Perspective

Possible ecosystems and the search for life on Europa

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No broadly accepted definition of life exists. Most proposed definitions (1–5) face severe objections (3, 6, 7). Nevertheless, one working definition of life has become influential in the origins-of-life community: "life is a self-sustained chemical system capable of undergoing Darwinian evolution" (8). The notion that "the origin of life is the same as the origin of evolution" is a popular corollary. But however valuable this Darwinian definition may be for guiding laboratory experiments, it is unlikely to prove useful to a remote *in situ* search for life (3, 6). In a search for extraterrestrial life in our solar system, we instead fall back on a less ambitious notion of "life as we know it," meaning life based on a liquid water solvent, a suite of "biogenic" elements (most famously carbon, but others as well), and a source of free energy (7). The availability of these on a given world would suggest life to be possible, so that further exploration may be warranted.

There is now great excitement over Jupiter's moon Europa as a possible location for extraterrestrial biology (9). Here we examine Europa's suitability for life as we know it and consider candidate ecosystems that seem plausible in light of current knowledge. We then sketch life detection experiments that could be conducted with a spacecraft lander.

On the Habitability of Europa

The idea of habitability was introduced by Dole (10, 11) to refer to those planetary conditions suitable for human life. The word has since come to imply requirements both less stringent and less anthropocentric, referring instead to the stability of liquid water at a world's surface. A circumstellar habitable zone is the volume of space around a single or multiple-star system within which an Earth-like world could support surface liquid water (12, 13).

The historical emphasis on surface liquid water is easy to understand. First, life on Earth—still our sole example of a biology—utterly depends on liquid water (7, 14). Second, primary production of organic matter is dominated by sunlight-driven photosynthesis at Earth's surface (15). In the traditional view, a planet's mass must be large enough to maintain sufficient geological activity to power the climate-stabilizing carbonate-silicate feedback cycle (16). For surface liquid water to persist longer than ≈1 Gyr, a planetary mass greater than ≈0.1 Earth masses seems required, by analogy to Mars (12). Similar constraints have been derived for satellites of giant planets (17).

Europa's putative subsurface ocean suggests that the traditional view of planetary habitability should be broadened (7, 11, 18). This suggestion is strengthened by the elucidation of the terrestrial subsurface biosphere (19), the microbial biomass of which appears comparable to Earth's entire surface biomass, although subsurface biological turnover times are long (20). If some terrestrial life exists or could exist independently of surface photosynthesis, then the possibilities for extraterrestrial biospheres greatly expand. If life originated on Mars during its apparent early clement period (21), it is possible that its progeny remain in subsurface hydrothermal niches (22).

A more fundamental question is whether life can originate at depth, independently of the sun. If not, then only worlds that have clement surfaces (Earth) or that once did (Mars) could host endemic biologies, although interplanetary transfer of microorganisms might still introduce life to previously sterile worlds (23). But if the origin of life could occur at depth, then worlds like Europa could host their own biologies. Processes at hydrothermal vents may have been important in Earth's origin of life (24, 25), but it remains unclear whether the entire origin of life could have been independent of sunlight-driven surface conditions and photochemistry.

Liquid Water and Biogenic Elements

A subsurface "ocean" of liquid water on Europa was suggested in the early 1970s (26), and further considered subsequent to the Voyager spacecraft flybys (27). The ground-based spectroscopic signature of Europa is dominated by water ice (28). The paucity of craters on Europa's surface, combined with estimates of the impact flux, suggest a geological resurfacing timescale ≈10 million years (29, 30). Galileo spacecraft gravity measurements indicate that Europa has a combined ice/liquid water shell ≈80–170 km thick overlying a metallic and rocky core and mantle (31, 32). Models indicate sufficient geothermal and tidal heating to maintain much of the ice shell as liquid water beneath an outer ice layer ≈10 km thick (26, 27, 33, 34).

High-resolution images of Europa seem consistent with this picture (35). The orientation and relative age relationships of lineaments is consistent with nonsynchronous rotation of an ice shell decoupled from a synchronously rotating interior by liquid water or ductile ice (36). There are regions of chaotic terrain, where broken pieces of the surface seem to have "rafted" into new positions (35, 37, 38), cracks and extensional bands, which likely were filled in with new, fluid material (39), and cycloidal cracking explicable in terms of changing diurnal stress (40). Such features could have been formed in a thin (≈1 km thick) frozen crustal layer overlaying liquid water (41), but solid-state formation mechanisms also have been suggested. The latter typically involve diapirism within a thick (tens of kilometers thick) ice shell, possibly including bodies of melt or partial melt, overlying a liquid water ocean (35, 42–44).

Perhaps the most compelling evidence for a subsurface liquid water layer on Europa comes from magnetic field results (45) that show the signal of an induced field. This field requires a near-surface global conducting layer, for which the most probable explanation is a salty ocean. All of this evidence, however, remains indirect in nature (46). A definitive answer must await the arrival of the Europa Orbiter spacecraft.

The abundance of most biogenic elements on Europa is not known. It is common to assume Europa's composition to be that of a carbonaceous chondrite meteorite (47), in which case biogenic elements would be abundant. Little is known observationally. Spectral evidence reveals certain organic functional groups (C—H, C≡N) on Jupiter's moons Ganymede and Callisto, and hints at their presence on Europa (48). Comet impacts over solar system history should have provided Europa with a supply

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of biogenic elements irrespective of its initial inventory. If comets have typical densities of 1 g·cm^{-3}, the quantity of biogenic elements accreted by Europa over 4 Gyr is quite substantial (49). However, more material would be lost in impact ejecta if comets are highly porous objects, and cometary porosity is poorly constrained.

Sources of Free Energy

Along with liquid water and suitable chemical elements, life requires a source of free energy. Photosynthesis would be extremely constrained by Europa's ice cover (50). Gaidos *et al.* (51) argue that because of this, most metabolic pathways operating on Earth would be denied to putative europan organisms. Methanogenesis at hydrothermal vents at the bottom of Europa's ≈100 km-deep ocean could supply similar amounts of energy to that which supports ecosystems at terrestrial vents, although the potential annual biomass production would be ≈10^8–10^9 times below terrestrial primary production based on photosynthesis (52). It is also possible that niches might exist within Europa's ice shell where transient near-surface liquid water environments could permit photosynthesis or other metabolic processes (41, 53).

A Radiation-Driven Ecosystem?

Radiation due to charged-particle acceleration in the jovian magnetosphere should simultaneously produce oxidants (54, 55) and simple organics (56, 57) at Europa's surface. Chyba (58, 59) suggested that these molecules, if delivered to the liquid water layer, could provide a source of free energy sufficient to sustain a europan ecosystem.

The radiation also destroys exposed molecules, leading to steady-state concentrations (56, 57). Erosion due to sputtering occurs when charged particles eject material (60, 61). This material can be lost entirely, or redistributed over length scales as long as ≈10^3 km. Sputtering erosion estimates at Europa's surface range from ≈0.02–2 μm·yr^{-1} (60–62). Simultaneously, impact gardening occurs due to small micrometeorites impacting the surface. Gardening is predominantly a vertical mixing process, whereas sputtering's major result is a steady removal of material from the uppermost part of the surface. Gardening is nonlinear, with initial mixing rates at Europa as high as 1.2 μm·yr^{-1} for a fresh surface (61), and slowing as a regolith develops.

Gardening and sputtering thus compete in the creation, destruction, and preservation of important compounds on Europa's surface. Chyba (58) used an estimate of sputtering at the europan surface (60) of 0.2 μm·yr^{-1}, and a gardening estimate (63), based on a lunar analogy, of 1–10 cm over a mean europan surface age of ≈10 Myr (29, 30). Chyba (58, 59) therefore took oxidants and organic molecules to be lost through sputtering before they were gardened down to depths at which they would be protected against further radiation processing or sputtering loss. He took the relevant radiation-processed depth at Europa's surface to be ≈1 mm, the stopping depth of incident electrons (56, 57), but the results of Cooper *et al.* (61) suggest that substantial radiation processing extends to depths >1 cm for a surface age of 10 million years.

However, more recent estimates (61) suggest that the sputtering rate at Europa is more than an order of magnitude lower, ≈0.02 μm·yr^{-1}, and that the gardening depth over 10^7 yr is ≈1 m, rather than 1–10 cm. In this case, oxidants and organics created by irradiation of Europa's surface can be efficiently buried by gardening, and therefore protected. Here we re-evaluate the model of Chyba (58, 59) for these new estimates. Our conclusions will in turn need to be reconsidered as our quantitative understanding of impact gardening at Europa further improves.

Fig. 1 shows a preliminary comparison of sputtering vs. gardening rates for Europa's surface. The curved line shows the gardening rate from Cooper *et al.* (61), derived from estimates of the interplanetary mass flux at Jupiter. The three straight lines show three different sputtering erosion rates, spanning the range of numbers in the literature (60–62). For the sputtering rate 2 μm·yr^{-1}, sputtering dominates over gardening, so material is removed from Europa's surface before it has a chance to be buried and preserved. However, for the current best-estimate 0.02 μm·yr^{-1} case (61), gardening is the dominant process over Europa's entire surface age, and material is buried faster than most of it can be removed through sputtering. For a mean surface age of ≈10^7 yr (29, 30), gardening should extend to a depth of 1.3 m (61). The radiation products produced over this time scale will be mixed through this layer.

Charged-particle interactions with water ice should produce molecular oxygen, hydrogen peroxide, and other oxidants (55–57, 60). Hydrogen peroxide has been detected on Europa at 0.13% by number relative to H_2O (54). If this concentration holds through the entire 1.3-m gardening layer, there should be 5.6×10^{21} molecules H_2O_2 cm^{-2} (0.13% of 4.3×10^{24} molecules cm^{-2} H_2O available) mixed down to 1.3 m.

This value may be compared with that from a simple production calculation based on radiation flux F, H_2O_2 G value (molecules produced per 100 eV), and irradiation time. The column density expected is given by n = FGt (56, 57, 61), mixed down to 1.3 m. For H_2O_2 in an H_2O/CO_2 ice mixture at 80 K, G(H_2O_2) ≈0.1 (55). The net radiation energy flux at Europa is 7.8×10^{13} eV cm^{-2}·s^{-1}, most of which is due to electrons (61). For t = 10^7 yr, these values give n = 2.5×10^{25} molecules H_2O_2 cm^{-2}. This represents ≈6 times as much H_2O_2 produced as there were H_2O molecules initially present in the upper 1.3 m. An analogous calculation for O_2, using $G(O_2)$ = 0.01 (61) implies that ≈60% of the water ice is converted to O_2. If the upper 1.3 m of ice is all that is available to be radiation processed over 10^7 yr, production must be substrate-limited. The production quantities of H_2O_2 and O_2 could be orders of magnitude higher than those we find here (61) if the upper meter of Europa's surface was recirculated downward, so that fresh material were regularly being exposed to the surface radiation flux.

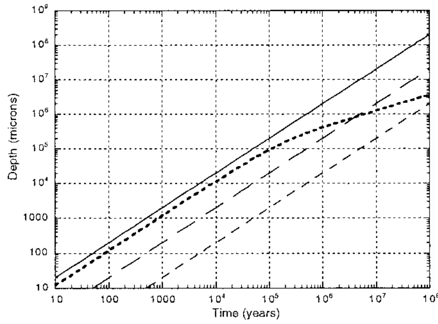

Fig. 1. Gardening (dotted line) vs. sputtering (2 μm·yr^{-1}, solid line; 0.2 μm·yr^{-1}, long dashes; 0.02 μm·yr^{-1}, short dashes) rates on Europa.

Instead, we accept the observed H_2O_2 abundance and use relative G values to estimate the production of other species. We take CO_2 to be present in Europa's ice at 0.2 wt% = 0.08% by number (58). Radiation will drive cycling among CO_2, CO, and organics in the ice (56, 57); organic groups may have been observed (48). Scaling from $G(H_2O_2)$, we use G values for the production of CO from CO_2 ice (55) and the production of formaldehyde from H_2O/CO ice (64) to estimate HCHO concentrations. G(HCHO) ≈1.0 (64) and G(CO) ≈ 9.0 (69). For 0.08% CO_2 in Europa's ice, we find the column density of CO to be N(CO) ≈ [G(CO)/G(H_2O_2)]N(H_2O_2) × 0.08% ≈ 4×10^{20} molecules CO, or ≈10% the abundance of CO_2. This in turn gives N(HCHO) ≈ [G(HCHO)/G(H_2O_2)]N(H_2O_2) × (CO/H_2O) ≈ 5×10^{18} molecules HCHO cm^{-2} mixed through the upper 1.3 m.

Surface–Ocean Exchange

For near-surface creation of oxidants or organics to be relevant to a subsurface ecosystem, exchange with the subsurface water layer must occur. Models of Europa's geology remain contradictory. In the tidal-cracking ridge formation mechanism of Greenberg *et al.* (39), material could exchange between the ocean and the surface. Formation models for chaotic terrain, which include rafting blocks of crust in liquid water or a slushy matrix (37, 38), also would allow surface-ocean communication. Other models may be less favorable. If chaotic terrain and other disrupted regions of Europa's surface were instead the surface expressions of solid-state diapiric activity (35, 42), it would be important to understand the extent to which this mechanism allows exchange of surface material with the ocean.

For a radius of 1,565 km, Europa's surface area is 3.1×10^{17} cm^2. If the upper 1.3 m of Europa's ice is recycled into the ocean in $\approx 10^7$ yr, $\approx 8 \times 10^{13}$ g HCHO and $\approx 7 \times 10^{17}$ g H_2O_2 would enter Europa's ocean every 10 million years. The H_2O_2 will decompose into H_2O via $2H_2O_2 \rightarrow 2H_2O + O_2$ with an activation energy of 71 kJ·mol^{-1} and an upper limit for the Arrhenius preexponential factor of $A = 1 \times 10^5$·s^{-1} in the absence of catalysis (65), giving a half life < 10 yr at 273 K.

A putative microbial ecology on Europa then could be powered by the reaction $HCHO + O_2 \rightarrow H_2O + CO_2$. The soil bacterium *Hyphomicrobium* can live on HCHO as its sole carbon source (66). Taking the dry mass of an aquatic cell to be 2×10^{-14} g (28) of which 50% is carbon (66), if 8×10^{13} g HCHO were incorporated with 100% efficiency in cell biomass, this would correspond to 3×10^{27} cells. If Europa's crust is recycled into the ocean over 10^7 yr, average cell synthesis would be $dn/dt \approx 3 \times 10^{20}$ cells·yr^{-1}. The steady-state biomass n is given by multiplying dn/dt by the biological turnover time τ. Adopting $\tau \approx 1 \times 10^3$ yr, appropriate for Earth's deep biosphere (28), $n \approx 3 \times 10^{23}$ cells.

A different estimate relies on the total chemical energy available over 10^7 yr from the reaction $HCHO + O_2 \rightarrow H_2O + CO_2$. Terrestrial methanotrophs oxidize CH_4 to HCHO, and then on to HCO_3^-. Oxidation of HCHO by these organisms yields 4.7 eV per molecule (66), giving 7.3×10^{29} eV·yr^{-1} = 2.8×10^7 kcal·yr^{-1}. We estimate the efficiency, φ, for microbial biomass (dry weight) production by dividing the dry mass that can be produced per mole of ATP, Y_{ATP}, by the energy required for ATP production, E_{ATP} (67). For a variety of microorganisms growing anaerobically or aerobically, $Y_{ATP} \approx 10$ g·mol^{-1} (68). Typically, $E_{ATP} \approx 10$ kcal·mol^{-1} (69), giving $\varphi \approx 1$ g·kcal^{-1}. Were all of the available energy used by microorganisms, this value for φ would give $\approx 1 \times 10^{24}$ cells. Thus both estimates—one assuming biomass to be carbon-limited, the other energy-limited—yield close to the same result.

A Europan ocean 100 km deep (31, 32, 35) has a volume about twice that of Earth's oceans. Were $\approx 10^{23}$–10^{24} cells distributed evenly throughout Europa's ocean, average cell densities would be about 0.1–1 cell·cm^{-3}. Even if this water reached the surface and froze, such low cell densities would render life detection extremely difficult. For example, for an instrument (perhaps fluorescent HPLC) with a sensitivity of $\approx 10^5$ cells, $\approx 10^2$–10^3 liters of ice would need to be melted and filtered (or evaporated) to yield sufficient sample for a detection. This requirement could be greatly lessened if organisms were strongly concentrated in nutrient-rich regions near the ice-water interface, as might be expected by analogy to the variable distribution of terrestrial microbes (20, 66). If the microorganisms maintained themselves within the upper 100 m of the ocean, ice derived from this layer could have concentrations $\approx 10^2$–10^3 cells·cm^{-3}, requiring ≈ 0.1–1 liter of meltwater to be processed.

Could There Be Europan Macrofauna?

It is natural to wonder whether analogs to giant squid or other macrofauna might exist in the europan ocean. Terrestrial metazoa require high levels of dissolved oxygen. For example, benthic macrofauna require O_2 concentrations above ≈ 20 μM (70). Even in a complete absence of O_2 sinks in Europa's ocean, the production rate of O_2 from H_2O_2 derived above would require ≈ 200 million years to oxygenate Europa's entire ocean to this level. Calculating H_2O_2 via $n = FGt$ would decrease this time to $\approx 5 \times 10^4$ yr, but this requires significant recycling of the upper meter of Europa's ice. If this does not occur, and if we assume that europan macrofauna would face the same high-energy respiration requirements as terrestrial macrofauna, we are challenged to find a sufficient source of O_2 production in the absence of photosynthesis.

Viking's Search for Life on Mars

Only once before have we conducted a robotic search for extraterrestrial life. The Viking spacecraft carried three experiments to search for life in martian soil samples (71), implicitly adopting a metabolic definition. But instead of finding unambiguous evidence of martian biology, Viking appears to have encountered unanticipated nonbiological oxidant chemistry (71, 72). The Viking gas chromatograph mass spectrometer (GCMS) failed to find any organic molecules (released in stages up to 500°C) in the martian soil at the ppb to ppm level (73). The GCMS provided a de facto search for life that implicitly assumed a biochemical definition: no (detected) organics, no life. In effect, a metabolic search for life yielding ambiguously positive results (71) was undercut by the negative results of a search based on biochemistry.

With the benefit of 25 years' hindsight, we suggest a number of lessons to be learned from the Viking experience (ref. 7; in the search for life on Europa). (*i*) If payload limits permit, a remote search for life should employ experiments that assume contrasting definitions of life. (*ii*) If only one life-detection experiment can be flown, the biochemical definition likely trumps other definitions. (*iii*) It is crucial to establish the geological and chemical context within which biological experiments will be conducted. Had the presence of the martian oxidants already been demonstrated, different biology experiments would have been flown on Viking. (*iv*) Life-detection experiments should provide valuable information even if they fail to find life. (*v*) Nevertheless, exploration often cannot be hypothesis testing. Much of what we do in planetary missions is simply exploration.

The Search for Life on Europa†

The first Europa lander should investigate a site where liquid water from the ocean has recently reached the surface. However, it is difficult on the basis of current knowledge to determine where these sites may be (or even if any exist). The Europa Orbiter mission will be crucial in helping to decide where to land. Galileo spacecraft-based models for Europa's geology are evolving rapidly, and there is no guarantee that they will converge to the correct model. When first described (37), chaos regions seemed 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 (74). Whether large cracks represent sites where ocean water reaches Europa's surface on a diurnal basis remains controversial, but if so they might be of special interest in a search for life (41). It is unclear how to interpret europan "ponds," which seem to indicate the eruption of liquid water from a subsurface source (35). However, if we had to choose a site for the first europan lander based on Galileo data alone, and assuming the ability to target a region only kilometers across, we might well recommend landing in such a place. Consistent with the recommendations of a recent National Academy of Sciences committee (9), the exploration of Europa should be seen as analogous to that of Mars, demanding a systematic program.

Chemical context should be established before or simultaneous with any biology experiments. Appropriate measurements would include abundances of the major cations and anions present, the salinity, the pH, an analysis of the volatiles (e.g., CO_2, O_2, CH_4, etc.) present in the water, and a search for organic molecules. In fact, the latter probably represents the highest-priority "bi-

†The conclusions of this section reflect those of a workshop on Europa life detection held at Harvard University, March 12–13, 1999, and cochaired by C. Chyba and S. Palumbi. Participants included J. Baross, C. Cavanaugh, J. Delaney, P. Falkowski, P. Geissler, P. Grunthaner, P. Gschwend, H. 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. The conclusions were formally communicated to the National Aeronautics and Space Administration's Solar System Exploration Subcommittee.

ology" experiment to be conducted. Additional experiments might include high-sensitivity searches for specific indicative organic molecules (such as amino acid enantiomers), a determination of key stable isotope ratios (such as $^{12}C/^{13}C$) or fluorescent microscopy.

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 (or perhaps evaporating) ice.

Current estimates (61) of charged-particle flux and gardening suggest that substantially radiation-processed material may extend down to $\approx$1 m on Europa for 10^7-yr-old terrain. Ideally, sample acquisition would take place below the processing depth. This emphasizes the importance of targeting the youngest terrain (where the gardening depth will be less), and of improving our models for impact gardening on Europa.

Planetary Protection

It is unclear whether any terrestrial microorganism could withstand a spacecraft journey to Europa plus subsequent transportation to and survival in Europa's ocean. But the fact that we can already speculate about possible europan ecologies using terrestrial analogies suggests that the recommendations of a recent National Research Council study (75) should be taken seriously until our knowledge improves: Spacecraft to Europa should have their bioload at launch reduced to a level consistent with a very low probability of contaminating a europan ocean with viable terrestrial microorganisms.

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