Enceladus Life Finder: The Search for Life in a Habitable Moon

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***Abstract*—Enceladus is one of the most intriguing bodies in the solar system. In addition to having one of the brightest and youngest surfaces, this small Saturnian moon was recently discovered to have a plume erupting from its south polar terrain and a global subsurface ocean. The Cassini Mission discovered organics and nitrogen-bearing molecules in the plume, as well as salts and silicates that strongly suggest ocean water in contact with a rocky core. However, Cassini's instruments lack sufficient resolution and mass range to determine if these organics are of biotic origin. The Enceladus Life Finder (ELF) is a Discovery-class mission that would use two state-of-the-art mass spectrometers to target the gas and grains of the plume and search for evidence of life in this alien ocean.**

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1. INTRODUCTION

Is there life elsewhere in the solar system? This simple question is one of the motivators for the exploration of our local planetary family. Guided by the principle that we can most easily recognize life as we know it—life that requires liquid water—three extraterrestrial environments are commonly called out as candidates for hosting life today: the deep crust of Mars, the subsurface ocean of Europa, and an ocean within Enceladus. Of these three, Enceladus is particularly attractive because liquid water from its deep

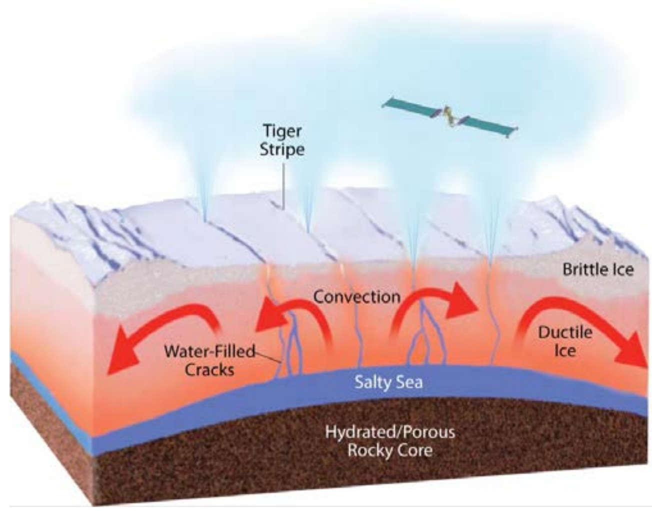

Figure 1. ELF will fly through the Enceladus plume over the Tiger Stripes and build on Cassini's discoveries in the search for life elsewhere in the solar system.

interior is actively erupting into space, making sampling of the interior much more straightforward. The Cassini Saturn Orbiter has demonstrated the feasibility of such sampling by making in-situ measurements of the Enceladus plume with relatively low-resolution mass spectrometers. The Enceladus Life Finder (ELF) builds on these successes by using two 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.

2. Enceladus Well Known from Previous Missions

A thousand times smaller than Ganymede, Enceladus was known from Voyager data to be extremely bright; that and a dearth of craters on some parts of its surface suggested geologic activity and an endogenic source of the E-ring. Cassini discovered the presence of a plume of material erupting from the south polar terrain (SPT) of Enceladus, comprised of many "geysers" or "jets" (which may form a "curtain-like" continuous plume [1]), and anomalous thermal emission along the fractures from which the geysers erupt [2]. In particular, at high resolution, spatial coincidences between individual geysers and small-scale hot spots revealed the liquid reservoir supplying the eruptions to be not in the near-surface but deeper within the moon [3], putting on a firm foundation the principle that sampling the plume allows us to probe the composition of the ocean (Fig. 1). Sensitive gravity and topography measurements established the location and dimensions of that reservoir: ~35 km beneath the SPT ice shell and extending out to at least 50 degrees latitude, implying an interior ocean large enough to have been stable over geologic time [4]. Recent reevaluation of Cassini gravity data [5] as well as investigation of Enceladus' libration using seven years of Cassini observations [6], confirm that this subsurface ocean is indeed global (Fig. 2). The Cassini Ion and Neutral Mass Spectrometer (INMS) discovered organic and nitrogen-bearing molecules in the plume vapor, and the Cosmic Dust Analyzer (CDA) detected salts in the plume icy grains, arguing strongly for ocean water being in contact with a rocky core [7, 8]. This argument was strengthened further with the recently reported detection of nanometer-diameter silica dust particles, which could only have been formed from ongoing high temperature (>90°C) hydrothermal reactions in the ocean [9]. **All of the ingredients for life as we know it—water, energy, and chemistry—appear to be present in Enceladus' ocean.** Cassini has taught us much about Enceladus, but this mission lacks instruments with the necessary sensitivity to tell us whether in fact the ocean hosts an active biota today. And Cassini cannot provide detailed information on the ocean environment—pH, redox state, available free energy, and temperature—that allow for a quantitative assessment of the potential for life. Acquiring such knowledge represents the essential first step in characterizing the nature of the subsurface ocean and its biological potential.

3. Enceladus Life Finder as the Logical Follow-on to Cassini

The Enceladus Life Finder is a solar-powered Saturn orbiter designed to fly multiple times through the plume of Enceladus (Fig. 3). The ELF payload consists of two time-of-flight instruments, optimized to analyze the plume gas and grains. Sample collection and processing are simple and

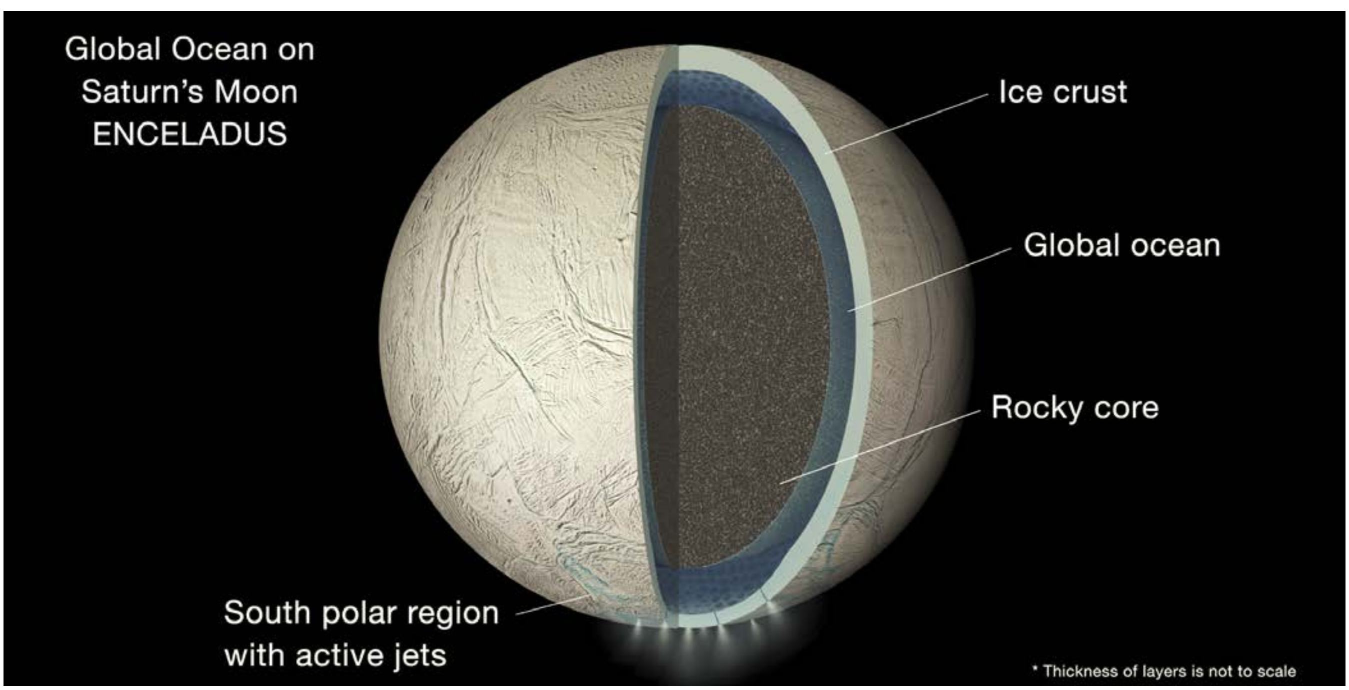

Figure 2. The most recent interpretation of Cassini data concerning Enceladus' interior indicates a global liquid water ocean. (Image Credit: NASA/JPL-Caltech)

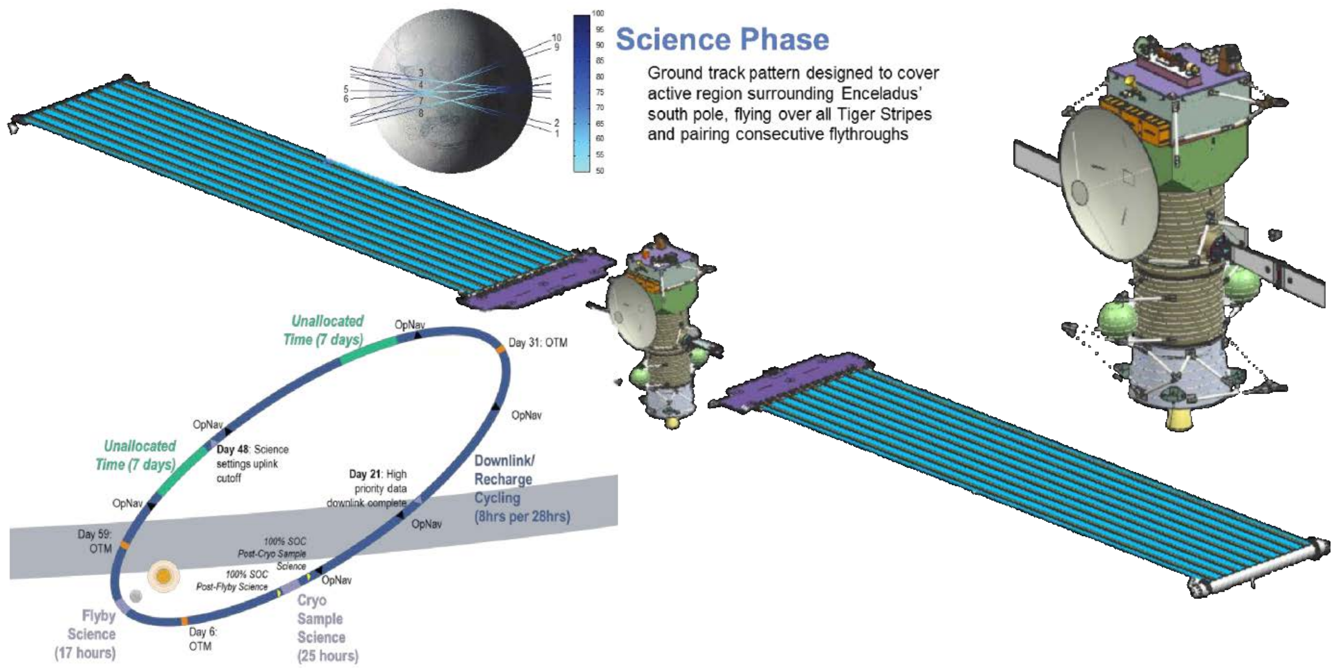

Figure 3. ELF is a solar-powered Saturn orbiter that will perform 10 flybys of Enceladus at approx. 50 km altitude.

robust; the high mass resolution and sensitivity available from the payload fully resolve composition (Fig. 4).

Mass Spectrometer for Planetary Exploration (MASPEX). MASPEX is a uniquely powerful instrument with the capability of measuring species with masses up to 1000 u at a demonstrated mass resolution (mass over mass channel width) exceeding 24,000 m/Δm and with a sensitivity of one part per trillion. In addition to its direct analysis of collected gases from the plume, a cryotrap concentrates species and allows for analysis post-flyby, enhancing ELF's ability to detect a wide range of species at trace concentrations.

Enceladus Icy Jet Analyzer (ENIJA). ENIJA is optimized to study individual ice and dust grains with diameters in the micron and sub-micron range. Developed by the same

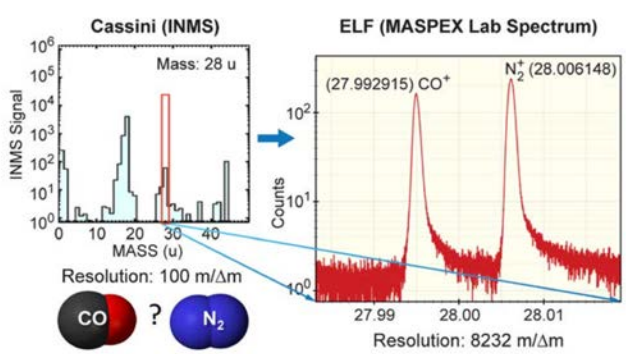

Figure 4. Mass resolution is crucial to removing ambiguities in species identification. *Left:* Cassini INMS data with resolution ~100 m/Δm from the second Enceladus flyby; there is a peak at mass 28, but it could be N_2, CO, or C_2H_4. *Right:* Increasing the mass resolution above 5000 m/Δm resolves all three species (C_2H_4 would be off the figure to the right).

research group that developed the Cassini Cosmic Dust Analyzer (CDA), ENIJA offers vast improvements in resolution and sensitivity. The instrument has a metal plate that fragments grains into neutral and ionized molecular constituents upon impact; in fact, ELF's flyby speed of 5 km/s is ideal to ionize, but not fragment, the organic molecules we are searching for. ENIJA operates sequentially in positive and negative ion modes to analyze all ionic species up to 2000 u with a resolution of 1000 m/Δm and a sensitivity of 100 parts per billion to 100 parts per trillion, depending on the species.

4. Science Objectives

The goals of the ELF mission are derived directly from the most recent decadal survey: first, to determine primordial sources of organics and the sites of organic synthesis today; and second, to determine if there are modern habitats in the solar system beyond Earth where the conditions for life exist today—and if life exists there now. Enceladus is the ideal outer solar system object to address these issues because of Cassini's discovery of an organic- and salt-rich water ocean, and the accessibility of its interior through the plume.

ELF carries compositional instruments of far greater mass range, dynamic range, resolution and sensitivity than those on Cassini. The science goals are addressed through three science objectives: evolution, habitability, and life.

Science Objective 1: Evolution. This objective is to determine if Enceladus' volatiles, including organic compounds, have evolved chemically over its history. ELF measures abundances of a carefully selected set of neutral species, some of which were detected by Cassini, to ascertain whether these volatiles have been thermally altered. Low abundances of acetylene and HCN, for example, would point to aqueous alteration, as these species react with liquid water to produce other compounds like alcohols, esters, and amides. ELF also determines the argon-to-nitrogen ratio, which is key for identifying the original molecular carrier of N (as either NH_3 or N_2).

Science Objective 2: Habitability. ELF determines the details of the interior marine environment—pH, oxidation state, available chemical energy, and temperature—that permit characterization of the life-carrying capacity of the interior. The ability to use mass spectrometry to assess habitability of the interior oceanic environment has been given a "first test" with Cassini INMS and CDA [10,11], which points to the interior ocean being a solution of Na-Cl-CO_3 with an alkaline pH of 9–12. Such a solution and pH could be produced via serpentinization of chondritic rock which in turn produces H_2, a very favorable circumstance for life were it occurring today [12]. However, pH is only one indicator of the characteristics of an aqueous environment, and Cassini has not yet been able to determine the H_2 abundance due to complications from titanium sputtering within the instrument aperture. ELF goes further to quantify the amount of H_2, and to determine the oxidation state, the energy available from oxidation-reduction reactions, and the temperature at which reactions are occurring to put together a detailed picture of the nature and habitability of Enceladus' aqueous environment.

Science Objective 3: Life. ELF looks for indications that organics are the result of biological processes through three independent types of chemical measurements widely recognized as strongly diagnostic of life (Fig. 5). The first test looks for a characteristic "flat" distribution of amino acids [13], the second determines whether the carbon number distribution in fatty acids or isoprenoids is biased toward a particular rule (even, odd, or divisible by a small integer) [14], and the third measures carbon and hydrogen isotopic ratios, together with the abundance of methane relative to other alkanes, to assess whether the values fall in the range for biological processes. The 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 completely different 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, given the expected ubiquity of amino acids and lipids in a broad range of such environments [13, 14].

5. Mission Architecture

A solar-powered, thermally conservative flight system (the fourth build of JPL's core avionics product line), ELF conducts eight science plume fly-throughs over a 3-year period, to pursue the implications of Cassini's spectacular discoveries of active jetting from, and existence of an ocean within, Enceladus. ELF leverages Cassini's tour and uses three gravity assists well above Titan's extended atmosphere to reach science orbit. 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.

ELF builds on Juno experience to pioneer an "outer solar

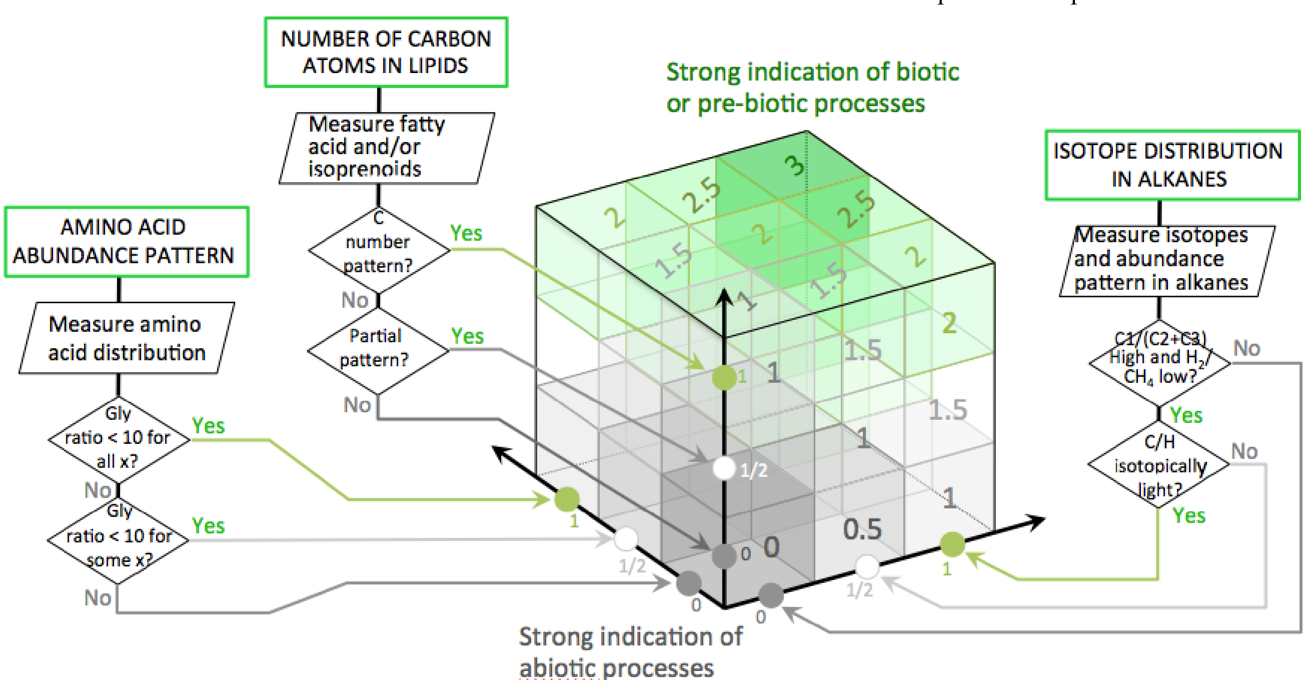

Figure 5. ELF's three distinct tests for life are as universal as possible, and seek properties of life that are inherent in its essential nature. Positive results for all three would strongly argue for life within Enceladus.

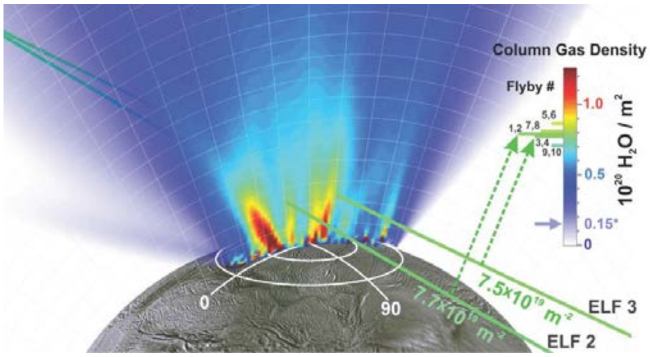

Figure 6. ELF uses a Cassini-based plume model to accurately predict plume densities of both gases and grains for its 10 flybys.

system solar" flight system at over 9 AU from the sun. Using commercial infusion of NASA's latest Space Technology Mission Directorate (STMD) developments, ELF utilizes lightweight ROSA arrays to provide 325 W (margined) End-of-Life (EOL) at Saturn. These arrays are now being qualified for extensive commercial use by Solar Systems Loral (SSL), and provide mass margin for ELF compared to conventional solar arrays.

ELF mission design and system design are tightly focused to perform the ten planned flybys and downlink the mass spectrometry data. A repetitive, 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. A thermal-pumped fluid architecture integrates Mars Science Laboratory (MSL) heritage components into a cold-optimized thermal-mechanical bus structure. The Mission Power Systems Engineer "phase lead" polices the energy balance from Phase A design through Phase D verification.

A three-maneuver-per-orbit strategy schedules a deterministic cleanup orbit trim maneuver (OTM) after each encounter, a deterministic targeting OTM close to apoapsis, and a statistical approach OTM before the next encounter. All flybys and maneuvers are scheduled well outside of Sun-Earth conjunction periods, which occur approximately every 380 days. The closest approaches target the plume over Enceladus' south-polar region at 50 km altitude, well within the flyby-altitude range demonstrated by Cassini. The ground-track pattern crisscrosses the active region over the south pole, flying over all tiger stripes and pairing consecutive ground tracks to optimize ENIJA's dissection of the plume with positive- and negative-ion measurements. All flybys pass within seven degrees of the South Pole.

6. Data Sufficiency

Cassini-based plume column density is many times higher than the ELF design point. The plume gas and grain density and composition are modeled using in situ INMS observations, UVIS occultation profiles, and CDA, CIRS, and ISS data to constrain model parameters. The low resolution of the INMS instrument requires a statistical fitting of candidate compounds to the data. The 3D model allows accurate prediction of plume gas and grain densities. The gas density assumed for computing MASPEX integration times is well below values predicted for the ELF trajectories (Fig. 6). Similarly, the number of particles required by ENIJA is well below model predictions.

6. Conclusion

ELF brings the most compelling question in all of space science within reach of NASA's Discovery Program, providing an extraordinary opportunity to discover life elsewhere in the solar system in a low cost program. Fifty years after Voyager 2's detailed imagery revealed the unusual nature of Enceladus' surface, ELF will make measurements that may tell us whether we share the solar system with another biosphere.

7. Acknowledgement

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BIOGRAPHY

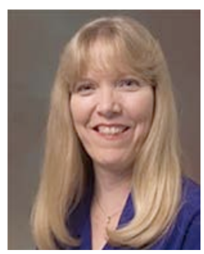
Morgan L. Cable *is a Research Scientist at the NASA Jet Propulsion Laboratory, California Institute of Technology, and Assistant Project Science Systems Engineer for the Cassini Mission. She earned her Ph.D. in Chemistry from the California Institute of Technology in 2010, where she investigated life in extreme environments. As a NASA Postdoctoral Fellow, she developed novel lab-on-a-chip devices and protocols for various organic molecules. Her current work continues to focus on organic and biomarker detection strategies, through both in situ and remote sensing techniques.*

Karla Clark *received her bachelor's degrees in chemistry and chemical engineering from Rice University in Houston, Texas. After graduation, Ms. Clark worked at Hughes Aircraft Company developing flight batteries for communications satellites. Ms. Clark continued her education and received master's degrees in both mechanical engineering and engineering management from the University of Southern California. In 1987, Ms. Clark joined JPL where she has held numerous technical and managerial roles. Her primary technical roles included system engineering efforts for the Cassini Power System and Outer Planets/Solar Probe Project. Her management roles have ranged from Task Manager for the Flight Battery Research; Power System Technical Manager for Cassini; Power Electronics Engineering Group Supervisor; Flight System Manager for the Europa Orbiter; Spacecraft Manager and Contract Technical Manager for the Prometheus Project and study lead for the NASA Europa Explorer Flagship Mission. Karla was the Division Manager for Mission Assurance for almost 5 years and has just recently taken on the role as the Assistant Director For the Office of Safety and Mission Success.*

Jonathan Lunine *is interested in how planets form and evolve, what processes maintain and establish habitability, and what kinds of exotic environments (methane lakes, etc.) might host a kind of chemistry sophisticated enough to be called "life." He pursues these interests through theoretical modeling and participation in spacecraft missions. He works with the radar and other instruments on Cassini, continues to work on mass spectrometer data from Huygens, and is co-investigator on the Juno mission launched in 2011 to Jupiter. He is on the science team for the James Webb Space Telescope, focusing on characterization of extrasolar planets and Kuiper Belt objects. Lunine is currently PI for a JPL-led study to send a probe into Saturn's atmosphere, and has contributed to mission concept studies for space-based astrometry and microlensing missions. Lunine is a member of the National Academy of Sciences and has participated in or chaired a number of advisory and strategic planning committees for the Academy and for NASA.*

Frank Postberg *has extensive experience in analyzing cosmic dust and ice particles by impact ionization mass spectrometry. He is especially experienced in the compositional characterization of ice grains in the Saturnian system emitted by Enceladus. He has executed development and lab testing of in situ dust instrumentation at the dust accelerator facility at the MPI-K in Heidelberg. He runs a laboratory located at the Earth Science Institute of University of Heidelberg. This laboratory is specialized in simulating ice particle impacts by laser dispersion and subsequent mass spectrometry. He has a general professional background in analytic chemistry and planetology.*

Kim Reh *is Deputy Program Manager for JPL's Solar System Exploration Mission Formulation Office, responsible for mission formulation through Phase A. Mr. Reh was Portfolio Manager for JPL's submittal to NASA Discovery 2010, Discovery 2014, NF3, and NF4 Programs, and he was Study Manager for JPL support to the Planetary Science Decadal Survey. He has also been Capture Lead and Pre-Project Manager for the collaborative NASA/ESA Titan Saturn System Mission; Science and Mission Design Manager for the Prometheus project (Jupiter Icy Moons Orbiter mission); Capture Lead/Proposal Manager for Phoenix Step 1 proposal for NASA's Mars Scout opportunity; and Manager of JPL's Avionic Systems Engineering section. Prior to JPL, he was a Project Engineer at General Dynamics Missile Systems for 13 years. Mr. Reh holds a BSE from the University of Michigan, an MSE from California State Polytechnic University, a Business Management Certificate from the University of California Riverside, and a Certificate of Executive Management from Caltech.*



Linda Spilker *is a NASA principal research scientist at the Jet Propulsion Laboratory, California Institute of Technology. She is currently the Cassini Project Scientist and a Co-Investigator on the Cassini Composite Infrared Spectrometer team. She has worked on Cassini since 1988. Since joining JPL in 1977 she has worked on the Voyager Project, the Cassini Project and conducted independent research on the origin and evolution of planetary ring systems. She received her Ph.D. from UCLA in geophysics and space physics. She is also a scientific spokesperson for the space program, engaging in public outreach activities from K-12 to university students to the general public.*

J. H. Waite *is a planetary scientist specializing in the application of mass spectrometry to the study of solar system biogeochemistry and aeronomy. He is involved in research projects in ion/neutral mass spectrometry, gas chromatography, biogeochemistry, thermospheric modeling, and planetary astronomy. Following completion of his undergraduate studies in physics at the University of Alabama in 1976, he began graduate work in atmospheric science at the University of Michigan. He received a M.S. in atmospheric science in 1978 and, in 1981, was awarded a Ph.D. for his development of a model of Saturn's ionosphere. From 1981 to 1988, Dr. Waite was a Research Scientist at NASA's Marshall Space Flight Center, where he was heavily involved in the analysis of Dynamics Explorer data on ion outflow from the Earth's ionosphere. From 1988 to 2000, Dr. Waite was at Southwest Research Institute (SwRI), where he was Director of the Space Science Department of the Instrumentation and Space Research Division. Although still involved in studies of the Earth's coupled ionosphere-magnetosphere system, Professor Waite's work at SwRI was strongly focused on planetary research. In January of 2001, Dr. Waite became a full professor in the University of Michigan, Department of Engineering, Atmospheric, Oceanic, and Space Sciences department. Dr. Waite returned to SwRI as an Institute Scientist in May of 2006 and was promoted to Program Director in 2013. His primary responsibilities include Director of the Center for Excellence in Analytical Mass Spectrometry, where he is involved in the definition and development of ion and neutral mass spectrometers and gas chromatographic techniques. He is PI for the Europa MASPEX investigation. He is the Team Leader for the Cassini Ion and Neutral Mass Spectrometer and Cassini Plasma Spectrometer investigations, co-investigator and lead SwRI hardware manager for the Rosetta/Rosina Reflectron Time-of-Flight, and a co-I on the Juno science team. Dr. Waite is a member of the American Geophysical Union, the American Astronomical Society, and Sigma Xi and a former editor of the AGU letters journal, Geophysical Research Letters. In 1996, he was named Distinguished Alumnus of the University of Michigan's College of Engineering.*