Brinicles and the fates of trapped salts in the ices of ocean worlds

Steven Vance\textsuperscript{1}, Laura Barge\textsuperscript{1}, Silvana Cardoso\textsuperscript{2}, Julyan Cartwright\textsuperscript{3}, and Baptiste Journaux\textsuperscript{4}

\textsuperscript{1}Jet Propulsion Laboratory, California Institute of Technology
\textsuperscript{2}University of Cambridge
\textsuperscript{3}CSIC-Universidad de Granada
\textsuperscript{4}University of Washington, Seattle

November 24, 2022

Abstract

Brinicles are self-assembling tubular ice membrane structures, centimeters to meters in length, formed by the downward migration of supercooled brine rejected from ice sheets, and found beneath sea ice in the polar regions of Earth. They provide a plausible setting for geochemical gradients amenable to life at the ice-ocean interface, in some ways analogous to hydrothermal vents at the seafloor-ocean interface. Their occurrence in icy ocean worlds like Europa and Enceladus remains hypothetical. The context of brinicles on Earth includes influences from oceanic flow, which will differ in other worlds, and surficial inputs from the atmosphere that do not exist in oceans with kilometers-thick global coverings of ice formed from the underlying ocean. Thus, it is difficult to project the likely occurrence and role of brinicles based on field observations of their earthly analogues. We discuss brinicles as they are currently understood, including their electrochemical properties in connection with potential habitats at the ice-ocean interface on Europa and Enceladus. We employ a fluid mechanical model (Cardoso and Cartwright, 2017) to assess the properties of brinicles on other worlds and consider their longevity relative to potential brine outflows from the overlying ice. We demonstrate how brinicles may grow by thermal diffusion, and provide simple scaling for their growth and outflow rates. The specifics of the composition and dynamics of both the ice and the ocean in these worlds remain poorly constrained. We demonstrate through calculations using FREZCHEM that sulfate likely fractionates out of accreting ice in Europa and Enceladus, and thus that an exogenious origin of sulfate observed on Europa’s surface need not preclude additional endogenous sulfate in Europa’s ocean. We suggest that, like hydrothermal vents on Earth, brinicles in icy ocean worlds constitute ideal places where ecosystems of organisms might be found.
Brinicles are self-assembling tubular ice membrane structures, reminiscent to meters in length, formed by the downward migration of supercooled brine rejected from ice sheets, and found beneath sea ice in the polar regions of Earth. They provide a plausible setting for geochemical processes amenable to life at the ice-ocean interface, in some ways analogous to hydrothermal vents at the seafloor-ocean interface. Their occurrence in icy oceans beyond Europa and Enceladus remains hypothetical.

The context of brinicles on Earth includes influences from oceanic flow, which will differ in other worlds, and surficial inputs from the atmosphere that do not exist on ice-covered kilometers thick global coverings of ice formed from the underlying ocean. Thus, it is difficult to project the likely occurrence and role of brinicles based on field observations of their earthly analogues. We discuss brinicles as they are currently understood, including their electrochemical properties in connection with equivalent habits at the ice-ocean interface on Europa and Enceladus. We employ a fluid mechanical model (Cardos and Cardinetti, 2017) to assess the properties of brinicles on other worlds and consider their longevity relative to potential brine outflows from the overlying ice. We demonstrate how brinicles may grow, expand, and provide simple scaling for their growth and outflow rates.

The specific composition of and dynamics between the ice and the ocean in these worlds remain poorly constrained. We demonstrate through calculations using FREZCHEM that sulfate likely fractions out of accreting ice in Europa and Enceladus, and that an exogenous oxygen of sulfate observed on Europa’s surface need not preclude additional endogenous sulfate in Europe’s ocean.

We suggest that, like hydrothermal vents on Earth, brinicles in icy ocean worlds constitute ideal places where ecosystems of organisms might be found.

Brinicle compositions in ocean worlds

Brinicles are due to the expulsion of brine pockets in ice. The magnitude of such expulsions in icy ocean worlds may create structures that persist over geologically significant time scales. Determining their possible occurrence on other worlds requires understanding the detailed workings of icy lithospheres: generation and transport of fluids, and role of salts.

The compositions and dynamics of ice and ocean in ocean worlds have few constraints: Europa’s ocean composition is mainly either SO2 or CI based on: spherical modeling (Zolotov, 2005); infrared reflectance spectra of the surface (McConnell et al., 1998, Brown and Hand 2013). Inferences from surface composition may be misleading: under slow equilibrium freezing at the ice-ocean interface, sulfates leave accreting ice (Marion et al., 2016). If Europa’s surface SO2 is excessive (Brown and Hand 2013) this need not preclude a sulfite-dominated ocean.

How much salt is in the ice?

Closed to assessing the feasibility of near-surface brine lakes, long-lived brinicles prevent freezing of sea ice is predicted trap up to 0.1wt% salt. That’s 10^5 kg of salt for 25 km-thick ice shell (Buffo et al., 2018). Over 10^6 yr, such high concentrations seem unlikely to sustain against return ice loss limits. If one substitutes into the ice matrix and interstices Partition coefficient = Ka/Chi = 1. For salt chlorides (e.g., NaCl), k = 2.37 (Gross et al. 1972) for a 3.4wt% NaCl ocean (~sea level), that’s 0.01wt% salt in the ice.

How long could brinicles persist?

Brines can be scaled to conditions in icy ocean worlds based on simple physics.

How are brines delivered?

In the above scenario, serpentinization is abundant on Europa, facilitating life’s origin and coexistence. Brinicles could be the means for supporting the most verdant part of Earth’s biosphere by serving as the conduit for oxygen-rich fluids from above.

References


