes (Reynolds *et al.*, 1983; Greenberg *et al.*, 2000; Gaidos and Nimmo, 2000). Gaidos *et al.* (1999) have emphasized the difficulty of identifying sources of chemical disequilibrium on an ice-covered world lacking photosynthesis, and the corresponding difficulty of sustaining a large biomass on Europa. Yet it is likely the case that Earth itself hosted a biosphere prior to the evolution of photosynthesis, so the absence of photosynthesis cannot be an overwhelming obstacle to maintaining some chemical disequilibrium that can provide the electron donors and acceptors to power life.

Pre-Galileo models for radiogenic and tidal heating in Europa's interior suggested that the heat flow at the base of the ocean might be 24 mW m^{-2} (Squyres *et al.*, 1983). The average heat flow from Earth's Moon is 29 mW m^{-2}, less than half that of the Earth (63 mW m^{-2}) (Vaniman *et al.*, 1991). Since the Moon is geologically dead, this simple comparison does not seem promising for hydrothermal activity at the base of Europa's ocean. However, hydrothermal vents might nevertheless be present. A liquid inner core for Europa would allow more tidal flexing and thus heat production in the mantle than suggested by the pre-Galileo models, and the resulting high heat flows could produce partial melting, resulting in volcanism at the interface between the ocean and mantle (McKinnon and Shock, 2001). But an alternative model of heat flow in Europa's interior (Moore and Schubert, 1999) suggests that heat transfer in Europa's mantle through convection could be efficient enough to prevent partial melting of silicates, thus precluding volcanic activity. McKinnon and Shock (2001) point out, however, that tidal heating is a non-linear and highly variable process, and that Europa could have evolved in and out of resonances with the other Galilean satellites over geologic time, resulting in periods of increased and decreased heat flow. This could lead to pulses of volcanic activity.

If hydrothermal vent activity does exist on Europa, delivery of carbon dioxide to the ocean (which can serve as an electron acceptor for, for example, molecular hydrogen 'weathered' from basalt) seems plausible (McKinnon and Shock, 2001). The methanogenic biomass that could be supported by such a system is difficult to calculate, but is likely small. McCollom (1999) estimates a potential annual biomass production $\sim 10^8$–10^9 g yr^{-1}, which he compares to the terrestrial primary production based on photosynthesis of $\sim 10^{17}$ g yr^{-1}. The extent to which such an ecosystem, lying at the base of a 100 km ocean, would be detectable by measurements at Europa's surface is unclear, but that would depend on the extent of vertical mixing in Europa's ocean.

A number of authors have discussed the production of oxidants (such as molecular oxygen and hydrogen peroxide) in Europa's uppermost ice layers due to charged-particle bombardment of water ice (Delitsky and Lane, 1997, 1998; Gaidos *et al.*, 1999; Chyba, 2000a, b; Chyba and Phillips, 2001; Cooper *et al.*, 2001). Since carbon dioxide also is present in the ice (McCord *et al.*, 1998), there will be a simultaneous production of simple organics such as formaldehyde (Delitsky and Lane, 1997, 1998; Chyba, 2000a, b; Chyba and Phillips, 2001). These effects of radiation processing on Europa's ice are reminiscent of the role of radiation in the production of cometary organics, throughout the cometary nucleus due to incorporated radionuclides, but especially in a comet's outermost layers due to cosmic ray bombardment (Chyba and Sagan, 1987).

The extent to which organics and oxidants produced at Europa's surface are available to power an oceanic ecosystem depends on the competition among charged particle and ultraviolet processing of the surface, sputtering (the erosion of surface molecules due to high-energy charged-particle collisions), impact gardening (surface overturn, mixing, and burial due to meteorite bombardment), and the communication of the surface layers with the oceans via endogenic geological processes (Chyba and Phillips, 2001; Cooper *et al.*, 2001). Accounting for all of these factors, and taking into account current uncertainties regarding impact gardening on Europa (Phillips and Chyba, 2001) and the extent to which radiation synthesis at Europa's surface is substrate-limited, gives a wide range of possible results. The more conservative estimates suggest that Europa's oceanic biomass could be limited to $\sim 10^{23}$–10^{24} prokaryotic-analog cells, and that it would be very difficult to supply the ocean with enough radiation-produced oxygen to reach levels capable of sustaining analogs to terrestrial macrofauna (Chyba and Phillips, 2001). Estimates that assume that the available substrate keeps pace with the intense radiation bombardment – so that the uppermost ice layers are constantly being replenished and substrate-limitation is never a factor – can push these estimates up by factors of 10^3 or more, and might even allow oxygen concentrations in Europa's ocean comparable to those on Earth (Cooper *et al.*, 2001, Chyba and Hand, 2001).

Chyba and Hand (2001) have considered additional sources of molecular oxygen and hydrogen on Europa. In particular, they consider simultaneous production of oxygen and hydrogen in Europa's bulk ice and in the ocean itself due to the decay of radioactive ^{40}K. These processes could allow a biomass production of $\sim 10^{10}$-10^{12} g yr^{-1}.

These production rates can be converted into estimates of steady-state biomass by using either an estimate of a biomass turnover time or a maintenance energy. If we use a turnover time $\sim 10^3$ yr, appropriate for Earth's deep biosphere (Whitman *et al.*, 1998), the above calculation permits a biomass of $\sim 10^{13}$–10^{15} g, compared with the terrestrial biomass of $\sim 10^{18}$ g.

Maintenance energies of terrestrial microorganisms are not well established; for some organisms it can be virtually zero for decades at a time (Weiss *et al.*, 2000). If we take a maintenance energy appropriate for the hydrogen-oxidizing baceria *Alcalignes eutrophus* in laboratory conditions of about 10^{-5} kcal g^{-1} s^{-1} (here as elsewhere, mass refers to dry cell mass) (see Weiss *et al.*, 2000), a production rate of $\sim 10^{10}$ mol yr^{-1} of O_2 in Europa's ocean due to ^{40}K decay (Chyba and Hand, 2001) could support a steady state biomass of only $\sim 10^9$–10^{10} g, assuming that each mole O_2 provides 474 kJ mol^{-1} of energy.

5. The Upcoming Search for Life on Europa

The Europa Orbiter mission will be important for clarifying the prospects for life on Europa. Above all, it should resolve with certainty whether a liquid water ocean definitely exists. Altimetry, gravity, radar sounding, and magnetometric measurements would help us understand the relationship between the ice cover and the ocean, including the energetically important question of material exchange between the surface and ocean. If the orbiter has the payload to do infrared spectroscopy, we should learn about the nature of organic and oxidant compounds on Europa's surface, though we must remember the extent to which any material seen optically at the surface (optical measurements probe only the upper microns of the surface) will have been substantially processed by ultraviolet light and ionizing radiation (Delitsky and Lane, 1997, 1998; Johnson, 1998; Cooper *et al.*, 2001). It is even possible that an orbiter could carry an ion mass spectrometer and perform mass spectroscopy of sputtered organic compounds (Johnson *et al.*, 1998). However, it is likely that a dedicated search for life itself will not be undertaken until the first lander mission.

There may be alternatives to a soft lander; one dramatic mission concept is the 'Ice Clipper,' which involves hitting Europa with what amounts to a cannonball timed with a flyby spacecraft so that a surface sample could be returned to Earth (Harris, 2000). In this article, we restrict our discussion to a possible soft surface lander. Information from the Europa Orbiter mission will be important in helping to choose a landing site for such a spacecraft. Given the three-year flight times to the jovian system, we should consider the option of a lander mission that would launch to Europa prior to the full results from the Orbiter having been received, even while being able to incorporate these results into mission planning while en route.

5.1. Definitions of Life Implicit in the Search

Any remote *in situ* search for life on a distant world must establish criteria for what would qualify as evidence of success. Any criterion implicitly or explicitly assumes a particular definition of life that will be applied to the empirical search. But no general definition of life has been broadly accepted by the scientific community. A wide variety of definitions has been suggested, including metabolic, thermodynamic, biochemical, and genetic (Sagan, 1970). Each of these definitions fails in so far as it seems to include entities or phenomena that we do not wish to consider to be alive, or it excludes entities that we believe are (Chyba and McDonald, 1995). To these definitions can be added others; Monod (1970) suggested that a necessary part of a definition of living entities must include the notion of purpose or 'teleonomy'; whereas Shapiro and Feinberg (1995) propose that life should be defined as 'the activity of a biosphere.' These proposals have their own problems, and in any case are unlikely to prove useful in a remote *in situ* search for life.

One working definition for life that has gained popularity in the origins-of-life community is the 'chemical Darwinian' definition (Chyba and McDonald, 1995); it is that 'life is a self-sustained chemical system capable of undergoing Darwinian evolution' (Joyce, 1994). The word 'chemical' has the effect of excluding computer 'life' by fiat. But while the Darwinian definition may be useful for interpreting laboratory experiments, or guiding thinking about how 'the origin of life' on early Earth is to be conceived ('the origin of life is the same as the origin of evolution' is a common corollary), it seems unlikely to prove of utility in a remote search for life. How long do we wait to determine if a candidate entity is 'capable of undergoing Darwinian evolution'? Moreover, the Darwinian definition excludes any individual sexually reproducing entity, as no such entity is itself 'capable of undergoing Darwinian evolution.' The Darwinian definition defines 'life' rather than 'living entity' (Fleischaker, 1990), yet it may well be the latter rather than the former that a remote spacecraft would need to detect.

From the point of view of *in situ* experiments to be conducted remotely elsewhere in the solar system, what we need are definitions (or implicit definitions) that prove useful in a remote exploration context. We suggest that there are useful insights to be gained from the Viking spacecrafts' search for life on Mars about how to conduct future searches, and the role that varying definitions of life might play.

5.2. The Viking search for life on Mars

The Viking biology package included three experiments (Klein, 1978; Horowitz, 1986), each of which can be described as a search for evidence of metabolism in martian soil samples. That is, the Viking biology package implicitly adopted a metabolic definition of life. One of the experiments, the labeled-release experiment, gave especially interesting results. The head of the Viking biology team wrote about these in 1978 that 'If information from other experiments ... had not been available, this set of data would almost certainly been interpreted as presumptive evidence for biology' (Klein, 1978).

Nevertheless, most of the scientific community does not hold that Viking did in fact detect life on Mars. There are several reasons for this. Theoretical modeling of the martian atmosphere and regolith predicts the production of oxidants (e.g. hydrogen peroxide) due to the action of ultraviolet light, and these oxidants seem more-or-less able to account for the results of the three biology package experiments (Horowitz, 1986). In this view, although the biology package hoped to find unambiguous evidence of martian biology, it instead discovered unanticipated martian non-biological chemistry.

Perhaps most important for the non-biological interpretation was the failure of the Viking gas chromatograph mass spectrometer (GCMS) to find any organic molecules (released in stages at temperatures up to 500 °C) in the martian soil at the parts-per-billion level for molecules containing three or more carbon atoms (and at the ppm level for molecules containing one or two carbons) (Biemann, 1977). Although not intended as a life-detection experiment, the GCMS can be viewed as a search for life that implicitly assumed a biochemical definition: no (detected) organics, no life. In effect, a metabolic search for life yielding apparently positive results was undercut by the negative results of an alternative search based on biochemistry.

The interpretation of the labeled-release results as due to the action of martian oxidants is still debated, and may yet prove to be premature (see, e.g., Levin and Levin, 1998; but also Klein, 1999). It is remarkable that a quarter century after Viking it is still the case that the chemical oxidant hypothesis for the biology package results remains untested on the martian surface, although this may soon change (Beaglez, 2001). Nevertheless, for the time being the extraordinary claim of life on Mars must defer to a more conservative chemical explanation in the absence of more compelling evidence.

5.3. Lessons from Viking

With the benefit of twenty-five years' hindsight, we suggest that there are a number of lessons to be learned from the Viking experience on Mars for future remote spacecraft searches for life: (1) If the payload permits the luxury of more than one life-detection experiment, a remote search for life is best conducted with experiments that in effect assume contrasting definitions of life. (2) Nevertheless, it is unlikely that, for example, the first Europa lander will permit more than ten or twenty kilograms of science payload. Thus, it may be unlikely that the first lander would carry more than one life-detection experiment. In this case, the Viking experience suggests that the biochemical definition trumps other definitions. In the absence of a compelling case based on organic chemistry, it seems unlikely that a biological interpretation of other experimental results will be accepted, barring some extraordinary result such as observations of motility. As discussed in Section 5.5 below, a 'biochemical' search for life might take advantage of a biological preference for particular enantiomers of chiral molecules, or other biosignatures. (3) It is crucial to establish the geological and chemical context within which any biological experiments will be conducted. Had the presence of abundant oxidants in the martian soil been widely anticipated and its implications understood, different experiments would no doubt have been flown in the Viking biology package. (4) The importance of negative results is axiomatic. Searches for life are best designed, where possible, to provide valuable information even if the searches fail to find any life. (5) We must nevertheless temper these conclusions with the realization that exploration need not, and often can not, be hypothesis testing. Much of what we do in planetary missions is simply exploration.

5.4. Where should the first lander land?

The first lander should touch down at a location that is a good candidate for a site where liquid water from Europa's ocean has recently reached the surface. However, it is difficult on the basis of current knowledge to determine with confidence where these sites may be (or even if any exist). Current models for Europa's surface geology are still evolving rapidly, and it may yet be several years before they settle down and, perhaps, converge. (Even then, of course, there is no guarantee that they will converge to the correct model.)

For example, when first described (Carr *et al*., 1998), Europa's chaos regions (Figure 1) seemed possibly to provide candidate locations where the ocean may have reached the surface through catastrophic melt-through events. Now, however, models of viscous creep in Europa's ice argue against this explanation, at least for thick ice layers (Stevenson, 2000). Nevertheless, even if chaos features are due to diapirism (Pappalardo *et al*., 1999), there might still be exchange of material between the surface and ocean (Stevenson, 2001). Whether large cracks represent sites where ocean water reaches Europa's surface on a diurnal basis remains controversial (Greenberg *et al*., 2000). It is unclear how to interpret 'ponds' on Europa's surface (Figure 2) that seem to indicate the eruption of liquid water from some source below the surface (Pappalardo *et al*., 1999; Thomas and Wilson, 2000). However, if we had to choose a site for the first Europa lander based on Galileo data alone, and assuming we had the ability to target a region only kilometers across, we might well argue to land in such a place.

Information from the Orbiter will prove of enormous help in choosing among the various geomorphological models and selecting the most appropriate landing site. It now appears likely, in light of theoretical models, geological observations, and Galileo magnetometer results, that an ocean exists beneath kilometers or tens of kilometers of Europa's surface ice (Pappalardo, 1998; Kivelson *et al*., 2000). The first lander need not wait for the Orbiter to determine the presence of an ocean – the presence of an ocean, if not its detailed characteristics, now seems likely – but we would want to make use of results from the Orbiter for landing site selection. Consistent with the recommendations of the National Academy of Sciences' Committee on Planetary and Lunar Exploration in *A Science Strategy for the Exploration of Europa*, (COMPLEX, 1999), we should regard europan exploration as analogous to that of Mars, demanding a systematic program of exploration. In the Mars program, we do not require all the results of each Mars mission to be in hand before designing, building, and launching a subsequent mission. Rather, we recognize that Mars is a target of such importance that it will require multiple missions over many decades for its exploration, and we therefore interweave these missions in a way that incorporates new knowledge as it becomes available into an ongoing program. This approach provides the correct model, we believe, for the exploration of Europa – all the more so since trajectories to the jovian system require three years, as opposed to the six-month trajectories possible between Earth and Mars.

5.5. Life Detection on Europa*

A search for life on Europa should examine ice from the youngest possible surface, and in the best case, ice that seems most likely to have been derived recently from the ocean. Prior to or simultaneous with any experiments to search for life itself, however, a suite of measurements intended to establish chemical context should be performed. These would include determining the abundances of the major cations and anions present, salinity, pH, an analysis of the volatiles (e.g. CO_2, O_2, CH_4, etc.) present, and a search for organic molecules. The latter is the highest-priority life detection experiment to be conducted. Given sufficient payload, additional experiments might include high-sensitivity searches for specific indicative organic molecules (such as amino acid enantiomers), a determination of certain key stable isotope ratios (such as $^{12}C/^{13}C$) or fluorescent microscopy. But the chemical context should be established simultaneously or first.

What life detection sensitivity is required at Europa? Models cannot answer this question, although most so far available (e.g. Gaidos *et al.*, 1999; McCollom, 2000; Chyba, 2000a, b; Chyba and Phillips, 2001; Chyba and Hand, 2001), and as discussed in Section 4 above, suggest that biomass would be limited. Because of these uncertainties, any search for life on Europa should either scan a large amount of material in a manner that chooses particular sites for subsequent high-sensitivity investigation, and/or take advantage of the opportunity to concentrate sample by melting and filtering Europa's ice. We examine only the latter option in more detail here; the former has been discussed in the martian context by Conrad and Nealson (2001). Both possibilities bear further investigation.

5.6. Sample concentration and handling

The amount of sample available for life detection on Europa could be maximized by the melting and filtration (or possibly evaporation) of ice. The capability to perform this sort of sample concentration would prove valuable for both *in situ* exploration as well as sample return missions. In the case of sample return missions, both pristine and concentrated samples would ideally be returned. Sample return to Earth following a soft landing on Europa currently represents a staggeringly difficult mission, however.

Sample acquisition from some depth into Europa's surface is essential. At a minimum, sampling should take place below the most severe radiation processing

∗ The conclusions of the first paragraph of this section derive from the results of an informal workshop on Europa life detection held at Harvard University in March, 1999 and co-chaired by C. Chyba and S. Palumbi. Participants included J. Baross, C. Cavanaugh, J. Delaney, P. Falkowski, P. Geissler, P. Grunthaner, P. Gschwend, H. P. Klein, W. McKinnon, M. Moldowan, K. Nealson, R. Pappalardo, J. Reeve, J. Rummel, and C. Van Dover. The workshop was sponsored by the Jet Propulsion Laboratory, the SETI Institute, and Harvard University. Its conclusions were communicated to the Campaign Strategy Working Group for Prebiotic Chemistry in the Outer Solar System of NASA's Solar System Exploration Subcommittee.

depth (depending on surface age, probably 1–10 cm; see Cooper *et al.*, 2001), and preferably below the impact gardening depth, likely to be a meter or perhaps more (Chyba and Phillips, 2001; Phillips and Chyba, 2001).

Sample acquisition and handling for chemical or biological analyses poses substantial challenges. Whether the sample is acquired from the ice directly, from melting ice, or from melting ice and concentrating its contents, sample acquisition on Europa presents difficult technical challenges not previously encountered, with implications for technology research and development.

How much ice could we hope to process during a surface lander mission with a duration of about one month (the length of time likely to be permitted by the intense radiation environment at Europa's surface)? The energy required to melt one kilogram of ice on Europa, starting at an average surface temperature of 100 K, is given by:

$$\Delta E = H_{\text{fusion}} + \int_{100}^{273} C(T)\text{d}T \ .$$

Here $H_{\text{fusion}} = 3.3 \times 10^5$ J kg^{-1} is the heat of fusion of ice and $C(T)$ is the temperature-dependent specific heat, which in J kg^{-1} K^{-1} for an absolute temperature T is $C(T) = 7.04T + 185$, giving $\Delta E = 6 \times 10^5$ J kg^{-1}. For a dedicated spacecraft power source of 20 W (chosen for the purposes of illustration to be comparable to the total electric power expected to be available for the science payload of the planned Europa Orbiter mission (NASA, 1999; Johnson *et al.*, 1999)), this calculation seems to suggest that $\sim$100 L is a likely upper limit for how much water could be melted and filtered during a month-long mission. However, a single dedicated radioisotope thermoelectric generator (RTG) 'brick' might provide an order of magnitude more thermal power than this (Zimmerman and Shakkotai, 1999), so these numbers are strongly dependent on decisions yet to be made regarding the power that a lander could in fact dedicate to the task.

Melting and filtration has drawbacks, however. In particular, filtration alone will not capture soluble organics. Some of these could be captured through an adsorption column, with the concomitant additional mass requirement. Alternatively, rather than filtering the water, one could imagine evaporating it – though vaporized organics would have to be captured in this case. Evaporation would require substantially more energy than melting; the relevant heat of vaporization for water is $H_{\text{vapor}} = 2.5 \times 10^6$ J kg^{-1}, or about eight times the heat of fusion (Reynolds *et al.*, 1983). All told, evaporation would require about $\Delta E = 3 \times 10^6$ J kg^{-1}, or five times as much energy (or five times less sample processed) as in the calculations above.

However, these calculations neglect the power requirements of the sampling system that would core into Europa's ice, withdraw samples, and introduce them into a melting chamber. This sampling system would likely pose substantial challenges and could limit the total amount of sample acquired over a mission lifetime to values below those suggested above. Melting directly at the surface (without withdrawing samples into a chamber) would pose much greater power requirements, due to heat conduction out into the ice. Indeed, the initiation of melting/sublimation at Europa's ice would require about a kilowatt of thermal power (Zimmerman and Shakkotai, 1999). A different approach would be to employ a melter probe that would descend into Europa's ice. Such a probe of cross-section 12 cm that descended into Europa's ice (such as those being developed at the Jet Propulsion Laboratory (Zimmerman and Shakkotai, 1999)) and captured the resulting meltwater could provide about 10^3 L of water for every 100 m of penetration depth.

6. Conclusion: Life vs. the Origin of Life

The possibility that life could be sustained in Europa's likely subsurface ocean suggests that the traditional view of planetary habitability should be broadened (Sagan, 1996; Chyba *et al.*, 2000). This suggestion is made even stronger by the elucidation of the subsurface terrestrial biosphere, which seems to harbor a subsurface biomass comparable to that at Earth's surface (Gold, 1992; Whitman *et al.*, 1998). Nevertheless, the existence of life at depth on Earth is not the same thing as saying that life can in fact originate at depth. If life cannot originate independently of the free energy available from the Sun, then only worlds that have clement surfaces (Earth) or that once did (Mars) could host endemic biologies, although interplanetary transfer of microorganisms (Mileikowsky *et al.*, 2000) would remain a possible way of introducing life from Earth or Mars to other bodies in the solar system. (As noted above, this is much more difficult to do with Europa than with Mars, in part because the martian atmosphere, like the Earth's, allows the deceleration of some meteors so that they make soft landings as meteorites. Europa has only the thinnest of sputter-driven atmospheres so that meteors would strike its surface at unimpeded velocities.)

If the origin of life could occur at depth, then Europa might harbor its own endemic biology (ignoring the possibility that early Europa may have briefly had an enormous greenhouse effect and so could have sustained liquid water at its surface for a very short period). Certain prebiotic processes under hydrothermal conditions may have been important in the origin of terrestrial life (Wächtershäuser, 1988; Cody *et al.*, 2000), on whichever world it may have first arisen, but it remains unlcear whether the entire origin of life could have proceeded in the absence of sunlight. If so, the scientific rewards for a successful search for life on Europa could hardly be greater.

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