SEARCHING FOR LIFE ON EUROPA FROM A SPACECRAFT LANDER

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Abstract

An in situ search for life on Europa using a spacecraft lander should examine ice that appears to have been liquid recently and that seems most likely to have been derived from the ocean. An important lesson from the Viking missions to Mars is that searches for extraterrestrial life on Europa should establish the geological and chemical context needed to inform the results. The amount of sample available for life detection analysis could be maximized by the melting and filtration (and possibly the evaporation) of ice. In the case of sample return missions, both pristine and concentrated samples should be collected. Sample acquisition from below the radiation processing depth on Europa is essential. Sample acquisition and handling on Europa presents difficult technical challenges.

Introduction: Definitions of Life

There is no broadly accepted general definition of life in the scientific community. A wide variety of definitions have been suggested, including metabolic, thermodynamic, biochemical, and genetic definitions. 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 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 definitions have their own important problems, and in any case are unlikely to prove useful in a remote search for life. One must also be careful not to conflate (as I am somewhat guilty of here) the distinct ideas of "a living entity" and "life" (Fleischaker 1990, Chyba and McDonald 1995).

One working definition for life that has attracted attention in the origins of life community is what we call 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 however useful the Darwinian definition may be 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 too is unlikely to be 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”?

In assessing the possibilities of life in various locations in the solar system, we instead fall back on the less ambitious, but practically useful, notion of “life as we know it,” meaning life based on a liquid water solvent, a suite of “biogenic” elements (most famously carbon present as organic molecules), and a useful source of free energy. From the point of view of in situ experiments to be conducted at these sites, what we need are definitions (or implicit definitions) that prove useful in a remote exploration context. I suggest that there are useful insights to be gained from the Viking search for life on Mars about how to conduct future searches for life, and the role that varying definitions of life might play.

The Viking Search for Life on Mars

The Viking biology package contained 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 provocative results. Indeed, with respect to the labeled-release results, the head of the Viking biology team wrote 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).

Why then is it largely held in the scientific community that Viking failed to find life on Mars? There are several reasons. Theoretical modeling of the martian atmosphere and regolith suggests the production of oxidants (e.g. hydrogen peroxide) by the action of ultraviolet light, and these seem more-or-less able to account for the results of the three biology package experiments (Horowitz 1986). In this view, while the biology package hoped to find unambiguous evidence of martian biology, it instead was initially misled by unanticipated martian non-biological chemistry.

Perhaps most important, however, 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 provided 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 a de facto search based on biochemistry.

The interpretation of the labeled-release results as due to the action of martian oxidants is still debated, and may be premature (see, e.g., Levin 1998, but also Klein 1999). It is a remarkable fact 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. Nevertheless, the extraordinary claim of life on Mars must defer to a plausible chemical explanation in the absence of more compelling evidence.

Lessons from Viking

With the benefit of twenty-five years' hindsight, I 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. In this case, it seems unlikely that for the first lander more than one life-detection experiment will be present. 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 is unlikely that a biological interpretation of other experimental results will be accepted. At a minimum, then, we want to understand the organic chemistry present in our sample.

(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 already been demonstrated, very different experiments would 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 simple exploration.

Where Should we Land on Europa?

A Europan lander is included as an upcoming mission in the current draft NASA Roadmap for solar system exploration. It is not premature to begin thinking about where a first lander mission should set down. At this time, however, it is difficult to give more than general guidelines to the answer to this question. Information from the Europa Orbiter mission will be crucial in helping us decide where to land. We should consider the option of a lander mission that would have the flexibility to launch to Europa prior to the full results from the Orbiter, and be able to take advantage of the Orbiter data returned.

The first lander should touch down at a location which we think represents 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.) When first described (Carr et al. 1998) chaos regions of Europa 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 seem to foreclose this explanation (Stevenson 2000). If lenticulae are in fact the expressions of solid-state diapirism in Europa's ice (Pappalardo et al. 1998), they too may prove poor locations for the first lander. 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 for a search for life (Greenberg et al. 2000). It is unclear how to interpret "ponds" on Europa's surface 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 Europan lander based on Galileo data alone, and assuming the ability to target a region only kilometers across, we might well decide to land in such a place.

Information from the Orbiter would play a major role 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 perhaps most importantly Galileo magnetometer results, that an ocean exists beneath kilometers or tens of kilometers of Europa's surface ice (Pappalardo 1998, Khurana et al. 1998). 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 certainly 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. Yet 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.

Life Detection on Europa*

A search for life on Europa should examine ice that appears to have been recently liquid and, in the best case, that seems most likely to have been derived 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, 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 life detection experiment to be conducted. If sufficient payload were available, additional experiments might include high-sensitivity searches for certain specific indicative organic molecules (such as amino acid enantiomers), a determination of key stable isotope ratios (such as $^{12}C/^{13}C$) or even 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. Gaidos et al. (1999) have emphasized the difficulty of identifying sources of chemical disequilibrium on an ice-covered world, and the concomitant difficulty of imagining large biomasses. Photosynthesis is extremely difficult on Europa, though perhaps not entirely excluded (Reynolds et al. 1983). Estimates of the biomass that could be supported by possible europan hydrothermal vents (McCollom 1999) are very uncertain, and the communication of biomass at the base of a 100 kilometer-deep ocean with Europa's surface is uncertain. Ecosystems supported by the production of oxidants and organics in Europa's surface ice (Chyba 2000a) seem likely to yield low cell densities (see the Appendix below).

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 (or perhaps evaporating) Europa's ice. I examine only the latter option in more detail here; both possibilities bear further investigation.

Sample Concentration and Handling

The amount of sample available for life detection on Europa should be maximized by the melting and filtration (or possibly evaporation) of ice. The capability to perform this sort of sample concentration is likely to be needed for both in situ exploration and sample return missions. In the case of sample return missions, both pristine and concentrated samples should be returned.

- The conclusions of this section draw on 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. 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 formally communicated to the Campaign Strategy Working Group for Prebiotic Chemistry in the Outer Solar System of NASA's Solar System Exploration Subcommittee.

Moreover, sample acquisition from some depth into Europa's surface is essential. At a minimum, sampling should take place below the radiation processing depth, and preferably below the impact gardening depth (see, e.g., Cooper et al. 2000). Certainly this means that sample acquisition should take place more than a centimeter below the surface (assuming densities of 1 g cm^{-3}), and preferably at depths of greater than 10 cm.

Moreover, attention must be paid to the challenges of sample acquisition and handling for chemical or biological analyses. 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 development.

How much ice can 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:

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

Here $H_{fusion} = 3.3 \times 10^5$ 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 $C(T) = 7.04\,T + 185$, giving $\Delta E = 6 \times 10^5$ J kg^{-1}. For a dedicated spacecraft power source of 20 W (chosen for this example to be comparable to the total electric power expected to be available for the science payload of the planned Europa Orbiter mission (NASA 1999)), this calculation might suggest that ~100 liters 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" could likely 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 necessary 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 $H_{vapor} = 2.5 \times 10^6$ J kg^{-1}, or nearly 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) poses 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 melter 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 liters of water for every 100 m of penetration depth.

Appendix: Radiation-Powered Life on Europa

I recently estimated the biomass that could be supported by mixing the ice irradiation products HCHO and H_2O_2 into Europa's ocean (Chyba 2000a). For growth limited by either energy or the carbon from HCHO, I found steady-state biomasses of $\sim 2 \times 10^{10}$ g and $\sim 4 \times 10^7$ g, respectively. E.J. Gaidos, K.N. Nealson, and J.L. Kirschvink of the California Institute of Technology have kindly informed me of a calculational error in the higher estimate. I correct that error here (Chyba 2000b) and briefly discuss its implications.

The calculation (Chyba 2000a) should be modified as follows. I 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}. For a variety of microorganisms growing anaerobically or aerobically, $Y_{ATP} \sim 10$ g mol^{-1} (Stouthamer 1979). Typically, $E_{ATP} \sim 10$ kcal mol^{-1} (Thauer et al. 1977), giving $\varphi \sim 1$ g kcal^{-1}. Were all the available energy used by microorganisms, this value for φ would lead, following Chyba (2000a), to a steady-state biomass $\sim 5 \times 10^8$ g. If microorganisms utilized only 10% of the available energy (Jakosky and Shock 1998) this value would be reduced by a factor of 10.

A biomass of $\sim 10^8$ g corresponds to $\sim 5 \times 10^{21}$ aquatic cells (Whitman et al. 1998). Were these cells distributed evenly throughout Europa's putative ocean—an unlikely scenario--average cell densities would be only about 1 cell per liter. 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 $\sim 10^5$ cells, tens of thousands of liters of ice would need to be melted and filtered to yield sufficient sample for a detection. For comparison, a melter 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 liters of water for every 100 m of penetration depth.

These requirements could be greatly lessened if organisms were strongly concentrated in nutrient-rich regions near the ice-water interface (Greenberg et al. 2000), as might be expected by analogy to the variable distribution of terrestrial microbes (e.g. Madigan et al. 1997, Whitman et al. 1998). For example, if the microorganisms maintained themselves within the upper 10 m of the ocean, ice derived from this layer could have concentrations ~ 10 cells cm^{-3}, requiring only ~10 liters of meltwater to be filtered. Biomass production at hydrothermal vents may also be possible at the bottom of Europa's ocean (McCollom 1999), a possibility not considered further here. These uncertainties emphasize the importance of establishing chemical and geological context as an early and ongoing step in any search for life on Europa. This search would be aided by a choice of landing site where water from the ocean seemed most likely to have reached the surface, and by an ability to concentrate and examine as much sample as practical.

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