EPSC Abstracts
Vol. 5, EPSC2010-461, 2010
European Planetary Science Congress 2010

Characterizing the Habitability of Europa and Ganymede

S. Vance, K. Hand and the JPL Icy Worlds Astrobiology Team
Jet Propulsion Laboratory, Caltech, Pasadena, USA (svance@jpl.nasa.gov / Fax: +01-818-393-4445)

Abstract

Ocean bearing icy worlds can be ideal places for life, despite a deficit of thermal and solar energy relative to Earth. Among icy worlds, Europa appears to be in a "sweet spot" in terms of its size and location in our planetary system. Europa's dynamical evolution has bestowed upon it a liquid layer in direct contact with rock, and the magnetic field of its host gas giant provides an important source of oxidants through surface radiolysis. Understanding the extent and nature of hydrothermal activity in such systems is important for assessing the availability of essential elements and organic compounds necessary for an origin of life. During periods of low heating in planetary mantles, hydrothermalism driven by serpentinization (hydration of ultramafic rock) may be extensive. Other water-rock interactions may yield more, and energetically complementary, materials in the vicinity of hydrothermal systems. Laboratory, computational and field investigations under way at the Jet Propulsion Laboratory, and elsewhere, as part of NASA's Astrobiology Institute, seek to improve our understanding of life's origins and prospects for survival under icy world conditions. We discuss these, with a focus on long-lived sources of energy and materials necessary to originate and support life in icy worlds.

1. Introduction

Constraining habitability in icy worlds is among the prime objectives for missions to the outer planets. Potentially the first mission to simultaneously study geologically active icy worlds in a gas giant system, the Europa Jupiter System Mission promises a "sea change" in our understanding of icy worlds. Europa and Ganymede serve as archetypes for large and mid-sized icy worlds that might one day be observed in other planetary systems. Their association with Io and Callisto provides an opportunity to constrain their origins and dynamics.

Europa, and maybe Enceladus and Ceres, could have been heated sufficiently — through incorporation of radionuclides —- for anhydrous and chemically reducing rocky interiors to result from heats of formation. These objects are small enough to sustain depths of fluid-accessible rocky mantle 10 to more than 100 times greater than for Earth. In larger icy worlds like Ganymede, by the same reasoning, fracture of mantle material is limited by high overburden pressures, suggesting, for example, that present-day water-rock interactions cannot explain the origin of Titan's methane atmosphere. In worlds where percolation of water into the rocky mantle is regulated by the rock's fracturability, the fracture front progresses downward as radiogenic heating decreases. Gradual serpentinization of this newly accessible material provides a means for measured release of heat and electron donors necessary for life, and a means for slowly releasing energy deposited by mineral dehydration during intense heating on formation and following periods of tidal activity or localized volcanism. Convection in icy world oceans and their overlying icy lithospheres provides a way to combine surface-deposited oxidants and reductants from the interior, and a means to move biosignature materials from the interior to the surface for detection.

2. From the Seafloor to the Icy Surface

Orbiters at Europa and Ganymede would look for surface expressions of subsurface processes. Of particular interest to the search for life, and for understanding heat transport in these moons, is the possibility of "seafloor" hydrothermal activity. The types of chemical signatures produced by such activity depend on the pH of the ocean, composition of the mantle and temperatures of reaction. Serpentinizing reactions anhydrous olivine- and pyroxene containing rocks (peridotites) operate in the range of 100-250 ^{o}C, depending on reaction rate, flow rate and amounts of supplemental volcanic heating (Lowell and DuBose, 2005; Vance and Goodman, 2009). Volcanically heated geochemistry on Earth occurs at temperatures exceeding water's critical temperature (374 ^{o}C) (Delaney *et al.*, 1992). Both types of activity imply the generation of hydrogen through oxidation of iron, and associated production of methane. The former is also associated with carbonate formation, whereas the latter creates sulfide structures and extracts metals and rare-earth materials from its hot rock walls. Moving these chemical signatures of activity to the surface requires an elevator on the order of 100 km tall. Ongoing research into plume dynamics and ice convection at JPL and elsewhere addresses these topics.

3. From Space to the Internal Ocean

The surfaces of Europa is chemically active owing to the influence of radiolysis, and probably also to "gardening" of material from Io and elsewhere. Sputtering of ice and radiolysis produce oxidized materials that useful to a potential redox cycle in Europa's ocean (Hand *et al.*, 2007). Impacts or putative subduction processes might be sufficient to transport these materials to Europa's ocean. Ganymede, farther from Jupiter's magnetic field and protected by its own internally generated field, serves as an intriguing geophysical laboratory, especially in contrast with Europa. Regarding these moons as possible analogues for exoplanetary moons, it is instructive to compare them with other moons in the Solar System.

Critical for radiolytic oxidant production is the strength of the magnetic field. Jupiter's magnetic field is by far the strongest field of any planet in our solar system, with a dipole moment over five orders of magnitude stronger than Earth's. Saturn, Uranus, and Neptune have dipole moments $\sim$1/20th, 1/400th, and 1/700th that of Jupiter, respectively. For Europa to experience a comparable field strength in Saturn's magnetosphere, it would have to be placed just outside of the orbit of Mimas. The field strength of the primary and the location of the satellite within the system are critical parameters driving radiolytic processing of surface ice. Ganymede's orbit would have to be cut in half, placing it between Dione and Rhea, in order for the saturnian magnetosphere to overcome the intrinsic field.

Laboratory studies of icy satellite surface radiolysis in the coming years will provide insight into the composition and abundance of surface oxidants on Europa and Ganymede. These studies of icy radiolysis and relevant solar wind interactions with Jupiter's magnetic field are crucial to preparation for future measurements in the Jupiter system.

4. Summary and Conclusions

Constraining Europa's habitability is a matter of knowing what to look for. At Ganymede, as well as at Europa, surface-subsurface exchange can be studied further using advanced computational machinery coupled with improved models of ice rheology. Surface chemistry can also be studied in the laboratory using improved methods for sample preparation, energy implantation and material characterization. All of this sets the stage for future robotic exploration. A Jupiter Europa Orbiter, currently being studied by NASA, along with a possible Jupiter Ganymede Orbiter under study by ESA, could seek indirect signs of relevant activity — thermal indications of hydrothermal plumes or spectral signatures of the ocean's bulk composition — but a landed suite of in situ instruments in conjunction with an orbiter provides the best chance for detecting trace indicators of internal activity.

Acknowledgements

This work is supported by the Icy Worlds team, part of NASA's Astrobiology Institute.

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