ENCELADUS HABITABILITY: CASSINI GROUNDWORK AND NEW POSSIBILITIES.

M. L. Cable[1], J. I. Lunine[2], L. J. Spilker[1], J. H. Waite[3], F. Postberg[4], K. B. Clark[1] and the ELF Science Team, [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (Morgan.L.Cable@jpl.nasa.gov), [2]Cornell University (jlunine@astro.cornell.edu), [3]Southwest Research Institute, San Antonio, TX, [4]University of Heidelberg, Germany.

Introduction: One of the main questions driving exploration of the solar system is whether life exists elsewhere other than Earth. Assuming we can most easily target water-based life, and therefore narrowing the search to candidate worlds with liquid water, three environments make the top of the list: the deep crust of Mars, the subsurface ocean of Europa, and the ocean within Enceladus. Of these, Enceladus is particularly attractive because liquid water from its interior is actively erupting into space. This means a mission can access the ocean of Enceladus without the need to land, dig or drill.

The Legacy of Cassini: Prior to Cassini, the best information about Enceladus came from Voyager. Enceladus was known to be extremely bright and to have few craters on some parts of its surface [1,2]. This suggested geologic activity and an endogenic source of the E-ring, but required more data to be confirmed.

Cassini discovered that Enceladus was indeed active, most prominently in the presence of a plume of material erupting from the south polar terrain. This plume is comprised of about a hundred jets which are fed from a liquid water reservoir ~35 km beneath the ice shell [3]. Subsequent gravity measurements and an investigation of Enceladus' libration confirm that this subsurface ocean is indeed global and geologically long-lived [4].

The Cassini Ion and Neutral Mass Spectrometer (INMS) discovered organic molecules in the plume vapor, and the Cosmic Dust Analyzer (CDA) detected salts in the plume ice grains, indicating that the ocean water is alkaline and in contact with a rocky core [5,6]. We also know that at this ocean-core interface there is moderate-temperature hydrothermal activity, perhaps akin to the Lost City vent structure on Earth's seafloor, which hosts a rich ecology [7,8]. All of the ingredients for life as we know it—water, energy, and chemistry—appear to be present in Enceladus' ocean.

Cassini has provided a wealth of information about Enceladus, but that mission lacks instruments with the necessary sensitivity to tell us whether in fact the ocean hosts life today. Cassini also cannot provide detailed information on the ocean environment—redox state, available free energy, and temperature—that allow for a quantitative assessment of the potential for life. Cassini has laid the groundwork, but it will be up to future mission to acquire this critical information to characterize the nature of the subsurface ocean of Enceladus and its biological potential.

Enceladus Life Finder as the Next Step: Thanks to Cassini, we know that a spacecraft can detect and quantify organic molecules and salts from the ocean of Enceladus through multiple fly-throughs of the plume.

The Enceladus Life Finder (ELF) would build on these successes and leverage modern instruments to detect unmistakable signs of ocean life in the Enceladus plume. ELF would use high-resolution mass spectrometers to analyze the plume gas and particles and provide an answer to this compelling question using three independent tests for life.

ELF would look for indications that organics are generated by biological processes through three independent types of chemical measurements widely recognized as diagnostic of life. The first test looks for a characteristic distribution of amino acids akin to the 'Lego principle', where life requires more than just one or two building blocks to generate the molecular machinery of life [9]. The second test determines whether the carbon number distribution in lipids is biased toward a particular rule (even, odd, etc.). Abiotic processes like Fischer–Tropsch synthesis produce carbon backbones of all lengths with no buildup from repeating subunits [10]. The third test measures carbon and hydrogen isotopic ratios, together with the abundance

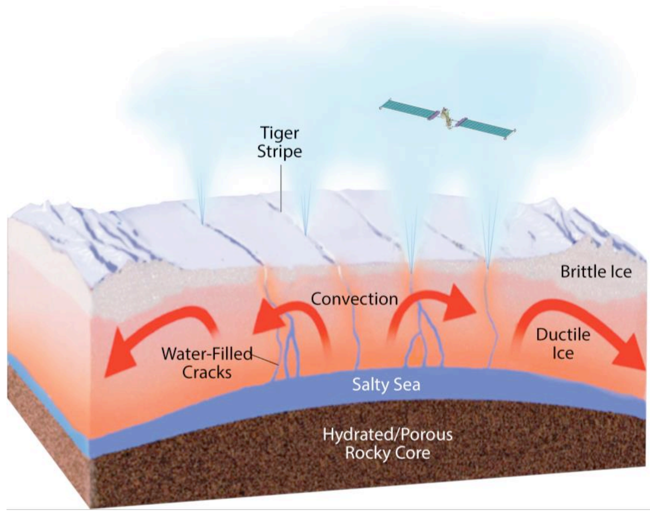

Figure 1. ELF would fly through the Enceladus plume over the Tiger Stripes and build on Cassini's discoveries in the search for life elsewhere in the solar system.

of methane relative to other alkanes, to assess whether the values fall in the range for biological processes [11].

The three life tests are designed to minimize the ambiguity involved in life detection by adhering to the following principles:

(1) They are distinct from each other; two are pattern related, one is isotopic. The two pattern tests involve separate classes of organic compounds.

(2) The tests seek properties of life that are inherent in its essential nature: the ability of life to overcome thermodynamic and kinetic barriers, and the use of repeating subunits to build molecules within a particular functional class.

(3) The tests are as universal as possible for water-based life as we know it, given the expected ubiquity of amino acids and lipids in a broad range of such environments.

ELF Mission Design: ELF leverages Cassini's tour and would use three gravity assists well above Titan's extended atmosphere to reach science orbit. ELF would then conduct eight science plume fly-throughs over a 2-year period. The baseline science is completed in four flybys, leaving ample time for follow-up measurements to resolve ambiguities or pursue the implications of discoveries. Two additional contingency flybys beyond the eight add further robustness to the mission. All flybys pass within seven degrees of the south pole.

ELF builds on Juno experience to pioneer an "outer solar system solar" flight system at over 9 AU from the sun. A 62-day orbit between plume encounters allows the interleaving of science acquisition and data-transmit sequences with periods of battery recharge. ELF has the same mission-design team, tools and processes as the Cassini and Juno Missions.

Conclusions: Enceladus is a natural laboratory for understanding how life (carbon- and water-based but not sharing Earth life's origin) may have arisen.

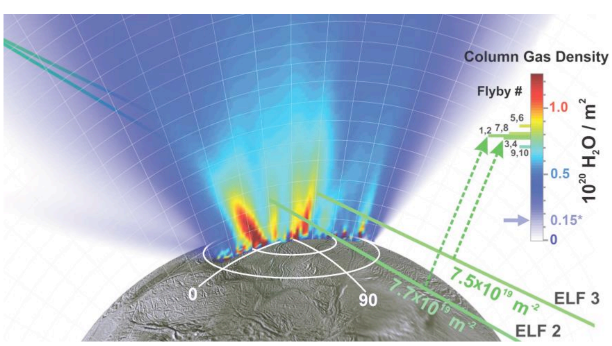

Figure 2. ELF uses a Cassini-based plume model to accurately predict plume densities of both gases and grains for its ten flybys.

ELF brings the most compelling question in all of planetary science within the reach of NASA's New Frontiers Program. To do so quickly without waiting for a future Flagship opportunity requires a focused mission that applies the most robust analytic techniques to the most easily accessed samples of the ocean—the plume itself. Fifty years after Voyager 2's detailed imagery revealed the unusual nature of Enceladus' surface, ELF would make measurements that may tell us whether we are alone in the solar system.

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