Enceladus: Cassini Observations and Implications for the Search for Life

Christopher D. Parkinson\textsuperscript{1\ast}, Mao-Chang Liang\textsuperscript{1}, Hyman Hartman\textsuperscript{2}, Candice J. Hansen\textsuperscript{3}, Giovanna Tinetti\textsuperscript{4}, Victoria Meadows\textsuperscript{5}, Yuk L. Yung\textsuperscript{1}

\textsuperscript{1}Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125
\textsuperscript{2}Center for Biomedical Engineering, Massachusetts Institute of Technology, USA
\textsuperscript{3}Jet Propulsion Laboratory, California Institute of Technology
\textsuperscript{4}European Space Agency/Institut d’Astrophysique de Paris, Observatoire de Paris, France
\textsuperscript{5}Spitzer Science Center, California Institute of Technology

\ast cdp@gps.caltech.edu

ABSTRACT

The recent Cassini discovery of water vapor plumes ejected from the south pole of the Saturnian satellite, Enceladus, presents a unique opportunity for the detection of extant life in our solar system. With its significant geothermal energy source propelling these plumes >80 km from the surface of the moon and the ensuing large temperature gradient with the surrounding environment, it is possible to have the weathering of rocks by liquid water at the rock/liquid interface. For the cases of the putatively detected salt-water oceans beneath the ice crusts of Europa and Callisto, an isolated subsurface ocean without photosynthesis or contact with an oxidizing atmosphere will approach chemical equilibrium and annihilate any ecosystems dependent on redox gradients unless there is a substantial alternative energy source. This thermodynamic tendency imposes severe constraints on any biota that is based on chemical energy. On Enceladus, the weathering of rocks by liquid water and any concomitant radioactive emissions are possible incipient conditions for life. If there is CO, CO\textsubscript{2} and NH\textsubscript{3} present in the spectra obtained from the plume, then this is possible evidence that amino acids could be formed at the rock/liquid interface of Enceladus. The combination of a hydrological cycle, chemical redox gradient and geochemical cycle give
favorable conditions for life. We discuss the search for signatures of these species and organics in the Cassini UVIS spectra of the plume and implications for the possible detection of life.

Subject headings: planetary systems—radiative transfer—atmospheric effects—planets and satellites: individual (Saturn, Enceladus)

1. Introduction

To assess the plausibility of life on Enceladus, we look at the fundamental requirements of life on Earth and consider studies done to assess the possibility of life on Europa (Gaidos et al. 1999).

Before the advent of photosynthesis, organisms on Earth could not use sunlight directly and hence depended on abiotic sources of chemical energy. On the early Earth, this would come in the form of disequilibrium concentrations of redox reactants driven by hydrothermal activity, solar ultraviolet radiation, electrical discharges, and impacts (Chang 1993; Greenberg et al. 1993; Navarro-Gonzalez et al. 1998; Gaidos et al. 1999). All such redox pairs would be depleted by abiotic reactions and biological activity, so without external energy sources such as sunlight or geothermal energy, chemical equilibrium will ultimately terminate all life. Similarly, this thermodynamic condition will impose some formidable constraints for life elsewhere in the solar system that is based on chemical energy (Gaidos et al. 1999).

On the Earth, we have seen the existence of life in hydrothermal vents, and potential analogues on Europa have been suggested (e.g. Chyba 2000), since it does not receive sunlight and is isolated from other potential ecosystems. Vent ecosystems depend almost exclusively on oxidants such as SO$_4^{2-}$, O$_2$, and CO$_2$ (Tunnicliffe 1991; Lutz and Kennish 1993; Gaidos et al. 1999). The geology and young age of Europa’s surface (Pappalardo et al. 1998; Greeley et al. 1998) plus the predicted heat flow due to radiogenic decay and tidal dissipation (Caseen et al. 1989; Ojakangas & Stevenson 1989) suggests a geologically active interior and liquid water at shallow depths. Do such conditions even more favorable to the formation of life occur elsewhere in the solar system?

The Cassini spacecraft had a close encounter with Saturnian moon Enceladus on July 14, 2005, resulting in one of the most unexpected discoveries from the Cassini mission. Evidence from multiple instruments on the spacecraft shows that there is a large plume (Dougherty et al. 2006) of water vapor and particles emanating from Enceladus’ south polar region. The moon’s weak gravitational field prevents the retention of an atmosphere on this icy body, which indicates that this gas is likely the result of some currently active
venting geothermal process. A hydrological cycle governing the weathering of rocks by liquid water at the rock/liquid water interface and any concomitant radioactive emissions or other geothermal energy sources are possible incipient conditions for life (Hartman et al. 1993) on Enceladus and we discuss the evidence for this below. By hydrologic cycle, we mean processes that describe the constant movement of water in all phases above, on and below Enceladus’ surface.

2. CASSINI DATA AND ANALYSIS

The Cassini UltraViolet Imaging Spectrograph (UVIS) observed the occultation of Bellatrix (γ-Orionis) as it passed behind Enceladus as seen from the spacecraft (Hansen et al. 2006). The UVIS high speed photometer recorded a decrease in signal intensity ∼24 seconds prior to occultation of the star by the hard limb, consistent with the presence of an atmosphere. The UVIS far ultraviolet (FUV) channel recorded water vapor absorption features as the starlight passed through the plume, with a column density of ∼1.5×10^{16} molecules cm^{-2} of water. This is the column density at 7 to 30 km above the surface along the line of sight of the spacecraft.

The analysis of the UVIS spectra for the presence of other molecules is carried out using the standard method of least-squares linear regression (Bevington & Robinson 1992). The residual, obtained by subtracting the H$_2$O signal (Hansen et al. 2006) from the UVIS spectra, is shown in the upper panel in Figure 1. We then apply the linear regression to estimate upper limits for several molecules of astrobiological interest. We find that the signals from other species are within the noise fluctuation. The 1-σ upper limits of these molecules are given in Table 1. The normalized cross sections used in the above analysis are shown in the lower panel of Figure 1.

3. DISCUSSION AND CONCLUSIONS

Our calculated values for the upper limit of the column density of several species listed in Table 1 are consistent with detections from the other instruments aboard the Cassini spacecraft. The Ion and Neutral Mass Spectrometer (INMS) made measurements of the gaseous composition of the plume at altitudes of greater than 175 km. Molecules of H$_2$O, CO$_2$, N$_2$ and/or CO, and CH$_4$ were detected (Waite et al. 2006). The Visual and Infrared Mapping Spectrometer (VIMS) determined that the surface of Enceladus is nearly pure water ice, with exception of some organics (short-chained hydrocarbons) and CO$_2$ at the
South Pole, especially in the long, parallel crevasses dubbed “tiger stripes” (Brown et al. 2005). Also, an upper limit of 5 precipitable nm is derived for CO in the plume. Very little \( \text{NH}_3 \) was seen (<2%) by the VIMS instrument, however our analysis shows a column density upper bound of \( 1.3 \times 10^{16} \) molecules cm\(^{-2} \), comparable to that of water.

The global temperature maps made by the Composite Infrared Spectrometer (CIRS) show that the “tiger stripes” are as much as 25 K warmer than the surrounding regions (Spencer et al. 2006). These temperature maps show that the south-polar region is anomalously warmer than predictions from solar heating models, consistent with heat escaping from an internal heating source from this region (Burger et al. 2005). Matson et al. (2005) developed a thermal evolution model for Enceladus as a function of time of formation. Their models using radiogenic species and tidal dissipation can raise the core temperature in the vicinity of 1000 K. This allows for the presence of a liquid layer at the interface between the rocky core and an icy mantle, although, for some cases, venting liquid water vapor can obtain from lower temperatures (lower enthalpy) due to friction at the interface (Raizer 1960; Herkenhoff & Stevenson 1984).

The Imaging Science Subsystem (ISS) observed a young surface and evidence of recent tectonic activity in the southern hemisphere (Johnson 2005; Helfenstein et al. 2005). Their estimates from cratering models place the age of the surface at less than 10-100 million years. The VIMS instrument saw that the ice in and around the “tiger stripes” is crystalline in nature, whereas it is amorphous elsewhere on the moon (Brown et al. 2005). The high degree of crystallinity seen in the coldest areas of the “tiger stripes” is consistent with fresh material, perhaps as young as a few decades. The albedo of a surface can be approximately described by \( R = 1 - (1-a)^{1/2} \), where \( a \) is the single scattering albedo of the scatterers. Comparing the surface of Dione that is not resurfaced and that of Enceladus which is resurfaced by the plumes, we can estimate a minimum flux of water from the plumes that remain on the surface. \( R = 0.55 \) for Dione implies \( a = 0.80 \). For Enceladus, \( R = 0.99 \) which implies \( a = 0.9999 \). The fraction of dark material to white material (ice) is \( 5 \times 10^{-4} \). Thus the flux of \( \text{H}_2\text{O} \) is about 2000 times that of meteoritic (dark) material. The micrometeoroid flux at Saturn is estimated to be \( 10^{-16} \) g cm\(^{-2} \) s\(^{-1} \) (Moses et al. 2000). (We assume all micrometeoroids are trapped in the ice. In reality, only a fraction will be trapped. That fraction remains to be estimated in a later paper.) Therefore, the flux of water must exceed \( 2 \times 10^{-13} \) g cm\(^{-2} \) s\(^{-1} \), or \( \sim 10^{-5} \) cm/yr. These extraterrestrial micrometeoroids will form a source of organic material for Enceladus. Subsequent resurfacing of the southern polar region due to plume material venting from the “tiger stripes” will eventually cause sinking of micrometeorite material down to the rock/ice interface (see Figure 2). We can estimate a higher resurfacing rate for Enceladus if we assume that a comparable mass of \( \text{H}_2\text{O} \) is retained as that lost in the plume, or \( \sim 150 \) kg/s (Hansen et al. 2006). Averaged over the surface of the southern
hemisphere of Enceladus, this is equivalent to $4 \times 10^{-4}$ cm/yr. For comparison, the erosion rate of the surface of Europa by ion sputtering has been estimated to be $2 \times 10^{-5}$ cm/yr (Ip et al. 1998). The resurfacing rate of Europa must be on the order of or larger than this rate.

Although the theory that life on Earth came from extraterrestrial sources ( panspermia) cannot be excluded, it is generally accepted that the first living systems on our planet are the result of a long chemical evolution that preceded biological evolution. Organic products can be obtained from submitting gas mixtures of various starting composition to electron or photon irradiation. Three important behaviors can be identified from these experimental data (Raulin 2005): (1) Only reducing mixtures such as $\text{CH}_4$-$\text{NH}_3$-$\text{H}_2$-$\text{H}_2\text{O}$ or $\text{CO}$-$\text{N}_2$-$\text{O}_2$ allow the production of organic molecules. On the contrary, $\text{CO}_2$-$\text{N}_2$-$\text{H}_2\text{O}$ do not, except if $\text{H}_2$ is present with an $\text{H}_2/\text{CO}_2$ ratio close to or greater than 1; (2) The gas mixture which gives rise to the widest variety of organics of prebiotic interest is a $\text{N}_2$-$\text{CH}_4$-$\text{H}_2\text{O}$ mixture; (3) When organics are produced, the formation occurs in the gas phase but also in the solid phase. The solid products are a prebiotic source of compounds of biological interest, such as amino acids and purine and pyrimidine bases (tholins). The primitive atmosphere of the Earth was probably not the starting point of the prebiotic organic processes, since its main composition ($\text{CO}_2$-$\text{N}_2$-$\text{H}_2\text{O}$) was not favorable to the formation of organics. The main sources of organics are currently believed to be either from extraterrestrial influx (i.e. comets - nucleus and interplanetary dust, macro- and micro- meteorites) or the synthesis of organic matter from inorganic molecules in the vicinity of submarine hydrothermal vents, as well as in shallow basins (Brack 1998; Raulin 2005).

Becker and Epstein (1982) showed that organic matter in carbonaceous chondrites can be separated into three fractions - (1) a fraction insoluble in both methanol and chloroform, (2) a fraction soluble in chloroform and (3) a fraction soluble in methanol. Hartman et al. (1993) interpreted the first component, the fraction that is insoluble in chloroform and methanol, as of interstellar origin and the other two fractions chloroform-soluble hydrocarbons and methanol-soluble polar organics to have been synthesized on a hydrothermally altered planetoid body. The hydrocarbons (soluble in chloroform) were synthesized by a Fischer-Tropsch mechanism on iron-rich clays on the planetoid body. The polar organic matter, i.e., amino acids, were synthesized close to the surface of the planetoid body by the radiolysis of hydrocarbons and ammonium carbonate in a liquid water environment on iron-rich clay surfaces. Ferrous ion acted as a protection against back reactions driven by radiolysis. The simultaneous synthesis of iron-rich clays with the polar organics may be indicative of events related to the origin of life on Earth.

The VIMS data shows clearly a $3.4 \mu m$ absorption feature corresponding to organic compounds. Rawlings et al. (2003) show that this feature can be explained by solid-phase
aliphatic hydrocarbons, with possible substructure identified with symmetric and asymmetric CH stretching modes. A good fit to interstellar 3.4 µm profiles was obtained by Greenberg et al. (1995) using solar-photolysed mixtures of simple laboratory-prepared ices.

Gaidos et al. (1999) illustrate that nearly all metabolic life-styles on the present Earth would not be possible for organisms inhabiting an ice-covered ocean on Europa because soluble oxidants will not be produced or transported into the water column. Geochemical energy could power a relatively feeble ecology but requires volcanic resurfacing or plate tectonics. For Enceladus, it appears that we have the necessary hydrological cycle as well as geologically active, energy-generating reactions sufficient to create a redox gradient favorable for life (see Figure 2). The most abundant oxidant on icy satellites is most likely H₂O₂, which has been detected on Europa (Carlson et al. 1999), with a volume mixing ratio as high as 0.13%. We can make a rough estimate of the rate of production of H₂O₂ by analogy with that on Europa, where the production rate by sputtering is estimated to be $2 \times 10^{11}$ molecules cm$^{-2}$ s$^{-1}$, based on the energy flux of charged particles (see Carlson et al. 1999 for details). Since the full energy spectra of charged particles in the Saturnian magnetosphere have not been derived, we assume that the ratio of the H₂O₂ production rate and the H₂O sputtering rate is the same for Europa and Enceladus. The sputtered H₂O flux is $1.4 \times 10^9$ molecules cm$^{-2}$ s$^{-1}$ for Europa (Shi et al. 1995; Cooper et al. 2001). On Enceladus, the H₂O sputtering flux (Jurac et al. 2002; Richardson and Jurac 2004) is $\sim 10^8$ molecules cm$^{-2}$ s$^{-1}$, implying that the production rate of H₂O₂ at Enceladus would be of the same magnitude as that on Europa $\approx 10^{11}$ molecules cm$^{-2}$ s$^{-1}$.

Following the same method as used for Europa (Chyba & Phillips 2001) it is possible to estimate the total number cells that could exist in an ecosystem underneath Enceladus’ ice crust in the vicinity of the plume vent. Using the previously estimated value of $\sim 150$ kg/s for the ice resurfacing rate at the south pole of Enceladus suggests a crust turn-over time of $\sim 10^6$ yr for an ice thickness of 1 km. Assuming the conditions (such as the concentrations of H₂O₂ and HCHO, and a recycling ice thickness of 1.3 m) of Enceladus are similar to those of Europa, we estimate the microbial ecology in the region of Enceladus’ plume to be $\sim 10^{20}$-$10^{21}$ cells (for a $10^3$ yr biological turn-over time). Our estimated value is an order of magnitude greater per unit area than that for Europa.

We have seen from analysis of the spectra obtained from the plume during the Cassini flyby of Enceladus that many required species such as CO, CO₂ and NH₃ may be present (see Table 1), and that there is possible evidence that amino acids could be formed at the rock/liquid interface of Enceladus, where clay formations should exist due to rock weathering from liquid water or from micrometeorite accumulation due to resurfacing. Power is not a problem since resonance with Dione forces tidal heating and there is radiogenic heating as
well. It is possible there is additional heating due to differentiation of the moon body with a molten core (Matson et al. 2005).

Gaining insight into the origin, evolution and distribution, as well as the future of life on Earth and elsewhere in the solar system and the universe, is the primary mission of astrobiology. The combination of a hydrological cycle, chemical redox gradient and geochemical cycle give favorable conditions for life on Enceladus. To our knowledge, these conditions are not duplicated anywhere else in our solar system except our planet. Compared to Mars, Titan and Europa, Enceledus is the only other object in our solar system that appears to satisfy the conditions for originating life at present. Mars may have had a hydrological cycle in its early history, but there is no evidence that one exists today. Titan may be a repository of pre-biotic organic chemicals, but the conditions do not appear favorable for the development of life. Europa currently may have a hydrological cycle, but it may be a closed chemical system that will eliminate any chemical redox gradient in a geologically short time. Presently Enceladus is the most exciting object in the solar system for the search of extant life. We have compelling evidence supporting the view that Enceladus has active hydrological, chemical and geochemical cycles, which are essential ingredients for originating and sustaining life.

Future ground based and space observations and future space missions are urgently needed to advance our understanding of Enceladus. These include (1) long-term observations to establish whether the plumes are transient or in steady-state, (2) searching for molecules of astrobiological significance, such as NH$_3$, (3) searching for the presence of photopigments (e.g. chlorophyll), (5) identifying the presence of oxidants on the surface, such as H$_2$O$_2$ and O$_3$, and (6) mapping the North-South gradient in surface properties to quantify the rate of impact erosion and resurfacing (Baratta et al. 1991). Laboratory studies are needed, (1) to identify the chemical species responsible for 3.4 $\mu$m absorption feature in the ice in the “tiger stripes” (Berstein et al. 2005), (2) to study the chemical evolution of organics in ice in the presence of energetic photons and particles, and (3) to quantify the rate of production of oxidants such as H$_2$O$_2$ and O$_3$ for conditions appropriate for Enceladus. Finally, modeling studies are needed to link the observations and laboratory experiments to the evolution of the hydrological, chemical redox and geochemical cycles on Enceladus.

We thank Xun Jiang for assistance with linear regression, Andy Ingersoll, G. Orzechowska, and David Stevenson for helpful discussions. We thank M. Gerstell and R. West for helpful comments and D. Shemansky for sharing the photoabsorption cross-sections of HCN. This work was supported by NASA grant NASA5-13296 to California Institute of Technology. The research at the Jet Propulsion Laboratory (JPL), California Institute of Technology, was performed under contract with the National Aeronautics and Space Admin-
REFERENCES


Davies, A. G. 1996, Icarus, 124, 45


Herkenhoff, K. E., and Stevenson, D. J. 1984, B.A.A.S., 15, 361.


Nagata, T., Kondow, T., Ozaki, Y., & Kuchitsu, K. 1981, Chemical Physics, 57, 45


Raizer, Y. P. 1960, Soviet Physics JETP, 37, 1229.


Fig. 1.— Upper panel: the ratio of occulted and unocculted Bellatrix’s spectra after H$_2$O vapor has been removed. Lower panel: the normalized cross section (from 0 to 1) of all molecules we have upper limits for in Table 1.
Fig. 2.— Schematic illustration the hydrological, geochemical and chemical redox cycles on Enceladus.
Table 1. Upper bound for molecules of astrobiological interest

<table>
<thead>
<tr>
<th>Molecules</th>
<th>Column density$^a$ (molecules cm$^{-2}$)</th>
<th>References$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>H$_2$O</td>
<td>$1.5 \times 10^{16}$</td>
<td>Hansen et al. (2006)</td>
</tr>
<tr>
<td>CO</td>
<td>&lt;$1.3 \times 10^{14}$</td>
<td>Hansen et al. (2006)</td>
</tr>
<tr>
<td>CO$_2$</td>
<td>&lt;$1.8 \times 10^{17}$</td>
<td>Yoshino et al. (1996)</td>
</tr>
<tr>
<td>O$_2$</td>
<td>&lt;$2.5 \times 10^{18}$</td>
<td>Yoshino et al. (1987)</td>
</tr>
<tr>
<td>CH$_4$</td>
<td>&lt;$5.6 \times 10^{15}$</td>
<td>Lee et al. (2001)</td>
</tr>
<tr>
<td>C$_2$H$_2$</td>
<td>&lt;$1.6 \times 10^{15}$</td>
<td>Smith et al. (1991)</td>
</tr>
<tr>
<td>C$_2$H$_6$</td>
<td>&lt;$4.0 \times 10^{15}$</td>
<td>Lee et al. (2001)</td>
</tr>
<tr>
<td>HCN</td>
<td>&lt;$2.7 \times 10^{15}$</td>
<td>Lee (1980)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nagata et al. (1981)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nuth &amp; Glicker (1982)</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>&lt;$1.3 \times 10^{16}$</td>
<td>Cheng et al. (2006)</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>&lt;$2.2 \times 10^{15}$</td>
<td>Rufus et al. (2003)</td>
</tr>
</tbody>
</table>

$^a$1-σ upper limit for which column density is not constrained.

$^b$References for laboratory measured photoabsorption cross sections. Values for H$_2$O and CO are the results derived by Hansen et al. (2006).