ASTROBIOLOGY
Volume 14, Number 4, 2014

DOI: 10.1089/ast.2014.1158

Forum Article

Follow the Plume: The Habitability of Enceladus

Christopher P. McKay,[1] Ariel D. Anbar,[2] Carolyn Porco,[3] and Peter Tsou[4]

Abstract

The astrobiological exploration of other worlds in our Solar System is moving from initial exploration to more focused astrobiology missions. In this context, we present the case that the plume of Enceladus currently represents the best astrobiology target in the Solar System. Analysis of the plume by the Cassini mission indicates that the steady plume derives from a subsurface liquid water reservoir that contains organic carbon, biologically available nitrogen, redox energy sources, and inorganic salts. Furthermore, samples from the plume jetting out into space are accessible to a low-cost flyby mission. No other world has such well-studied indications of habitable conditions. Thus, the science goals that would motivate an Enceladus mission are more advanced than for any other Solar System body. The goals of such a mission must go beyond further geophysical characterization, extending to the search for biomolecular evidence of life in the organic-rich plume. This will require improved *in situ* investigations and a sample return. Key Words: Ice—Life detection—Icy moon. Astrobiology 14, 352–355.

1. Introduction

The initial exploration of the Solar System revealed many worlds of interest to astrobiologists due to the presence of liquid water today or in the past. However, for many of these liquid water environments, other factors critical to habitability, such as the availability of carbon or nitrogen, remain unknown. Furthermore, in many cases, access to the zones of astrobiological interest poses a complex problem. Compounding this is the realization that sophisticated astrobiology missions will be challenging and expensive. Thus, it is important to prioritize the astrobiology targets, taking into account both the potential interest and technical difficulties. Shapiro and Schulze-Makuch (2009) provided one such prioritization and argued that Titan should be the top priority because it offers the possibility of encountering truly exotic hydrocarbon-based life. Mars was listed as a second priority partly on the strength of the reports of methane, which have since been shown to be incorrect (Zahnle *et al.,* 2011; Webster *et al.,* 2013). The other arguments for priority for Mars centered on the ALH84001 results (McKay *et al.,* 1996) and a novel reinterpretation of the Viking results (Houtkooper and Schulze-Makuch, 2007). A more conventional and prudent consideration of priorities would focus on the environments that are most habitable for known Earth life and that are most easily accessible. From this perspective, the plume of Enceladus, a small icy moon of Saturn, presents a readily accessible target; and its composition, which is known, indicates that the plume originates from a habitable environment. In this paper, we present the case that the plume of Enceladus currently represents the best astrobiology target in the Solar System and that missions to the plume must go beyond demonstrating habitability to the search for evidence of life and would best involve both *in situ* analyses and sample return.

2. The Habitability of Enceladus

The search for evidence of life on another world is a key motivation for astrobiology. Because all known life requires liquid H_2O, the first guiding principle in this search has been ‘‘follow the water.’’ As a result of spacecraft exploration, we know that liquid water is present now, or was in the past, on many worlds in our Solar System; so what do we ‘‘follow’’ next? There have been three published suggestions: energy (Hoehler *et al.,* 2007), carbon (Shapiro and Schulze-Makuch, 2009), and nitrogen (Capone *et al.,* 2006). These, and the requirement for water, map out the four key requirements for habitability. All are present in the source region of the jets of vapor and icy particles observed erupting from Enceladus. And based on our current knowledge, this is the only place outside of Earth where these four requirements are met.

Data on Enceladus' plume returned by the Cassini mission at Saturn over the last decade yielded strong evidence

---

[1] NASA Ames Research Center, Moffett Field, California.
[2] Arizona State University, Tempe, Arizona.
[3] CICLOPS, Space Science Institute, Boulder, Colorado.
[4] Sample Exploration Systems, La Canada, California.

for a liquid water subsurface source. The mass in solid particles is explicable only if they are frozen droplets of liquid water (Porco *et al.,* 2006). Their salinity, comparable to that of Earth's oceans, strongly suggests a water reservoir in contact with a rocky core (Postberg *et al.,* 2011). And the correspondence between individual jets and small-scale hot spots points to condensation of vapor and liquid as the source of this thermal emission (Porco *et al.,* 2013). Enceladus' subsurface sea was likely produced geothermally, by tidally induced flexure, during a much earlier epoch of higher orbital eccentricity (Běhounková *et al.,* 2012). Geothermal flows on Earth often contain redox pairs, such as H_2 and CO_2, that can be the basis for biological processes (*e.g.,* Stevens and McKinley, 1995; Chapelle *et al.,* 2002); by analogy, this has been suggested for Enceladus (McKay *et al.,* 2008). Both H_2 and CO_2 are present in the plume (Waite *et al.,* 2009).

Carbon and nitrogen are not only present in the plume but exist in forms conducive to biology. Organic carbon molecules, such as CH_4 ($\sim$1%), HCN ($\sim$1%), and a suite of other compounds up to C_6, have been detected (Waite *et al.,* 2009); the possibility that the latter may be the products of fragmentation in Cassini's mass spectrometer suggests the presence of even larger organic molecules (Waite *et al.,* 2009). Nitrogen is present as NH_3 ($\sim$1%), which is readily used by microorganisms. All these compounds are likely to derive directly from the source reservoir.

Phosphorous, potassium, sodium, sulfur, and calcium—the next most abundant elements in bacteria (Davies and Koch, 1991)—are also required for life. And it is difficult to imagine life without iron and other transition elements, which catalyze redox reactions. Of these, only sodium has been detected (Postberg *et al.,* 2011). However, all these elements are likely to be present in Enceladus' subsurface water reservoir as a consequence of the interaction between water and rock.

In a direct comparison with Mars, Europa, and Titan, only Enceladus is known at this time to have these four key requirements for habitability. Mars clearly had, and possibly has, liquid water. Carbon and energy are present near its surface, but the atmospheric nitrogen level is too low to be used by microorganisms (Klingler *et al.,* 1989), and it is not clear that there are nitrates in the soil. Europa has water under its ice shell, but nothing is known about its energy, carbon, or nitrogen budgets. Furthermore, its ocean is very likely inaccessible. However, recent observations indicate a plume arising from the southern hemisphere of Europa (Roth *et al.,* 2013). If that plume contains organics and if it derives from the ocean, it would be of great astrobiological interest. The surface of Titan is rich in organics containing both carbon and nitrogen, and there is clearly a source of chemical energy at the surface (McKay and Smith, 2005). However, liquid water does not exist at the surface; so life, if it exists, would be profoundly different from our own. While this makes Titan a fascinating target for exploration, it also makes the detection of life on Titan profoundly more challenging and speculative.

Unlike other astrobiologically interesting bodies, the samples from the zone of interest on Enceladus are demonstrably accessible. No landing or drilling is required because missions can directly sample the environment by flying through the plume. This makes a sample return mission to Enceladus surprisingly viable (Tsou *et al.,* 2012). Such a mission would allow the most sophisticated, continually improving, ground-based instrumentation to be used in the search for distinctive markers of life.

Astrobiological exploration of Enceladus is also compelling because, more so than is the case for Mars or even Europa, Enceladus' distance from Earth makes natural exchange of materials, via meteorites, between the two relatively unlikely. Worth *et al.* (2013) recently computed the probabilities of exchange between Earth and the Saturn System to be over 6 times lower than between Earth and the Jupiter System. If life is detected on Enceladus, it is more likely that we will have found a second genesis of life in our Solar System (McKay, 2001).

Because this small moon meets four of the key requirements of habitability, Enceladus provides a testing ground for the widely held hypothesis that the probability of life emerging is very high if minimal conditions are met. In this context, the absence of life on Enceladus would be nearly as profound as its presence. Either way, a search for evidence of life on Enceladus would yield new constraints on the chemical conditions and timescales for the origin of life and on our understanding of the prospects for life on other worlds.

3. Complex Investigation Needed

On Mars, the next steps in astrobiology are the detection of organics of any sort and the demonstration that they are native to Mars, as well as the determination of biologically available nitrogen. On Europa, astrobiology investigation must next determine the nature and accessibility of the ocean. For Enceladus, because of nearly a decade's worth of study by Cassini, such preliminary steps to confirm its astrobiology potential are done. Indeed, our understanding of Enceladus is such that the next step for astrobiology is an investigation of the complexity of the organic content of the plume and the search for evidence of life.

It is unlikely that we can plan in advance the analytical steps in an organic and life search in the plume of Enceladus, because the subsequent steps in the search will depend on the results from previous steps. For example, if amino acids are detected, then we would want to know if some subset of amino acids is abundant and predominantly of the same chiral excess. This line of inquiry would be expected because, on Earth, proteins are composed of a set of 20 amino acids with common chirality. The discovery of an alternate subset of amino acids with chirality opposite that of Earth life would not only be strong evidence of life but also of a second genesis of life independent of our own. However, amino acids may not be present, and life on Enceladus may be best investigated with other organic molecules. In this case, a completely different set of follow-up investigations would be indicated if the biogenic nature of these other organics is to be investigated. Unlike geophysical and geochemical investigations, the search for organic biomarkers as evidence for life does not lend itself to a direct approach and the use of a predetermined set of instruments. Instead, the investigations and the instruments needed will be path-dependent—a compelling argument for sample return.

4. Planetary Protection

The reason Enceladus is of such interest to astrobiology is the presence of a habitable environment. For this same reason, we must be extremely careful in spacecraft exploration of that world lest we seed it with life from Earth that would readily grow there (National Research Council, 2012).

A sample return from the plume also poses questions with regard to the protection of Earth from possible life on Enceladus. To date, there have been three sample return missions beyond the Moon: Stardust, Genesis, and Hayabusa, none of which returned material from a habitable environment. A sample return from the plume of Enceladus would be a Restricted Category V mission (COSPAR, 2008). This would require ''breaking the chain of contact'' between the Enceladus plume material and Earth's environment. Generally, the returned sample must be sterilized or sealed in a container to achieve this goal. Sterilization with heat or radiation will destroy or severely compromise the organic biomarkers that are the very motivation for returning the samples. The preferred approach is the return of an unsterilized sample in a container followed by an investigation for safety in a suitable containment facility. Ensuring that there is no accidental contamination would put a high burden of reliability on the containment system and increase the complexity and cost of the mission. Finding a way forward on the issue of back contamination for Enceladus Sample Return will require innovative approaches.

5. The Origin of Life

A key unknown in the astrobiology of Enceladus is how long the habitable conditions we see today have persisted. This time span may affect the prospects for life. Shapiro and Schulze-Makuch (2009) listed Enceladus below Titan, Mars, and Europa in priority for astrobiology, citing ''origin of life unlikely,'' because of the belief that its habitable zone is very short-lived. However, the constraints on the time required for the origin of life are very weak. The fossil record on Earth provides only the very broad constraint that life first appeared on this planet before 3.5 billion years ago (*e.g.,* Noffke *et al.,* 2013). Before this time, evidence of life is contentious or nonexistent, but this may be because of the paucity of well-preserved sedimentary rocks from the first billion years of Earth history. The process of life's origin may have been much faster. In a review of this question, Lazcano and Miller (1994) suggested that ''in spite of the many uncertainties involved in the estimates of time for life to arise and evolve to cyanobacteria, we see no compelling reason to assume that this process, from the beginning of the primitive soup to cyanobacteria, took more than 10 million years.'' However, Orgel (1998) criticized this result and stated that we do not understand the steps that lead to life; consequently, we cannot estimate the time required. ''Attempts to circumvent this essential difficulty are based on misunderstandings of the nature of the problem.'' The problem remains unsolvable with the current data. Valuable new data would be provided by a careful investigation of Enceladus, whether life is present there or not.

6. Conclusion

It is quite remarkable that the results from the Cassini mission have shown that the source region of the plume of Enceladus would be habitable for Earth-like life. Even more remarkable is that samples from this habitable zone are jetting out into space. This makes a sample return mission a possibility to consider (Tsou *et al.,* 2012). With samples of the organic material from the plume, we could search in terrestrial laboratories for organic biomarkers that would be conclusive evidence for life. If the biomarkers were clear but distinct from the biomolecules used by Earth life, we would have the first detection of a second genesis of life. The detection of biogenic, or even prebiotic, organic molecules in the plume of Enceladus would fulfill the long-sought goal of planetary science to discover something of astrobiological interest, something other than just ice and rock.

References

Běhounková, M., Tobie, G., Choblet, G., and Čadek, O. (2012) Tidally induced melting events as the origin of south-pole activity on Enceladus. *Icarus* 219:655–664.

Capone, D.G., Popa, R., Flood, B., and Nealson, K.H. (2006) Follow the nitrogen. *Science* 312:708–709.

Chapelle, F.H., O'Neill, K., Bradley, P.M., Methe, B.A., Ciufo, S.A., Knobel, L.L., and Lovley, D.R. (2002) A hydrogen-based subsurface microbial community dominated by methanogens. *Nature* 415:312–315.

COSPAR. (2008) *COSPAR Planetary Protection Policy* (20 October 2002, Amended 24 March 2005, 20 July 2008), COSPAR, Paris. Available online at https://cosparhq.cnes.fr/sites/default/files/pppolicy.pdf

Davies, R.E. and Koch, R.H. (1991) All the observed universe has contributed to life. *Philos Trans R Soc Lond B Biol Sci* 334:391–403.

Hoehler, T.M., Amend, J.P., and Shock, E.L. (2007) A ''follow the energy'' approach for astrobiology. *Astrobiology* 7:819–823.

Houtkooper, J.M. and Schulze-Makuch, D. (2007) A possible biogenic origin for hydrogen peroxide on Mars: the Viking results reinterpreted. *International Journal of Astrobiology* 6:147–152.

Klingler, J.M., Mancinelli, R.L., and White, M.R. (1989) Biological nitrogen fixation under primordial martian partial pressures of dinitrogen. *Adv Space Res* 9:173–176.

Lazcano, A. and Miller, S.L. (1994) How long did it take for life to begin and evolve to cyanobacteria? *J Mol Evol* 39:546–554.

McKay, C.P. (2001) The search for a second genesis of life in our solar system. In *First Steps in the Origin of Life in the Universe,* edited by J. Chela-Flores, T.C. Owen, and F. Raulin, Kluwer Academic Publishers, Dordrecht, pp 269–277.

McKay, C.P. and Smith, H.D. (2005) Possibilities for methanogenic life in liquid methane on the surface of Titan. *Icarus* 178:274–276.

McKay, C.P., Porco, C.C., Altheide, T., Davis, W.L., and Kral, T.A. (2008) The possible origin and persistence of life on Enceladus and detection of biomarkers in the plume. *Astrobiology* 8:909–919.

McKay, D.S., Gibson, E.K., Jr., Thomas-Keprta, K.L., Vali, H., Romanek, C.S., Clemett, S.J., Chillier, X.D., Maechling, C.R., and Zare, R.N. (1996) Search for past life on Mars: possible relic biogenic activity in martian meteorite ALH84001. *Science* 273:924–930.

National Research Council. (2012) *Assessment of Planetary Protection Requirements for Spacecraft Missions to Icy Solar System Bodies,* The National Academies Press, Washington, DC.

Noffke, N., Christian, D., Wacey, D., and Hazen, R.M. (2013) Microbially induced sedimentary structures recording an ancient ecosystem in the *ca.* 3.48 billion-year-old Dresser Formation, Pilbara, Western Australia. *Astrobiology* 13:1103–1124.

Orgel, L.E. (1998) The origin of life—how long did it take? *Orig Life Evol Biosph* 28:91–96.

Porco, C.C., Helfenstein, P., Thomas, P.C., Ingersoll, A.P., Wisdom, J., West, R., Neukum, G., Denk, T., Wagner, R., Roatsch, T., Kieffer, S., Turtle, E., McEwen, A., Johnson, T.V., Rathbun, J., Veverka, J., Wilson, D., Perry, J., Spitale, J., Brahic, A., Burns, J.A., Delgenio, A.D., Dones, L., Murray, C.D., and Squyres, S. (2006) Cassini observes the active south pole of Enceladus. *Science* 311:1393–1401.

Porco, C., DiNino, D., and Nimmo, F. (2013) How the jets, heat and tidal stresses across the south polar terrain of Enceladus are related [abstract 1775]. In *44th Lunar and Planetary Science Conference Abstracts,* Lunar and Planetary Institute, Houston.

Postberg, F., Schmidt, J., Hillier, J., Kempf, S., and Srama, R. (2011) A salt-water reservoir as the source of a compositionally stratified plume on Enceladus. *Nature* 474:620–622.

Roth, L., Saur, J., Retherford, K.D., Strobel, D.F., Feldman, P.D., McGrath, M.A., and Nimmo, F. (2013) Transient water vapor at Europa's south pole. *Science* 343:171–174.

Shapiro, R.S. and Schulze-Makuch, D. (2009) The search for alien life in our solar system: strategies and priorities. *Astrobiology* 9:335–343.

Stevens, T.O. and McKinley, J.P. (1995) Lithoautotrophic microbial ecosystems in deep basalt aquifers. *Science* 270: 450–454.

Tsou, P., Brownlee, D.E., McKay, C.P., Anbar, A.D., Yano, H., Altwegg, K., Beegle, L.W., Dissly, R., Strange, N.J., and Kanik, I. (2012) LIFE: Life Investigation For Enceladus, a sample return mission concept in search for evidence of life. *Astrobiology* 12:730–742.

Waite, J.H., Lewis, W.S., Magee, B.A., Lunine, J.I., McKinnon, W.B., Glein, C.R., Mousis, O., Young, D.T., Brockwell, T., Westlake, J., Nguyen, M.J., Teolis, B.D., Niemann, H.B., McNutt, R.L., Perry, M., and Ip, W.H. (2009) Liquid water on Enceladus from observations of ammonia and 40 A in the plume. *Nature* 460:487–490.

Webster, C.R., Mahaffy, P.R., Atreya, S.K., Flesch, G.J., and Farley, K.A. (2013) Low upper limit to methane abundance on Mars. *Science* 342:355–357.

Worth, R.J., Sigurdsson, S., and House, C.H. (2013) Seeding life on the moons of the outer planets via lithopanspermia. *Astrobiology* 13:1155–1165.

Zahnle, K., Freedman, R.S., and Catling, D.C. (2011) Is there methane on Mars? *Icarus* 212:493–503.

Address correspondence to:
Christopher P. McKay
Space Science Division
NASA Ames Research Center
Moffett Field, CA 94035

E-mail: chris.mckay@nasa.gov

Submitted 13 February 2014
Accepted 17 February 2014