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LIFE: Life Investigation For Enceladus A Sample Return Mission Concept in Search for Evidence of Life

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Abstract

Life Investigation For Enceladus (LIFE) presents a low-cost sample return mission to Enceladus, a body with high astrobiological potential. There is ample evidence that liquid water exists under ice coverage in the form of active geysers in the "tiger stripes" area of the southern Enceladus hemisphere. This active plume consists of gas and ice particles and enables the sampling of fresh materials from the interior that may originate from a liquid water source. The particles consist mostly of water ice and are 1–10 μ in diameter. The plume composition shows H_2O, CO_2, CH_4, NH_3, Ar, and evidence that more complex organic species might be present. Since life on Earth exists whenever liquid water, organics, and energy coexist, understanding the chemical components of the emanating ice particles could indicate whether life is potentially present on Enceladus. The icy worlds of the outer planets are testing grounds for some of the theories for the origin of life on Earth.

The LIFE mission concept is envisioned in two parts: first, to orbit Saturn (in order to achieve lower sampling speeds, approaching 2 km/s, and thus enable a softer sample collection impact than Stardust, and to make possible multiple flybys of Enceladus); second, to sample Enceladus' plume, the E ring of Saturn, and the Titan upper atmosphere. With new findings from these samples, NASA could provide detailed chemical and isotopic and, potentially, biological compositional context of the plume. Since the duration of the Enceladus plume is unpredictable, it is imperative that these samples are captured at the earliest flight opportunity. If LIFE is launched before 2019, it could take advantage of a Jupiter gravity assist, which would thus reduce mission lifetimes and launch vehicle costs. The LIFE concept offers science returns comparable to those of a Flagship mission but at the measurably lower sample return costs of a Discovery-class mission. Key Words: Astrobiology—Habitability—Enceladus—Biosignatures. Astrobiology 12, 730–742.

Introduction

The recent discovery of water vapor plumes ejected from fissures near the south pole of Saturn's satellite Enceladus compels us to point out the relevance of this icy satellite to the evolution of organics and possibly life in this unique physical and chemical environment (Spencer *et al.*, 2006). Cassini's first look at Enceladus' south pole revealed a series of approximately parallel fissures, nicknamed the "tiger stripes" (Hansen *et al.*, 2006; Porco *et al.*, 2006; Spencer *et al.*, 2006), that are the source of water vapor plumes propelled 200 km above the surface as shown in Fig. 1. These discoveries indicated that there is very likely a heated liquid subsurface ocean. The region around the fissures has been extensively resurfaced, and thermal emission from the region indicates a strong source of subsurface heating. Although the physical mechanism for production of the heat is being debated, there is no question that a significant and persistent heat source is present, possibly through tidal interactions as Enceladus orbits Saturn (Schneider *et al.*, 2007; Hansen *et al.*, 2008; Postberg *et al.*, 2009). Clearly, sufficient heat is present to generate the energetic flux of water vapor from the fissures and elevate the temperature

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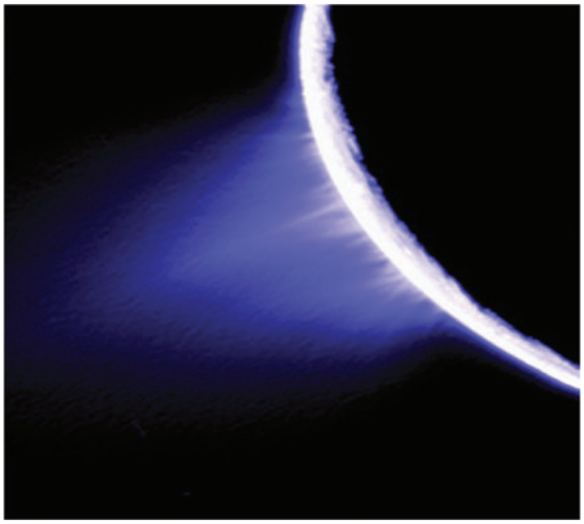

FIG. 1. False-color image of jets (blue areas) in the southern hemisphere of Enceladus taken with the Cassini spacecraft narrow-angle camera on November 27, 2005. This material has fed the diffuse Saturn E ring for at least three centuries. The individual jets that comprise the plume may also be discerned. Credit: NASA/JPL/Space Science Institute.

of the surrounding region. Substantial subsurface spatial temperature gradients are expected. It is possible that weathering of rocks by liquid water occurs beneath the icy surface. Enceladus' active hydrological cycle, where ice is heated and water vapor is expelled from the fissures (some of which coats its surface, resulting in Enceladus' extraordinarily high albedo), is a unique and promising new environment in which to trace organic chemical evolution and possibilities for life.

On Earth, there is life whenever there is an energy source, liquid water, and organics. This makes Enceladus one of the prime candidates for a mission to search for signatures of life (McKay *et al.,* 2008). The proposed Life Investigation For Enceladus (LIFE) mission would bring back particles of Enceladus in the search for evidence of life. The importance of sample returns from Enceladus, the science from sample analysis, and the key features of the LIFE mission concept are described below.

Cradle of LIFE

The probable presence of CO, CO_2, and N_2 suggests that embryonic formation of amino acids at any rock/liquid interfaces on Enceladus is feasible (Amend *et al.,* 2010). Ultraviolet photolysis results in chemistries that are highly variable, depending upon trace impurities. Additionally, the large spatial temperature gradient may be a driving force behind the generation of organic matter. The hydrological cycle on Enceladus, along with the action of energetic UV photons on water vapor, may result in the continuous production of hydrogen peroxide (H_2O_2). Photochemically produced H_2O_2 has been suggested as driving the evolution of oxygen-mediating enzymes, which leads to oxygenic photosynthesis (Liang *et al.,* 2007).

As a potential cradle of life, an active hydrological cycle on Enceladus may have an obvious advantage over an isolated subsurface ocean sealed beneath an ice crust, similar to those postulated for Europa and Ganymede, where without photosynthesis or contact with an oxidizing atmosphere the system would approach chemical equilibrium and annihilate ecosystems dependent on redox gradients unless there is a substantial alternative energy source (for example, geothermal). This thermodynamic tendency imposes severe constraints on any biota that is based on chemical energy (Gaidos *et al.,* 1999) but would be immaterial for Enceladus.

Cassini findings

Cassini's Ion and Neutral Mass Spectrometer (INMS), Cosmic Dust Analyzer (CDA), and Visual and Infrared Mapping Spectrometer (VIMS) detected and characterized the Enceladus plume up to 100 amu. These instruments confirmed that water dominates the active plume from Enceladus' south polar region (Hansen *et al.,* 2006; Spencer *et al.,* 2006; Waite *et al.,* 2006). It is important to note that none of Cassini's instruments were designed to analyze this type of material; hence the astrobiological potential beyond the identification of the liquid water and main chemical components has had to be inferred. Currently, Cassini is in the extend mission phase and is expected to continue to analyze the composition and flux of the plume at least to the year 2017. After that, no direct monitoring of the plume would be possible until a mission to Enceladus is developed and launched.

The INMS measured the gas composition of the plume to be H_2O ($\sim$90%), CO_2 (5%), CO or N_2 ($\sim$4%), and CH_4 ($\sim$1%), with other organic molecules consisting of C_nH_m ($<$1%) (Waite *et al.,* 2006) with subsequent data confirming that NH_3 and Ar and CO (rather than N_2) were present (Waite *et al.,* 2009). Additionally, E-ring ice particle composition has been determined by the CDA and found to contain Na, K, and other elements (Postberg *et al.,* 2009). The *in situ* detection of sodium in the E ring indicates that a subsurface ocean likely exists and provides a plausible site for complex organic chemistry and even biological processes (Matson *et al.,* 2007; McKay *et al.,* 2008; Parkinson *et al.,* 2008).

Importance of sample return

Significant new knowledge of the Moon, comets, and the Sun came from the highly in-depth analyses of samples returned by Apollo, Stardust (Brownlee *et al.,* 2003), and Genesis (Burnett *et al.,* 2009) missions, respectively. These in-depth analyses would not have been possible without the return of samples. Samples returned to the laboratory can be independently and repeatedly studied by multiple scientists with vastly different but complementary techniques and state-of-the art instruments. Laboratory study capitalizes on the adaptation of existing techniques or the development of new analysis techniques inconceivable at the time of instrument design. Since a consensus description of "life" as we know it on Earth has not been reached, the identification of "life" in the extraterrestrial environment is even more difficult (Nealson and Conrad, 1999; Pace, 2001). Having samples in hand would provide scientists from different disciplines the opportunity to synergistically question, define, and perform experiments for understanding "life" and provide relevant and effective planning for subsequent space exploration for life in the outer Solar System, which, of course, would be subject to limitations imposed by the amount of contamination—free material successfully captured and returned to Earth.

The recent confirmation of cometary glycine (a fundamental building block of proteins) from Stardust Wild 2 samples (Elsila *et al.*, 2009) showed that an amino acid can be captured and retained in a flyby mission without special preservation techniques. That this glycine could be determined as extraterrestrial, originating from the comet 81P/Wild 2 and not derived from Earth contaminants, was the result of 3 years of meticulous effort to perfect the measurement of the carbon isotopic ratio from extremely minute samples. This important finding indicates the presence of both free glycine and bound glycine precursors in comet 81P/Wild 2 and represents the first compound-specific isotopic analysis of a cometary organic compound. Similarly, years of nanoSIMS development enabled the isotopic measurements of H, C, and O in Stardust samples to a precision unachievable with *in situ* instrumentation (McKeegan *et al.*, 2006). X-ray fluorescence measured the chemical composition of the entire Wild 2 particle track 19 (860 μm long) captured by Stardust in aerogel as shown in Fig. 2 (Flynn *et al.*, 2006). The elemental identification was obtained at the synchrotron from the Argonne National Laboratory, which currently has no equivalent flight instrument. The intensities and distributions of multiple elemental compositions for the entire particle track were observed (only four elements are shown). This result delimits the elemental abundance present where the comet formed and gives clues as to the chemical makeup of the solar nebula.

Given the current sub-femtomole detection capability with the existing terrestrial instruments, future detection limits 20 years after launch promise unprecedented sensitivity approaching the single molecule scale (Armani *et al.*, 2007; Huang *et al.*, 2007; Harris *et al.*, 2008; Eid *et al.*, 2009). With these expected improvements in ground-based instrument sensitivities, many of the measurements for life detection deemed desirable, but not attainable, today would be achievable by some laboratories in the future; nevertheless, sensitivities and resolutions achievable in the laboratory will always be orders of magnitude greater than with *in situ* instrumentation.

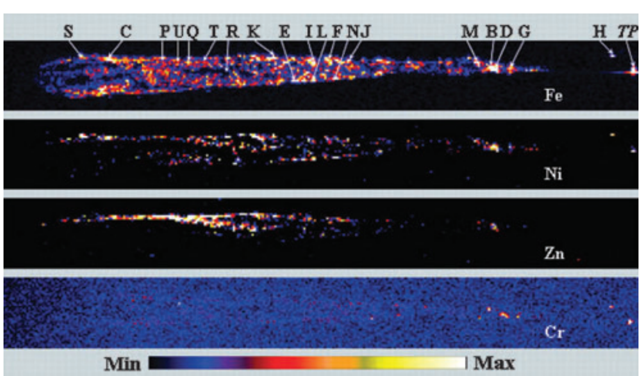

FIG. 2. X-ray fluorescence analysis of a Stardust Wild 2 particle made this 860 long track in the silica aerogel cell. Maps of Fe, Ni, Zn, and Cr fluorescence intensities were obtained with a step size of 3 pixels and a dwell time of 0.5 s/pixel. The 19 hot spots with the most intense concentration of elements (letters B, C to N, P to U) are indicated on the Fe map.

A complement to in situ *measurements*

Direct chemical and physical analysis of samples in terrestrial laboratories would almost always be preferred to *in situ* analysis. Due to the long flight qualification development process, *in situ* spaceflight instrument development tends to be about a decade behind the state of the art. For example, when Stardust was proposed in 1994, the standard for dust sample analysis was particles that were 15 μm or larger; and in 2006, when Stardust samples were returned, sample analyses were routinely conducted at submicron levels by utilizing the focused ion beam technique in the laboratory. Furthermore, for *in situ* instruments, all human judgments and actions as the necessary part of the measurement process had to be conceived and automated for a flight instrument, such as, for example, judging the state of the phenomenon to determine the best means of measurement, assessing the measurement environment as it affects the measurement, adapting the minimum intrusive handling techniques, and so on (Beegle *et al.*, 2008, 2009). Additionally, a sample return eliminates the mass, volume, power, adjustment, and maintenance restrictions imposed on *in situ* instruments. This allows synergistic modification of the laboratory-based measurement processes and equipment to achieve a measurement objective, for example, to validate cometary glycine (Elsila *et al.*, 2009). Returning a sample from an extraterrestrial body is a rare opportunity due to the prohibitive cost and the considerable risk of these missions; rare laboratory analysis of the extraterrestrial sample would compliment the more accessible *in situ* measurements made before sample return.

At Enceladus, the amount of material in the geysers is estimated to be ~150–300 kg/s, and when this material spreads out at the encounter height, it diffuses to approach ~1 ice particle per cubic meter at ~80 km, which makes *in situ* analysis of the trace molecules indicative of life (Beegle *et al.*, unpublished data) even more challenging. The amount of material collected by a fly-through would make even bulk chemical analysis difficult, much less the determination of habitability questions *in situ*. Definitive life-detection measurements require very high sensitivity, ultrahigh resolution, the consensus of repeated measurements, and peer reviews as demonstrated by the 3 years of meticulous improvement in laboratory instrumentations and measurement techniques that led to the proof of the first cometary glycine from Stardust (Elsila *et al.*, 2009).

Urgency in returning Enceladus samples

While understanding the processes of the formation of the Enceladus satellite and the subsurface ocean are important goals, this mission concept's most urgent purpose is the question of life: Does it exist, and has it existed in the liquid water jets of this outer planetary body? Other than comets, Enceladus is the only known planetary body that ejects its inner material in the form of jets, which enables the capture of this material by a low-cost flyby sample return mission. This time-critical mission for collecting and returning samples to Earth is "low hanging fruit" in planetary exploration and represents a rare and unique opportunity that should not be missed.

The size of the Saturn E ring suggests that the Enceladus plume has existed for at least three centuries (Feibelman, 1967). This does not mean, however, that the geysers have been continually active or that they would continue to persist in the foreseeable future. Since we do not know whether the plumes are continuously active, it makes sense to sample them as soon as practically possible. If the plume ceases, it would require a costly and risky operation, involving a lander mission that would locate and then drill through the crust (estimated to be several kilometers thick) to reach the liquid reservoir that feeds the geysers, a mission which may not be fiscally or even technically possible in the near to distant future. All these factors would contribute to, prevent, or delay important scientific findings from these samples that would potentially benefit the efficacy of future missions to Enceladus. Thus, an urgency for an early sample return mission to Enceladus as LIFE is warranted.

To reduce both the size of the launch vehicle and the mission duration, LIFE needs to be launched by 2019 to capitalize on a Jupiter gravity-assist opportunity, since the next Jupiter gravity-assist opportunity is 2058. This adds an additional urgency to the LIFE mission. The earliest flight opportunity in NASA could be the next Discovery mission.

E-ring samples

The E ring was first detected in 1966 in photographs taken during Earth's passage through the ring plane (Feibelman, 1967) and later confirmed (Kuiper, 1974). Saturn's E ring is a faint, diffuse ring that extends almost 1 million kilometers, from the orbit of Mimas out to the orbit of Titan. Spacecraft data on the E ring were provided by images and by charged particle absorption signatures obtained during the Pioneer 11 and Voyager flybys (Smith *et al.*, 1981, 1982; Sittler *et al.*, 1981; Carbary *et al.*, 1983; Hood, 1983). E-ring samples would not be pristine as compared to samples captured directly from the geysers, since they will have been processed by UV, galactic, cosmic, and solar radiation in varying duration (Haff *et al.*, 1983; Horanyi *et al.*, 2008). However, the ability to collect an enormous quantity of material from the E ring despite its exposure to radiation increases its value for analysis. Since the LIFE trajectory would cross the E ring multiple times, E-ring samples of various ages would also provide time series information on the nature of degradation and the aging process of organics at 10 AU.

Can aerogel retain volatiles?

Silica aerogel has the unique property of having a very high internal surface area that prevents the internal convection of molecules. Due to cost, provisions for the direct collection of volatiles on Stardust were descoped, so there were low expectations for the retention of organic volatiles collected from Wild 2. It was not expected that measurable labile organics would be found in the aerogel after 2 years of high space vacuum on the return flight (Tsou *et al.*, 2006). It has been shown that it is possible for organics in the aerogel medium to be differentiated from cometary organics (Sandford *et al.*, 2006). The optical images of Stardust Wild 2 tracks 4 and 6 are shown in Fig. 3 with the corresponding false-color IR images of the same tracks at the same scale below. Clearly, track 4 retained considerable organics, and track 6 did not. Infrared peaks are similarly measured at 3322 cm^{-1} (–OH), 2968 cm^{-1} (–CH_3), 2855 cm^{-1} (–CH_3 and –CH_2), and 1706 cm^{-1} (C=O), but only 2923 cm^{-1} (–CH_2) is shown

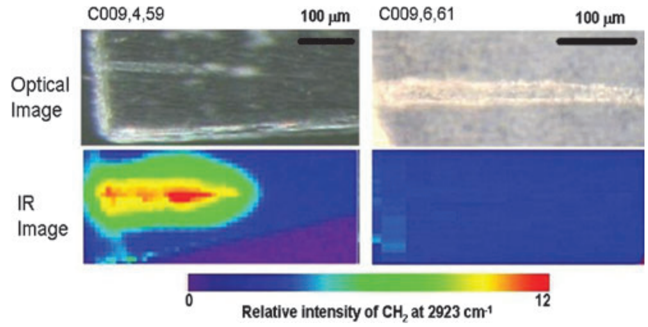

FIG. 3. Retention of CH_3 in aerogel. Optical images of track 59 from Stardust Wild 2 cell C009 showing strong IR CH_3 image below while no signal for track 61 from the same cell.

here. Infrared absorption bands extend beyond the visible edge of the particle track well into the surrounding aerogel. This distribution suggests that the incoming cometary particles contained an organic component that subsequently diffused into the surrounding aerogel. This material is not believed to be an effect of impact-altered organics from the aerogel because tracks of similar lengths and geometries were found in the same pieces of aerogel showing essentially no IR-detectable organics beyond those found in the original aerogel, as shown for track 6. All impacting particles with identical velocities and tracks of comparable length probably had similar impact energies. Consequently, similar amounts of organics in all tracks would be expected if this material came solely from the reprocessing of carbon in the aerogel. Also, if impact-driven oxidation of carbon in the original aerogel was occurring, the 1706 cm^{-1} C=O band might be expected to be seen in and around all tracks. Instead, C=O features are only seen in tracks that produced the other organic features. Finally, locations near tracks show no deficits of the -CH_3 original to the aerogel, which would be expected if this aerogel carbon component was being efficiently converted to other forms.

Related studies on Enceladus sample return

The Titan and Enceladus $1B Mission Feasibility Study (Reh *et al.*, 2007) and the Enceladus Flagship Mission Concept Study (Razzaghi *et al.*, 2007) were prepared for NASA's Planetary Science Division and addressed specifically the options for an Enceladus plume sample return. The National Research Council's (NRC) Decadal Survey commissioned an Enceladus mission study in 2010 on a range of mission concepts to Enceladus from orbiter, lander, and sample returns. The Titan and Enceladus $1B study concluded that the potential value of science for an Enceladus plume sample return is very high, but the mission was considered high risk due to sample capture speeds of greater than 10 km/s, mission durations of at least 18 years, and a cost of more than $1.3 billion. The Enceladus Flagship report also ranked an Enceladus flyby sample return to have very high potential science value, but the mission duration of 26 years was deemed too long, sample capture speeds of ~7 km/s were considered too high to be effective for capturing volatile material, and a single opportunity for sample collection was judged to be too high risk. The most recent Enceladus mission study considered sample return, but the cost was very high, partially due to planetary protection requirements for both inflight and ground mitigations. LIFE's mission concept resolves these concerns: it proposes a new trajectory design that would reduce the encounter speed to less than half that of Stardust (at 6.12 km/s) and consist of a mission duration of 13.5 years, well within the design lifetime of the current nuclear power sources, such as the Advanced Sterling Radioisotope Generator (ASRG).

Science from LIFE

It is evident from both the NRC decadal survey and NASA's Roadmaps that questions about life in the Solar System (searching for signatures of life, habitability, etc.) have been central to the US space exploration program. For example, the 2003 NRC Decadal Survey on Solar System Exploration defined four main themes: (1) The First Billion Years of Solar System History, (2) Volatiles and Organics: The Stuff of Life, (3) The Origin and Evolution of Habitable Worlds, and (4) Processes: How Planetary Systems Work. Twelve outstanding questions were identified within these four themes. Similarly, NASA's 2006 Solar System Exploration Roadmap and Science Mission Directorate Science Plan stated that a unifying theme for the exploration of our Solar System for the next three decades is habitability—the ability of worlds to support life (NASA, 2006).

In the search for life in the outer Solar System, NASA has focused on three targets—Europa, Titan, and Enceladus. Of the theories for the origin of life on Earth or Mars (Davis and McKay, 1996), three could apply to Enceladus, which makes it a very attractive target for astrobiological exploration: (1) origin in an organic-rich liquid water mixture, (2) origin in the redox gradient of a submarine vent, and (3) panspermia (McKay *et al.*, 2008). Each of these theories could be tested with the direct analysis of plume material (McKay *et al.*, 2008).

Finding chemical or biological evidence of extinct life on Enceladus would be, to put it mildly, sensational. The presence of extant life would be even more so and would revolutionize our understanding of the chemistry of life throughout the Universe and on Earth (McKay *et al.*, 2008).

Sample science

The proposed LIFE mission would advance scientific knowledge by returning samples from two satellites of Saturn: Enceladus, which has shown a potential to harbor life, and Titan, which is generally considered an analog to a prebiotic Earth with a substantial atmosphere and an active methane hydrological cycle. The primary science objective of LIFE would then be to capture, preserve, and return samples from the Enceladus plume (as shown in an artist's concept in Fig. 4), the Saturn E ring, and the upper Titan atmosphere. The secondary science objective of LIFE would be to perform improved *in situ* measurements complementary to Cassini's observations of both Enceladus and Titan with increased mass range and sensitivity. Titan would be a target of opportunity, since the flyby of Enceladus at low encounter speeds requires a Titan gravity assist. To reduce drag, a $\sim$750 km altitude would be targeted for the Titan flyby.

Since the Saturn E ring is generated by the Enceladus plume, ring samples make the stable components of the Enceladus plume available to sophisticated terrestrial laboratory instrumentations. As Titan has been called a prebiotic chemical factory, analysis of samples from its upper atmosphere would offer some detailed understanding of the complex organic chemistry and its processing by the 10 AU environment. In the sample return of Titan's atmosphere, LIFE would build upon the successful Stardust sampling approach while making significant augmentations to the sample collector to accommodate volatile samples by including a descoped continuous deposition collector to trap volatiles.

FIG. 4. Artist's conception of the Enceladus plume from the tiger stripes area with Saturn in view. Color images available online at www.liebertonline.com/ast

Specifically, the proposed LIFE mission would augment the Stardust success of capturing volatiles by (1) potentially reducing the sample capture speed to as low as 2 km/s, (2) reducing the aerogel entry density by a factor of 5, (3) maintaining sample temperatures well below the sample ambient temperature ($\sim$230 K), and (4) operating an active volatile trapping and sealing deposition collector. Reducing capture speeds and entry densities would result in a gentler capture by more than a hundredfold. Maintaining a freezing temperature would greatly increase volatile retention. The continuous deposition trapper would capture and seal the volatile samples until their safe Earth return.

The trajectory design for the LIFE concept would enable multiple flybys and multiple samplings of the Enceladus jets, each at a different altitude. The size and types of the grains in the jets would likely be altitude-varying. By capturing several samples, we could better understand the dynamics and the processing of jets. Capturing E-ring material of different ages would also give us a better understanding of the sublimation process and the survival of organic compounds in that environment with the passage of time. Multiple samples of Titan upper atmosphere might also allow us to capture more organic haze molecules.

In situ *measurements*

Like its Stardust heritage, the *in situ* measurements of LIFE would not only generate highly valuable science data instantaneously, they would also provide a valuable context for the collected samples. *In situ* measurements of the target environment at the moment of capture provide data that fully characterizes the target body, such as volatiles that might escape capture, degrade, or be lost after capture.

Cassini arrived at Saturn in July 2004, with an extended mission to 2017 to observe the spring and summer seasons. The earliest arrival of LIFE at Saturn would be 2023 in the fall season as shown in Fig. 5. At Enceladus, the proposed LIFE mission could determine the seasonal variability of the jets. Observations from mass spectrometry and IR spectrometry, and the composition, temperature, and grain size of the jets, especially the active regions within the "tiger stripes," would then be compared to Cassini's observations. The chemical compositions of the jets, especially of the larger >100 amu molecules, and grain flux would be ascertained. Rapid imaging of the jets in multiple flybys would help characterize the dynamics of jetting events.

At Titan's upper atmosphere, approximately 600–1200 km altitude, copolymers, aromatics, nitriles, and polyynes intermix (Lavvas *et al.*, 2008). These would be recorded *in situ* by a mass spectrometer with high mass range and a high resolution capability to distinguish these organics. A spectrometer sensitive to 2.7 and 5 μm bands can measure Titan's surface features and their organic composition, which would complement Cassini's observations for an additional season. Together, these *in situ* measurements would complete a seasonal observation of two Saturn satellites to supply added observations for astrobiological discussions of habitability and life in these compelling moons.

Trajectory

The trajectory for the LIFE concept was designed to meet both science and fiscal objectives (Landau, 2009): (1) its low-encounter speed reduces sample modification for greater intact capture and multiple sampling opportunities, and (2) its minimal mission duration reduces the operations cost for the mission. The outbound portion of LIFE's novel solution to these challenges is shown in Fig. 6. LIFE projects a sample encounter speed of potentially down to 3 km/s—Stardust encountered at 6.12 km/s—and a total mission duration in the range of 13.5 years. The encounter speed reduction would be achieved with a gravity assist from Titan

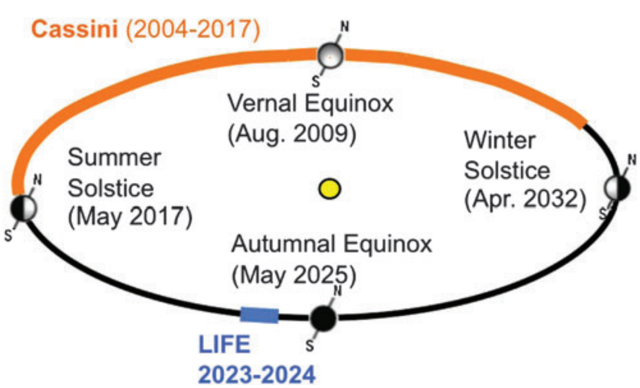

FIG. 5. Complementing the Saturn season. Cassini will cover the spring and summer seasons of Saturn while LIFE will cover the autumn season.

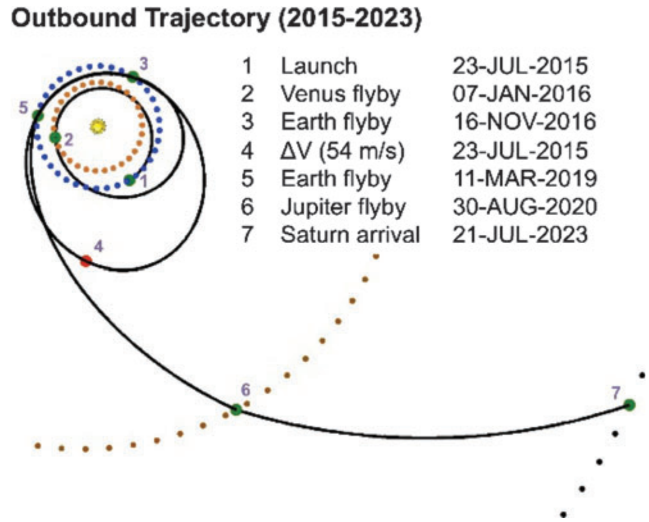

FIG. 6. Projected LIFE outbound trajectory. The outbound trajectory departs Earth for, respectively, Venus-, Earth-, and Jupiter-gravity assists, then a Saturn orbit insertion.

and would decrease the impact energy from Stardust by a factor of 4, thus offering a much gentler capture for the organic materials at Enceladus. This trajectory would also permit multiple sampling opportunities at Enceladus, which would allow sample captures of the plume from multiple altitudes, E-ring material of several ages, and particles from the upper Titan atmosphere. The 13.5-year total mission time would reduce operations cost and provide more rapid delivery of samples from Enceladus (the return portion of the trajectory is shown in Fig. 7). Table 1 presents key parameters for the trajectory design.

Payload

LIFE's sample capture and return instrument serve to provide the proposed primary science goal. The sample collector is a second-generation device that incorporates further improvements from Stardust and is complemented by an active volatiles collector descoped in Stardust. The high heritage *in situ* instruments offer both proven flight history and application to similar environment at the Enceladus, Saturn E-ring, and Titan upper atmosphere flybys. An optical navigation camera, as used in Stardust, would be shared for science imaging to capture the dynamics of the Enceladus jets.

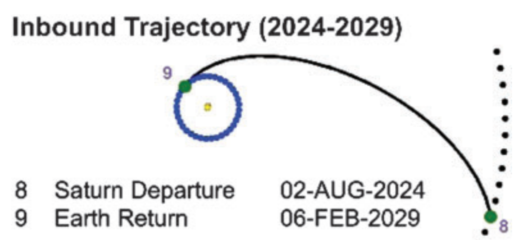

FIG. 7. Projected LIFE inbound trajectory. After 8 months of a Saturn tour, deorbits Saturn for a 5-year Earth direct return.

Table 1. LIFE Mission Design Parameters

Mission duration	13.5 year
Launch C3	16–18 km^2/s^2
Total mission delta-V	2.8–3.2 km/s
Number of Enceladus flybys	3–4
Sample collection speed	3–4.5 km/s
Earth entry speed	16 km/s
Spacecraft wet mass (MEV)	1190–1360 kg
Atlas 401 launch mass	1980 kg (for max C3)

Sample collector

The sample collection and retention instrument would consist of an upgraded silica aerogel collector originally flown successfully on Stardust. One instrument concept under consideration consists of a rotating collector of aerogel that has the capacity to expose one or more designated sectors at a time, as shown in Fig. 8. This would allow multiple samplings at each of the three different target bodies (Enceladus plume, Saturn E ring, and Titan upper atmosphere). The first significant improvement to aerogel is reducing the surface density at the top of the aerogel to 2 mg/mL (the density of air is 1.3 mg/mL). This reduces the Stardust aerogel density (about 10 mg/mL) by a factor of 5. Combining the sample encounter speed reduction with this density reduction would result in reduction of shock energy by a factor of at least 20. Since aluminum foil proved to be very successful for small grain collection on Stardust, a soft and pure foil would also be used for LIFE. Another significant augmentation to the Stardust collector consists of maintaining the captured samples in a frozen state at all times. If the sample were to be maintained at temperatures much below freezing, it would exasperate the cold finger effect upon return to Earth, and the sample would be severely contaminated by atmospheric organics that are several orders of magnitude higher than the returned samples.

Based on the number of tracks examined by Stardust, 10 particles per target per flyby would be more than adequate for a productive preliminary examination. Thus, a smaller collector vessel would be more amenable to maintaining a freezing temperature.

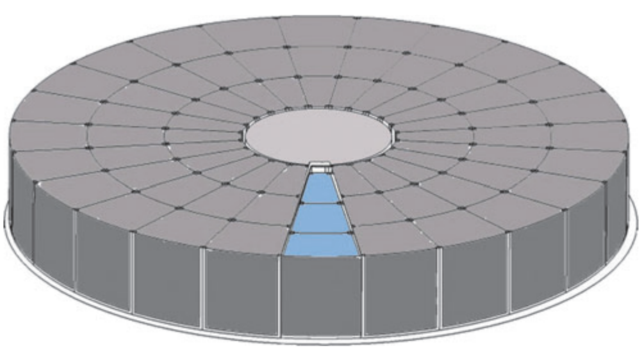

FIG. 8. Fifty-centimeter rotating collector exposes the selected blue aerogel cells for a selected sample target and flyby collection. The central circular area is a soft metal area for volatile collection.

Active volatiles collector

The active volatile collector would capture the incoming volatiles and seal them by continuous deposition of different vaporizing materials onto several different substrates. To provide for a broad spectrum of volatile types and a wide range of analysis techniques, multiple subliming materials (metallic and nonmetallic) made into filaments and several substrates (Al, sapphire, or Au) would be considered (Hohenberg *et al.,* 1997).

In situ *payload*

Cassini results have suggested the existence of larger organic molecules with intriguing astrobiological possibilities in both the Enceladus jets and Titan's atmosphere. The proposed LIFE payload would include a mass spectrometer with significantly greater mass resolution than the 99 amu resolution of the Cassini INMS. To control cost, only *in situ* instruments with high heritage would be considered, with foreign contributions preferred.

CHIMS

The CHopper/Ion Neutral Mass Spectrometer (CHIMS) is an improved and upgraded mass spectrometer for ion and neutral analysis based upon the ROSINA, which is flying on the Rosetta Mission toward 67P/Churyumov-Gerasimeno as shown in Fig. 9, but with half the mass and nearly half the power. At Enceladus, CHIMS would determine the composition of the *in situ* atmosphere and the velocity of charged volatiles. CHIMS is a reflectron type time-of-flight mass spectrometer with a mass range of 1 to >300 amu and a mass resolution of 5000. This instrument is optimized for high sensitivity ($M/\Delta M$) over a very broad mass range. The second sensor is comprised of two pressure gauges that would provide density and velocity measurements of the volatiles (Balsiger *et al.,* 2007). CHIMS is a contributed instrument.

Opnav camera

Since optical navigation is needed for target acquisition, an imaging camera—an engineering instrument—would be required. Dynamic images of the jets can be acquired with this engineering camera (as successfully implemented in the Stardust mission). Multiple images from this camera would elucidate the process of jet formation and the dynamics within the jets.

Flight Hardware

The LIFE flight system utilizes a strong heritage of previous deep space missions with new design improvements

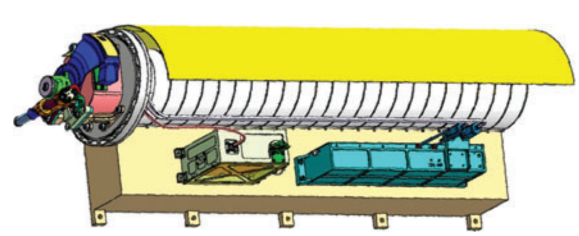

FIG. 9. CHIMS is an improved and upgraded ROSINA time-of-flight mass spectrometer and pressure sensor instrument with a shutter to prevent contamination.

that maximize the sample return capacity from the Saturn system. Improved sample collection hardware builds on the Stardust aerogel design to accommodate multiple collection opportunities and provide impact protection as for Stardust. The return capsule design, an enhanced version of the successful Hayabusa recovery system, would allow greater material return. Fully redundant spacecraft elements first utilized on Deep Impact, with Ka-band communication improvements from Kepler, provide the core elements of the spacecraft. A high efficiency dual-mode propulsion system would re-fly components from the Cassini and MESSENGER missions. The power system takes advantage of NASA development of ASRGs to provide consistent flight system power, independent of distance from the Sun. Figure 10 shows the flight system configuration, and Table 2 shows the preliminary key flight element parameters.

Mission operation costs are minimized and flight safety improved by utilizing hibernation modes and auto navigation techniques developed on Deep Impact. Multi-stage debris shield techniques based on Deep Impact designs protect critical spacecraft components from high-speed dust impacts. A 440 N bipropellant main engine provides sufficient thrust and high Isp to support trajectory corrections, Saturn capture and escape, and capsule return. Multiple gravity assists from Jupiter and Titan lower the required delta-V to current chemical propulsion capability levels.

Spacecraft thermal control maintains the sample collectors below freezing and avionics temperatures between 0–50°C at all times. Fuel is maintained above 10°C by recovering about 150 W of ASRG waste heat. Deep Impact, Stardust, and other Discovery missions have demonstrated that a NASA Class C

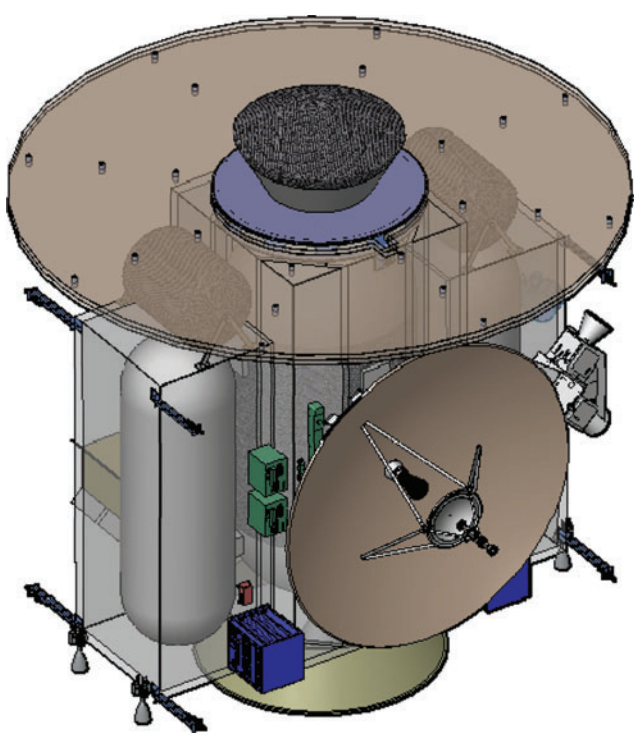

FIG. 10. The LIFE flight system includes a sample return system (top), debris shield, ASRG power (back), Ka-band 2.5 m telecom antenna, and 900 kg of MMH/NTO propellant capacity.

TABLE 2. FLIGHT SYSTEM KEY PARAMETERS

Parameter	*Design point*
Design life	13.5 years
Launch vehicle compatibility	ELV Atlas V 401
Minimum fairing size	Atlas standard 4 m fairing
Flight system wet mass	1586 kg at launch
Attitude control	3 Axis stabilized w/stellar inertial, <0.03 pointing accuracy, 3s
Propulsion	Dual mode w/440N main engine—2.8–3.2 km/s dV
Command and data handling	Redundant RAD750 avionics with 53 Gbit science storage
Navigation	RF ranging w/Optical Nav. Rendezvous
Electrical Power	Two ASRGs providing 245 W EOL
Communications	Ka band to 34 m DSN, 42.5 kbps at 10 AU
Payloads	Sample system, ROSINA, VIRTIS, dust counter
Sample return capsule	Hayabusa-based 34 kg capsule

spacecraft can remain fully operational for long missions and successfully return samples to Earth, thus providing confidence that the 13.5-year duration required for the proposed LIFE mission would be successful within reasonable cost constraints.

The LIFE mission design and flight hardware is compatible with a standard Atlas V ELV. Figure 11 shows the vehicle fit into the 4 m fairing static envelope. Preliminary mass properties and launch margins are shown in Table 3.

Due to the more than 2 h of round-way light time to Saturn, all operational decisions have to be autonomous. The Deep Impact and follow-on EPOXI missions have demonstrated the feasibility of autonomous navigation for such encounters. The EPOXI mission has also shown that a Stardust Class C spacecraft can remain fully operational for many years in deep space, providing confidence that the 13.5-year duration required for the proposed LIFE mission could be met within reasonable cost constraints.

Cost

Cost has been an increasing challenge for spaceflights. The LIFE concept faces inherent hurdles due to the tremendous distance to Saturn and the need for Earth sample return. The most cost-effective and low-risk approach is to adapt as much as possible from the two successful robotic sample return missions: Stardust and the recently successful Hayabusa mission. The proposed LIFE mission's next NASA flight opportunity could be the next Discovery mission solicitation.

The 2010 Discovery Announcement of Opportunity offered a cost cap of $425 million along with a basic launch vehicle and up to two ASRGs as Government Furnished Equipment. In a favorable scenario, LIFE could fit within a future Discovery cost cap if similar Government Furnished Equipment were provided along with a contribution for the sampling and Earth return portions of the mission.

Cost for any large endeavor is very dependent on the project management mindset. The essence of any significant on-cost and on-schedule flight project must include

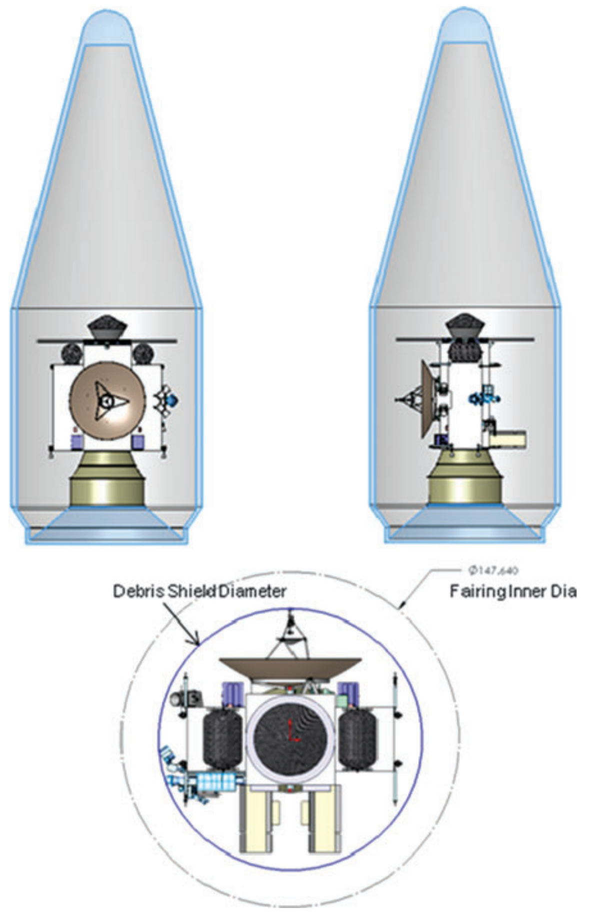

FIG. 11. The LIFE flight system is fully compatible with the Atlas V 401 launch vehicle.

deliberate and careful establishment and implementation of rigorous cost control objectives equal in vigor to any science and engineering requirements as demonstrated by Stardust. Key science participants of Stardust are with LIFE; their participation would ensure the concerted discipline of a design-to-cost mindset to achieve another on-cost and on-schedule replication (Tsou, 2009).

Planetary Protection

Understanding conditions under the ice sheet of Enceladus and identifying potential extant life on Enceladus are the main reason for flying the proposed LIFE sample return mission. To protect Enceladus from terrestrial contamination were the LIFE spacecraft to crash at the surface, and to protect Earth from extraterrestrial contamination from Enceladus, we would have to ensure a sterile spacecraft and the ability for the sample return capsule to break the chain of contact from Enceladus to surfaces in contact with Earth during entry, descent, and landing.

The Committee for Space Research (COSPAR) maintains the planetary protection policy for bodies in the Solar System. There are five categories of space missions ranging from completely unrestricted to the Earth return of potential biology. The proposed LIFE mission is defined as the strictest type, a Category V mission, and fits under the most extensive planetary protection requirements. The exact requirements are not yet worked out and would have to be addressed by a combination of COSPAR and the planetary protection officer at NASA Headquarters in conjunction with the principal investigator of the LIFE mission. We are refining what these requirements would likely be, but at the minimum they would include complete system level contamination controls, minimization of the potential for crashing on sample return, breaking the chain of contact with the sample return capsule, and quarantining the sample until a full biological analysis of sample hazards had been determined. The closest analogue to Enceladus is Europa, which has some of its planetary protection requirements worked out (NRC, 1999, 2000; Raulin *et al.*, 2010). We are assuming that a Viking-level system sterilization, heating the entire spacecraft to over 125°C, would be necessary to ensure the elimination of bioload. An added step of cleaning the collection materials before system sterilization would have to be performed in order to remove the nonviable microbes and the possibility of false positives. This cleaning of hardware may have to occur through plasma cleaning or baking under high pressure and temperature (500°C).

Stardust was categorized as a Category 5 unrestricted return by NASA Planetary Protection Officer Michael Meyers during phase B in 1995 (M. Meyers, personal communication, 1995). This status was confirmed by John Rummel, NASA Planetary Protection Officer at the time of sample return in 2006. The proposed LIFE mission would replicate the method and medium of intact capture at hypervelocity utilized by the Stardust mission (Tsou *et al.*, 2003), albeit with significant density reduction of the aerogel capture medium. The actual amount of the sample mass collected by LIFE would be less than the mass returned by Stardust. Since the mission concept envisions that LIFE samples would be kept frozen at all times, the dissipation of the returned ice would be greatly reduced. Like Stardust, the second robotic sample return by Hayabusa was granted similar unrestricted status for its returned samples as confirmed by COSPAR. Without this unrestricted status, the cost for planetary protection alone could exceed the cost estimate for the proposed LIFE mission. Consequently, the impact of planetary protection costs would have a potential extinguishing effect on LIFE and other sample return missions.

TABLE 3. FLIGHT SYSTEMS MASS PROPERTIES

Parameter	*Mass (kg)*
Spacecraft, dry	590
Payloads	96
Flight system, dry	686
Propellant	900
Flight system, wet	1586
Atlas V 401 Performance per NLS-III@c3 = 18 km^2/s^2	2035

Conclusion

After the January 2006 return of the Stardust samples, its unexpected and extraordinary results have been reported in the December 2006 special issue of *Science* (Brownlee *et al.*, 2006; Flynn *et al.*, 2006; Hörz *et al.*, 2006; Keller *et al.*, 2006;

McKeegan *et al.*, 2006; Sandford *et al.*, 2006; Zolensky *et al.*, 2006). Since that special issue, there have been more than 50 publications each year on the Stardust samples (Brownlee *et al.*, 2007, 2008, 2009, 2010, 2011). Sample return missions are missions that continually yield results long after the preliminary examination of the returned samples is completed (Moseman, 2009). In its search for evidence of life in the outer planets, the proposed LIFE mission would make profound scientific contributions to astrobiology as did its predecessor Stardust for Kuiper belt objects and the formation of the Solar System. LIFE's significant contributions, however, would extend beyond increasing our knowledge of the outer Solar System, as it would also impact subsequent missions in their pursuit of understanding the habitability and potential for life on Enceladus.

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Abbreviations

ASRG, Advanced Sterling Radioisotope Generator; CDA, Cosmic Dust Analyzer; CHIMS, CHopper/Ion Neutral Mass Spectrometer; COSPAR, Committee for Space Research; INMS, Ion and Neutral Mass Spectrometer; LIFE, Life Investigation For Enceladus; NRC, National Research Council.

References

Amend, J.P., McCollom, T.M., Hentscher, M., and Bach, W. (2010) Geochemical energy for life in deep-sea hydrothermal systems [abstract 5134]. In *Astrobiology Science Conference 2010: Evolution and Life: Surviving Catastrophes and Extremes on Earth and Beyond,* LPI contribution No. 1538, Lunar and Planetary Institute, Houston.

Armani, A.M., Kulkarni, R.P., Fraser, S.E., Flagan, R.C., and Vahala, K.J. (2007) Label-free, single-molecule detection with optical microcavities. *Science* 317:783–787.

Balsiger, H., Altwegg, K., Bochsler, P., Eberhardt, P., Fischer, J., Graf, S., and the ROSINA team. (2007) Rosetta Orbiter Spectrometer for Ion and Neutral Analysis. *Space Sci Rev* 128:745–801.

Beegle, L.W., Johnson, P.V., Hoydess, R., Mielke, R., Orzechowska, G.E., Sollitt, L., and Kanik, I. (2008) Toward the *in situ* quantification of organic molecules in solid samples: development of sample handling and processing hardware. *Geochim Cosmochim Acta* 72:A66.

Beegle, L.W., Feldman, S., Johnson P.V., and Dreyer, C.B. (2009) Instruments for *in-situ* sample analysis. In *Drilling in Extreme Environments: Penetration and Sampling on Earth and Other Planets*, edited by Y. Bar-Cohen and K. Zacny, Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, pp 643–706.

Brownlee D.E., Tsou, P., Anderson, J.D., Hanner, M.S., Newburn, R.L., Sekanina, Z., Clark, B.C., Hörz, F., Zolensky, M.E., Kissel, J., McDonnell, J.A.M., Sandford, S.A., and Tuzzolino, A.J. (2003) Stardust: Comet and interstellar dust sample return mission. *J Geophys Res* 108, doi:10.1029/2003JE002087.

Brownlee, D., Tsou, P., Aléon, J., Alexander, C.M., Araki, T., Bajt, S., Baratta, G.A., Bastien, R., Bland, P., Bleuet, P., Borg, J., Bradley, J.P., Brearley, A., Brenker, F., Brennan, S., Bridges, J.C., Browning, N.D., Brucato, J.R., Bullock, E., Burchell, M.J., Busemann, H., Butterworth, A., Chaussidon, M., Cheuvront, A., Chi, M., Cintala, M.J., Clark, B.C., Clemett, S.J., Cody, G., Colangeli, L., Cooper, G., Cordier, P., Daghlian, C., Dai, Z., D'Hendecourt, L., Djouadi, Z., Dominguez, G., Duxbury, T., Dworkin, J.P., Ebel, D.S., Economou, T.E., Fakra, S., Fairey, S.A., Fallon, S., Ferrini, G., Ferroir, T., Fleckenstein, H., Floss, C., Flynn, G., Franchi, I.A., Fries, M., Gainsforth, Z., Gallien, J.P., Genge, M., Gilles, M.K., Gillet, P., Gilmour, J., Glavin, D.P., Gounelle, M., Grady, M.M., Graham, G.A., Grant, P.G., Green, S.F., Grossemy, F., Grossman, L., Grossman, J.N., Guan, Y., Hagiya, K., Harvey, R., Heck, P., Herzog, G.F., Hoppe, P., Hörz, F., Huth, J., Hutcheon, I.D., Ignatyev, K., Ishii, H., Ito, M., Jacob, D., Jacobsen, C., Jacobsen, S., Jones, S., Joswiak, D., Jurewicz, A., Kearsley, A.T., Keller, L.P., Khodja, H., Kilcoyne, A.L., Kissel, J., Krot, A., Langenhorst, F., Lanzirotti, A., Le, L., Leshin, L.A., Leitner, J., Lemelle, L., Leroux, H., Liu, M.C., Luening, K., Lyon, I., Macpherson, G., Marcus, M.A., Marhas, K., Marty, B., Matrajt, G., McKeegan, K., Meibom, A., Mennella, V., Messenger, K., Messenger, S., Mikouchi, T., Mostefaoui, S., Nakamura, T., Nakano, T., Newville, M., Nittler, L.R., Ohnishi, I., Ohsumi, K., Okudaira, K., Papanastassiou, D.A., Palma, R., Palumbo, M.E., Pepin, R.O., Perkins, D., Perronnet, M., Pianetta, P., Rao, W., Rietmeijer, F.J., Robert, F., Rost, D., Rotundi, A., Ryan, R., Sandford, S.A., Schwandt, C.S., See, T.H., Schlutter, D., Sheffield-Parker, J., Simionovici, A., Simon, S., Sitnitsky, I., Snead, C.J., Spencer, M.K., Stadermann, F.J., Steele, A., Stephan, T., Stroud, R., Susini, J., Sutton, S.R., Suzuki, Y., Taheri, M., Taylor, S., Teslich, N., Tomeoka, K., Tomioka, N., Toppani, A., Trigo-Rodríguez, J.M., Troadec, D., Tsuchiyama, A., Tuzzolino, A.J., Tyliszczak, T., Uesugi, K., Velbel, M., Vellenga, J., Vicenzi, E., Vincze, L., Warren, J., Weber, I., Weisberg, M., Westphal, A.J., Wirick, S., Wooden, D., Wopenka, B., Wozniakiewicz, P., Wright, I., Yabuta, H., Yano, H., Young, E.D., Zare, R.N., Zega, T., Ziegler, K., Zimmerman, L., Zinner, E., and Zolensky, M. (2006) Comet 81P/Wild 2 under a microscope. *Science* 314:1711–1716.

Brownlee, D.E., Joswiak, D., Matrajt, G., Gainsforth, Z., Butterworth, A., Fakra, A.S., Marcus, M.A., Snead, C., and Westphal, A.J. (2007) Coordinated mineralogical autopsy of a fragment-rich comet particle collected by Stardust. *70th Annual Meteoritical Society Meeting, Meteoritics and Planetary Science Supplement*, Vol. 42, p 5148.

Brownlee, D.E., Tsou, P., Joswiak, D., Matrajt, G., and Bradley, J (2008) Analysis of comet particles collected by the Stardust mission, findings versus expectations [abstract 8262]. In *Asteroids, Comets, Meteors 2008,* LPI Contribution No. 1405, Lunar and Planetary Institute, Houston.

Brownlee, D.E., Joswiak, D., Matrajt, G., Messenger, S., and Ito, M. (2009) Silicon carbide in Comet Wild 2 & the abundance of pre-solar grains in the Kuiper Belt [abstract 2195]. In *40th Lunar and Planetary Science Conference Abstracts,* Lunar and Planetary Institute, Houston.

Brownlee, D.E., Joswiak, D., Matrajt, G., Ramien, N., Bradley, J., Ishii, H., Westphal, A.J., and Gainforth, Z. (2010) The nature of moderately fragmenting comet dust: case studies of Tracks 25 (Inti) and Track 77 [abstract 2146]. In *41st Lunar and Planetary Science Conference Abstracts,* Lunar and Planetary Institute, Houston.

Brownlee, D.E., Joswiak, D., and Matrajt, G. (2011) Large coarse-grained solid particles in comets—a ubiquitously distributed component in the solar nebula? [abstract 2235]. In *42nd Lunar and Planetary Science Conference Abstracts,* Lunar and Planetary Institute, Houston.

Burnett, D.S. (2009) Genesis discovery mission science results. In *Highlights of Astronomy,* Vol. 14, edited by K. van der Hucht, Cambridge University Press, Cambridge, pp 321–322.

Carbary, J.F., Kirmigis, S.M., and Ip., W.-H. (1983) Energetic particle microsignatures of Saturn's satellites. *J Geophys Res* 88:8947–8958.

Davis, W.L. and McKay, C.P. (1996) Origins of life: a comparison of theories and application to Mars. *Orig Life Evol Biosph* 26:61–73.

Eid, J., Fehr, A., Gray, J., Luong, K., Lyle, J., Otto, G., Peluso, P., Rank, D., Baybayan, P., Bettman, B., Bibillo, A., Bjornson, K., Chaudhuri, B., Christians, F., Cicero, R., Clark, S., Dalal, R., Dewinter, A., Dixon, J., Foquet, M., Gaertner, A., Hardenbol, P., Heiner, C., Hester, K., Holden, D., Kearns, G., Kong, X., Kuse, R., Lacroix, Y., Lin, S., Lundquist, P., Ma, C.C., Marks, P., Maxham, M., Murphy, D., Park, I., Pham, T., Phillips, M., Roy, J., Sebra, R., Shen, G., Sorenson, J., Tomaney, A., Travers, K., Trulson, M., Vieceli, J., Wegener, J., Wu, D., Yang, A., Zaccarin, D., Zhao, P., Zhong, F., Korlach J., and Turner, S. (2009) Real-time DNA sequencing from single polymerase molecules. *Science* 323:133–138.

Elsila, J.E., Glavin, D.P., and Dworkin, J.P. (2009) Cometary glycine detected in samples returned by Stardust. *Meteorit Planet Sci* 44:1323–1330.

Feibelman, W.A. (1967) Concerning the "D" ring of Saturn. *Nature* 214:793–794.

Flynn, G.J., Bleuet, P., Borg, J., Bradley, J.P., Brenker, F.E., Brennan, S., Bridges, J., Brownlee, D.E., Bullock, E.S., Burghammer, M., Clark, B.C., Dai, Z.R., Daghlian, C.P., Djouadi, Z., Fakra, S., Ferroir, T., Floss, C., Franchi, I.A., Gainsforth, Z., Gallien, J.P., Gillet, P., Grant, P.G., Graham, G.A., Green, S.F., Grossemy, F., Heck, P.R., Herzog, G.F., Hoppe, P., Hörz, F., Huth, J., Ignatyev, K., Ishii, H.A., Janssens, K., Joswiak, D., Kearsley, A.T., Khodja, H., Lanzirotti, A., Leitner, J., Lemelle, L., Leroux, H., Luening, K., Macpherson, G.J., Marhas, K.K., Marcus, M.A., Matrajt, G., Nakamura, T., Nakamura-Messenger, K., Nakano, T., Newville, M., Papanastassiou, D.A., Pianetta, P., Rao, W., Riekel, C., Rietmeijer, F.J., Rost, D., Schwandt, C.S., See, T.H., Sheffield-Parker, J., Simionovici, A., Sitnitsky, I., Snead, C.J., Stadermann, F.J., Stephan, T., Stroud, R.M., Susini, J., Suzuki, Y., Sutton, S.R., Taylor, S., Teslich, N., Troadec, D., Tsou, P., Tsuchiyama, A., Uesugi, K., Vekemans, B., Vicenzi, E.P., Vincze, L., Westphal, A.J., Wozniakiewicz, P., Zinner, E., and Zolensky, M.E. (2006) Elemental compositions of Comet 81P/Wild 2 samples collected by Stardust. *Science* 314:1731–1735.

Gaidos, E.J., Nealson, K.H., Jayakumar, P., and Kirschvink, J.L. (1999) Molecular inferences in the origin of oxidant-associated enzymes [abstract 7484]. In *Ninth Annual V. M. Goldschmidt Conference,* Lunar and Planetary Institute, Houston.

Haff, P.K., Siscoe, G.L., and Eviatar, A. (1983) Ring and plasma—the enigmae of Enceladus. *Icarus* 56:426–438.

Hansen, C.J., Esposito, L., Stewart, A.I.F., Colwell, J., Hendrix, A., Pryor, W., Shemansky, D., and West, R. (2006) Enceladus' water vapor plume. *Science* 311:1422–1425.

Hansen, C.J., Esposito, L.W., Stewart, A.I.F., Meinke, B., Wallis, B., Colwell, J.E., Hendrix, A.R., Larsen, K., Pryor, W., and Tian, F. (2008) Water vapor jets inside the plume of gas leaving Enceladus. *Nature* 456:477–479.

Harris, T.D., Buzby, P.R., Babcock, H., Beer, E., Bowers, J., Braslavsky, I., Causey, M., Colonell, J., Dimeo, J., Efcavitch, J.W., Giladi, E., Gill, J., Healy, J., Jarosz, M., Lapen, D., Moulton, K., Quake, S.R., Steinmann, K., Thayer, E., Tyurina, A., Ward, R., Weiss, H., and Xie, Z. (2008) Single-molecule DNA sequencing of a viral genome. *Science* 320:106–109.

Hohenberg, C., Thonnard, N., Kehm, K., Meshik, A., Berryhill, A., and Glenn, A. (1997) Active capture of low-energy volatiles: bringing back gases from a cometary encounter [abstract 1522]. In *28th Lunar and Planetary Science Conference Abstracts,* Lunar and Planetary Institute, Houston.

Hood, L.L. (1983) Radial diffusion in Saturn's radiation belts: a modeling analysis assuming satellite and E ring absorption. *J Geophys Res* 88:808–818.

Horanyi, M., Juhasz, A., and Morfill, G.E. (2008) Large-scale structure of Saturn's E-ring. *Geophys Res Lett* 35:L04203.

Hörz, F., Bastien, R., Borg, J., Bradley, J.P., Bridges, J.C., Brownlee, D.E., Burchell, M.J., Chi, M., Cintala, M.J., Dai, Z.R., Djouadi, Z., Dominguez, G., Economou, T.E., Fairey, S.A., Floss, C., Franchi, I.A., Graham, G.A., Green, S.F., Heck, P., Hoppe, P., Huth, J., Ishii, H., Kearsley, A.T., Kissel, J., Leitner, J., Leroux, H., Marhas, K., Messenger, K., Schwandt, C.S., See, T.H., Snead, C., Stadermann, F.J., I, Stephan, T., Stroud, R., Teslich, N., Trigo-Rodríguez, J.M., Tuzzolino, A.J., Troadec, D., Tsou, P., Warren, J., Westphal, A., Wozniakiewicz, P., Wright, I., and Zinner, E. (2006) Impact features on Stardust: implications for comet 81P/Wild 2 dust. *Science* 314:1716–1719.

Huang, B., Wu, H.K., Bhaya, D., Grossman, A., Granier, S., Kobilka, B.K., and Zare, R.N. (2007) Counting low-copy number proteins in a single cell. *Science* 315:81–84.

Keller, L.P., Bajt, S., Baratta, G.A., Borg, J., Bradley, J.P., Brownlee, D.E., Busemann, H., Brucato, J.R., Burchell, M., Colangeli, L., d'Hendecourt, L., Djouadi, Z., Ferrini, G., Flynn, G., Franchi, I.A., Fries, M., Grady, M.M., Graham, G.A., Grossemy, F., Kearsley, A., Matrajt, G., Nakamura-Messenger, K., Mennella, V., Nittler, L., Palumbo, M.E., Stadermann, F.J., Tsou, P., Rotundi, A., Sandford, S.A., Snead, C., Steele, A., Wooden, D., and Zolensky, M. (2006) Infrared spectroscopy of comet 81P/Wild 2 samples returned by Stardust. *Science* 314:1728–1731.

Kuiper, G.P. (1974) On the origin of the Solar System I. *Celestial Mechanics* 9:321–348.

Landau, D. (2009) Low-time-of-flight trajectory for Enceladus sample return mission. Private communication.

Lavvas, P.P., Coustenis, A., and Vardavas, I.M. (2008) Coupling photochemistry with haze formation in Titan's atmosphere, part II: results and validation with Cassini/Huygens data. *Planet Space Sci* 56:67–99.

Liang, M.-C., Heays, A.N., Lewis, B.R., Gibson, S.T., and Yung, Y.L. (2007) Source of nitrogen isotope anomaly in HCN in the atmosphere of Titan. *Astrophys J* 664:L115–L118.

Matson, D.L., Castillo-Rogez, J.C., Vance, S.D., Davies, A.G., Johnson, T.V. (2007) The early history of Enceladus: setting the scene for today's activity [abstract 6052]. In *Workshop on Ices, Oceans, and Fire: Satellites of the Outer Solar System,* LPI Contribution No. 1357, Lunar and Planetary Institute, Houston.

McKay, C.P., Porco, C.C., Altheide, T., Davis, W.L., and Kral, T.A. (2008) The possible origin and persistence of life on Enceladus and detection of biomarkers in the plume. *Astrobiology* 8:909–919.

McKeegan, K.D., Aléon, J., Bradley, J., Brownlee, D., Busemann, H., Butterworth, A., Chaussidon, M., Fallon, S., Floss, C., Gilmour, J., Gounelle, M., Graham, G., Guan, Y., Heck, P.R., Hoppe, P., Hutcheon, I.D., Huth, J., Ishii, H., Ito, M., Jacobsen, S.B., Kearsley, A., Leshin, L.A., Liu, M.C., Lyon, I., Marhas, K., Marty, B., Matrajt, G., Meibom, A., Messenger, S., Mostefaoui, S., Mukhopadhyay, S., Nakamura-Messenger, K., Nittler, L., Palma, R., Pepin, R.O., Papanastassiou, D.A., Robert, F., Schlutter, D., Snead, C.J., Stadermann, F.J., Stroud, R., Tsou, P., Westphal, A., Young, E.D., Ziegler, K., Zimmermann, L., and Zinner, E. (2006) Isotopic compositions of cometary matter returned by Stardust. *Science* 314:1724–1728.

Moseman, A. (2009) NASA's greatest mission? Stardust finds amino acids, keeps on giving to science. *Popular Mechanics* (*see* http://www.popularmechanics.com/science/space/nasa/4328452).

NASA. (2006) *Solar System Exploration,* the 2006 Solar System Exploration Roadmap for NASA's Science Mission Directorate, National Aeronautics and Space Administration, Washington DC.

Nealson, K.H. and Conrad, P.G. (1999) Life: past, present and future. *Philos Trans R Soc Lond B Biol Sci* 354:1923–1939.

NRC, A Science Strategy for the Exploration of Europa (1999) ISBN 0309064937, *Committee on Planetary and Lunar Exploration, National Research Council*.

NRC, Preventing the Forward Contamination of Europa (2000) ISBN NI000231, *Task Group on the Forward Contamination of Europa, Space Studies Board, National Research Council*.

Pace, N.R. (2001) The universal nature of biochemistry. *Proc Natl Acad Sci USA* 98:805–808.

Parkinson, C.D., Liang, M.-C., Yung, Y.L., and Kirschivnk, J.L. (2008) Habitability of Enceladus: planetary conditions for life. *Orig Life Evol Biosph* 38:355–369.

Porco, C. and Team, C. (2006) The geysers of Enceladus: an overview of Cassini results [abstract #P22B-01]. In *AGU Fall Meeting 2006,* American Geophysical Union, Washington DC.

Postberg, F., Kempf, S., Schmidt, J., Brilliantov, N., Beinsen, A., Abel, B., Buck, U., and Srama, R. (2009) Salt-ice grains from Enceladus' plumes: frozen samples of a subsurface ocean. In *EPSC Abstracts,* Vol. 4, European Planetary Science Congress, p. 411.

Raulin, F., Hand, K.P., McKay, C.P., and Viso, M. (2010) Exobiology and planetary protection of icy moons. *Space Sci Rev* 153:511–535.

Razzaghi, A.I., Bly, V., Di Pietro, D., Quinn, D., Sneiderman, G., Tompkins, S., Via, L., Barr, A., Brinkerhoff, W., Buratti, B., Dalton, J.B., Dombard, A., Glavin, D., Helfenstein, P., Kirschvink, J., Mitchell, D., Nimmo, F., Simon-Miller, A., and Spencer, J. (2007) Enceladus: Saturn's active ice moon. Enceladus flagship mission concept study, Goddard Space Flight Center, Greenbelt, MD.

Reh, K., Elliott, J., Spilker, T., Jorgensen, E., Spencer, J., and Lorenz, R. (2007) Titan and Enceladus $1B mission feasibility study report, JPL D-37401 B, Jet Propulsion Laboratory, Pasadena, CA.

Sandford, S.A., Aléon, J., Alexander, C.M., Araki, T., Bajt, S., Baratta, G.A., Borg, J., Bradley, J.P., Brownlee, D.E., Brucato, J.R., Burchell, M.J., Busemann, H., Butterworth, A., Clemett, S.J., Cody, G., Colangeli, L., Cooper, G., D'Hendecourt, L., Djouadi, Z., Dworkin, J.P., Ferrini, G., Fleckenstein, H., Flynn, G.J., Franchi, I.A., Fries, M., Gilles, M.K., Glavin, D.P., Gounelle, M., Grossemy, F., Jacobsen, C., Keller, L.P., Kilcoyne, A.L., Leitner, J., Matrajt, G., Meibom, A., Mennella, V., Mostefaoui, S., Nittler, L.R., Palumbo, M.E., Papanastassiou, D.A., Robert, F., Rotundi, A., Snead, C.J., Spencer, M.K., Stadermann, F.J., Steele, A., Stephan, T., Tsou, P., Tyliszczak, T., Westphal, A.J., Wirick, S., Wopenka, B., Yabuta, H., Zare, R.N., and Zolensky, M.E. (2006) Organics captured from comet 81P/Wild 2 by the Stardust spacecraft. *Science* 314:1720–1724.

Schneider, N.M., Burger, M.H., Johnson, R.E., Kargel, J.S., Schaller, E.L., and Brown, M.E. (2007) No ocean source for Enceladus' plumes [abstract #P11F-08]. In *AGU Fall Meeting 2007,* American Geophysical Union, Washington DC.

Sittler, E.C., Jr., Scudder, J.D., and Bridge, H.S. (1981) Distribution of neutral gas and dust near Saturn. *Nature* 292:711–714.

Smith, B.A., Cook, A.F., II, Feibelman, W.A, and Beebe, R.F. (1981) On a suspected ring external to the visible rings of Saturn. *Icarus* 25:466–469.

Smith, B.A., Soderblom, L., Batson, R., Bridges, P., Inge, J., Masursky, H., Shoemaker, E., Beebe, R., Boyce, J., Briggs, G., Bunker, A., Collins, S.A., Hansen, C.J., Johnson, T.V., Mitchell, J.L., Terrile, R.J., Cook, A.F., II, Cuzzi, J., Pollack, J.B., Danielson, G.E., Ingersoll, A.P., Davies, M.E., Hunt, G.E., Morrison, D., Owen, T., Sagan, C., Veverka, J., Strom, R., and Suomi, V.E. (1982) A new look at the Saturn system: the Voyager 2 images. *Science* 215:505–537.

Spencer, J.R., Pearl, J.C., Segura, M., Flasar, F.M., Mamoutkine, A., Romani, P., Buratti, B.J., Hendrix, A.R., Spilker, L.J., and Lopes, R.M.C. (2006) Cassini encounters Enceladus: background and the discovery of a south polar hot spot. *Science* 311:1401–1405.

Tsou, P. (2009) Stardust comet coma flyby sample return [#1440]. In *2009 IEEE Aerospace Conference,* Institute of Electrical and Electronics Engineers (IEEE), Piscataway, NJ.

Tsou P., Brownlee, D.E., Anderson, J.D., Bhaskaran, S., Cheuvront, A.R., Clark, B.C., Duxbury, T., Economou, T., Green, S.F., Hanner, M.S., Hörz, F., Kissel, J., McDonnell, J.A.M., Newburn, R.L., Jr., Ryan, R.E., Sandford, S.A., Sekanina, Z., Silen, J., Tuzzolino, A.J., Vellinga, J.M., and Zolensky, M.E. (2003) Stardust encounters Comet 81P/Wild 2. *J Geophys Res* 108, doi:10.1029/2004JE002317.

Tsou, P., Brownlee, D.E., Flynn, G.J., Hörz, F., Keller, L., McKeegan, K., Sandford, S.A., and Zolensky, M.E. (2006) STARDUST's Comet Wild 2 and contemporary interstellar stream sample status [abstract 2189]. In *37th Lunar and Planetary Science Conference Abstracts,* Lunar and Planetary Institute, Houston.

Waite, J.H., Magee, B.A., Gell, D.A., Kasprzak, W.T., Cravens, T., Vuitton, V.S., and Yelle, R.V. (2006) Titan's complex neutral composition as measured by Cassini INMS [abstract #P41A-1255]. In *AGU Fall Meeting 2006,* American Geophysical Union, Washington DC.

Waite, J.H., Jr., Lewis, W.S., Magee, B.A., Lunine, J.I., McKinnon, W.B., Glein, C.R., Mousis, O., Young, D.T., Brockwell, T., Westlake, J., Nguyen, M.-J., Teolis, B.D., Niemann, H.B., McNutt, R.L., Perry, M., and Ip, W.-H. (2009) Liquid water on Enceladus from observations of ammonia and ^{40}Ar in the plume. *Nature* 460:487–490.

Zolensky, M.E., Zega, T.J., Yano, H., Wirick, S., Westphal, A.J., Weisberg, M.K., Weber, I., Warren, J.L., Velbel, M.A., Tsuchiyama, A., Tsou, P., Toppani, A., Tomioka, N., Tomeoka, K., Teslich, N., Taheri, M., Susini, J., Stroud, R., Stephan, T., Stadermann, F.J., Snead, C.J., Simon, S.B., Simionovici, A., See, T.H., Robert, F., Rietmeijer, F.J., Rao, W., Perronnet, M.C., Papanastassiou, D.A., Okudaira, K., Ohsumi, K., Ohnishi, I., Nakamura-Messenger, K., Nakamura, T., Mostefaoui, S., Mikouchi, T., Meibom, A., Matrajt, G., Marcus, M.A., Leroux, H., Lemelle, L., Le, L., Lanzirotti, A., Langenhorst, F., Krot, A.N., Keller, L.P., Kearsley, A.T., Joswiak, D., Jacob, D., Ishii, H., Harvey, R., Hagiya, K., Grossman, L., Grossman, J.N., Graham, G.A., Gounelle, M., Gillet, P., Genge, M.J., Flynn, G., Ferroir, T., Fallon, S., Fakra, S., Ebel, D.S., Dai, Z.R., Cordier, P., Clark, B., Chi, M., Butterworth, A.L., Brownlee, D.E., Bridges, J.C., Brennan, S., Brearley, A., Bradley, J.P., Bleuet, P., Bland, P.A., and Bastien, R. (2006) Mineralogy and petrology of comet 81P/Wild 2 nucleus samples. *Science* 314:1735–1739.

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