Overview of SPRITE: Saturn PRobe Interior and aTmosphere Explorer Concept

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The Saturn PRobe Interior and aTmosphere Explorer (SPRITE) mission concept targets high-priority Planetary Science Decadal Survey science objectives. This mission concept would deliver the SPRITE entry probe into the Saturn atmosphere to obtain in situ measurements of elemental abundances and isotopic ratios, which would help distinguish the role Saturn played in the solar system formation and co-evolution of other planets. An Atmospheric Structure Investigation sensor package on the entry probe would provide in situ measurements of the pressure/temperature and wind structure below the cloud-tops, and a Quadrupole Mass Spectrometer and Tunable Laser Spectrometer suite would determine the composition of Saturn's atmosphere. The SPRITE mission concept described in this paper uses a solar-powered carrier-relay spacecraft to deliver the battery-powered entry probe to Saturn after a 10-year Venus-Earth-Earth gravity-assist trajectory, and then relays the probe data back to Earth during the carrier-relay spacecraft Saturn flyby. A high-heritage design approach is implemented for the flight elements to minimize technical risk and enable successful return of this high-value science data.

Key Words: Saturn, Probe, Entry, Atmosphere

1. Introduction

The most recent Planetary Sciences Decadal Survey[1] provided a recommended set of missions that NASA should consider for future planetary investigations. One of the missions suggested for consideration under the NASA New Frontiers program is a Saturn entry probe. This mission concept uses a carrier-relay spacecraft to deliver an entry probe (similar to the Galileo Probe) into Saturn's atmosphere to obtain atmospheric composition measurements, most notably noble gas abundances and isotopic ratios for H, C, N, and O. The mission would also characterize the pressure, temperature, and dynamical structure of Saturn's atmosphere at the probe descent location.

SPRITE (Saturn PRobe Interior and aTmosphere Explorer)[2] is a concept proposed to fulfill these high priority Decadal Survey science objectives. While Cassini remote sensing has provided considerable insight into Saturn's upper-level atmosphere, in situ measurements are required to provide ground truth and connection of the observed cloud-top motions to deeper circulation. Additionally, the composition of the deep well-mixed atmosphere, including noble gases, cannot be detected by remote sensing techniques.

The SPRITE concept addresses these science questions through the use of an atmospheric entry probe containing two composition instruments and an atmospheric structure instrument sensor package. The two spectrometers measure the composition of the atmosphere, including noble gas abundances and isotopic ratios. The atmospheric structure instrument characterizes the entry accelerations and perform atmospheric sampling throughout descent via pressure and temperature sensors. Finally, a Doppler wind radio science experiment provides insight into the vertical profile of horizontal winds at Saturn.

2. SPRITE Concept Science Overview

2.1. Saturn's Role in Solar System Formation

The location and speed of Saturn's formation plays a leading role in determining the history of our solar system formation (see Fig. 1). Planetary migration models suggest that Jupiter may have migrated to the inner planet zone 100,000 years after its formation,[3] which would have swept up terrestrial planets forming in that period. However, if Saturn formed quickly and close enough to Jupiter, it could have arrested this migration.[4] In other scenarios, no migration is required. Determining the role of Saturn in these solar system formation hypotheses requires an accurate estimate of the age and composition of Saturn for comparison with Jupiter.

Remote sensing allows estimation of a gas giant planet's temperature. In Saturn's case, the temperature is warmer than would be expected after 4.55 billion years of cooling, implying that it formed long after Jupiter.[5] If correct, this indicates Saturn may not have played a role in arresting Jupiter's migration to the inner solar system. This inconsistency raises questions regarding the various solar system formation models – did Saturn arrest Jupiter's migration, or was some other mechanism present that led to the current solar system configuration? Is Saturn as young as the temperature estimate would indicate?

One of the primary goals of SPRITE would be to perform in situ measurements of the Saturn atmosphere to accurately characterize Saturn's age. In the case of Jupiter, Galileo Probe measurements detected a slight depletion of helium and strong depletion of neon,[6-7] which suggests the possible formation of helium raindrops mixed with neon that precipitated and released heat.[8] Measuring the abundances of helium and neon at Saturn provides a key indicator of whether a similar helium rain process might be responsible for Saturn's remotely

Predecisional information for planning and discussion only

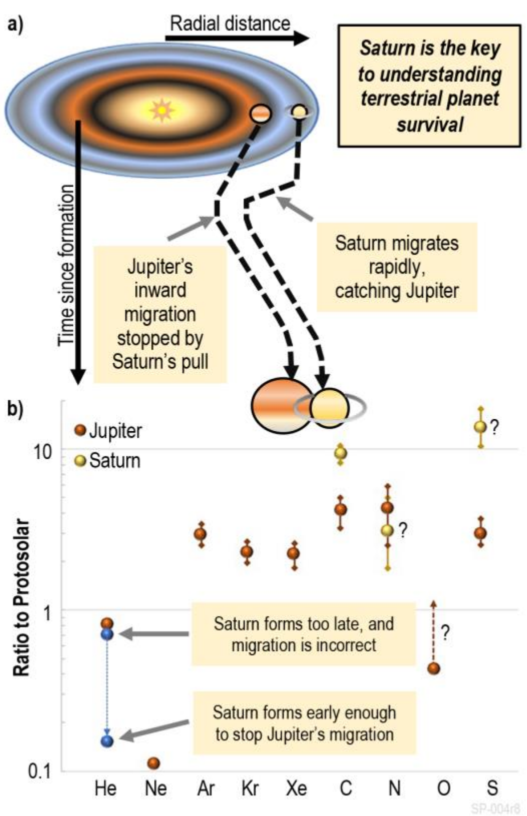

Fig. 1. A) Saturn's age and formation location have profound implications for the other planets. In one scenario, Saturn arrests Jupiter's migration. B) Present day composition reflects where and when Saturn formed, but data (yellow circles) are limited or poorly constrained ("?"), insufficient for comparing with Jupiter values (orange circles) and competing models.

observed temperature. Additionally, in situ measurements of Saturn's atmospheric elemental abundances and isotopic ratios indicate where Saturn formed in the protosolar nebula (based on predicted composition patterns), and allow comparison with Galileo Probe measurements of Jupiter to test theories regarding giant planet formation and co-evolution.

2.2. Truth Beneath Saturn's Clouds

Without in situ measurements, knowledge of planetary atmospheres is limited to remote sensing of the upper atmosphere (in and above cloud-tops) and modeling through computer simulations. However, attempting to model the general circulation and reproduce observed weather patterns requires data on the vertical profiles of horizontal winds and temperature below the opaque clouds. Additionally, estimates of Saturn's cloud composition are inferred from assumed temperature profiles and atmospheric composition – these imply the presence of NH_3, NH_4SH, and H_2O ice clouds at pressures that correspond to their condensation temperatures (see Fig. 2).

More than 10 years of infrared observations by Cassini, coupled with radio occultations by Voyager and Cassini, have characterized the temperature structure of the upper Saturn atmosphere (i.e., above the 1 bar pressure altitude). At altitudes deeper than 1 bar, the temperature profile is assumed to

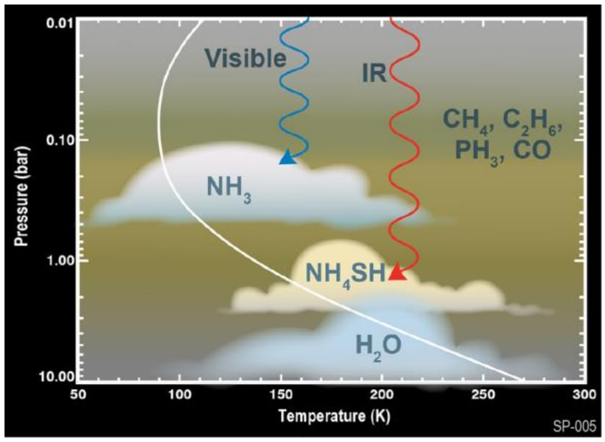

Fig. 2. Current estimates of Saturn's cloud composition and temperature profile are inferred from models and remote-sensing observations, which are unable to penetrate below the cloud tops.

increase with depth depending on atmospheric heat capacity.[9] In reality, the atmospheric structure is likely more complex than this simple assumption. For example, there may be different levels of instability and stratification at different altitudes, indicating active or impeded atmospheric convection.

To accurately determine Saturn's atmosphere properties and dynamics, in situ measurements of pressure, temperature, wind, and cloud properties are required. In the upper atmosphere, this provides the ground truth data needed to correlate with remote sensing observations of Saturn and bound global circulation and analytical models of time-variable cloud-top motions, and in the deeper atmosphere can provide measurements that are not available by in any other way.

2.3. Proposed SPRITE Instrument Suite

To address the mission concept's science goals, the SPRITE entry probe is proposed to carry three primary instruments: a Quadrupole Mass Spectrometer (QMS), a Tunable Laser Spectrometer (TLS), and an Atmospheric Structure Instrument (ASI). The SPRITE carrier-relay spacecraft contains a fourth instrument: a Multi-Channel Imager (MCI).

The QMS provides the capability for high-precision measurements of elemental (C, S, O) and noble gas (He, Ne, Ar, Kr, and Xe) abundances, as well as isotopic ratios (He, Ne, Ar, Kr, Xe, $^{13}C/^{12}C$, and D/H) in the Saturn troposphere. The ion source and analyzer provide a high dynamic range and sensitivity for measurements in the 0.2 to 10 bar pressure range.

The TLS measures the elemental abundances and isotopic ratios of key H, S, C, and O species, and abundances of disequilibrium species, providing the mixing ratios of targeted trace atmospheric constituents (H_2O, H_2S, CH_4, C_2H_6, CO, PH_3, NH_3) and isotopic ratios (D/H, S, C, N, O). The TLS achieves a high sensitivity and precision by scanning narrow molecular spectral absorption lines.

The QMS and TLS instrument suite is based on the Sample Analysis at Mars (SAM) suite (see Fig. 3) currently operating on the Mars Curiosity rover. For SPRITE, the primary modifications are to the gas handling system to enable operations in the primarily H and He Saturn atmosphere. A set of break-off caps at the bottom of the entry probe provide the

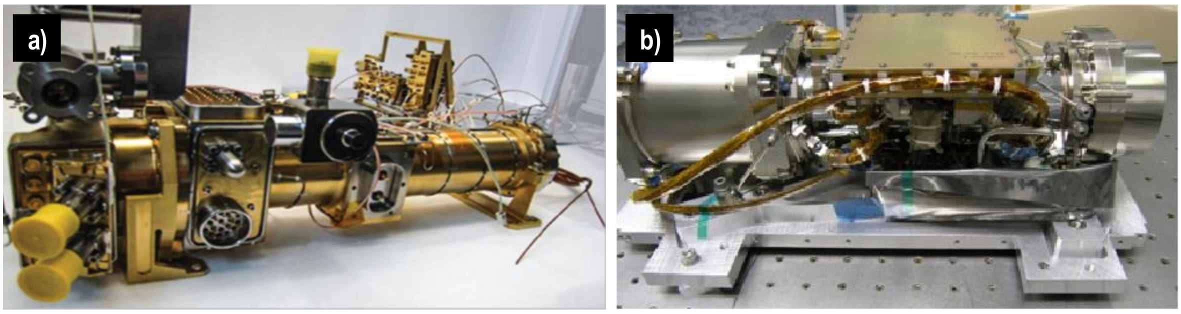

Fig. 3. The SPRITE concept contains two mass-spectrometers based on the SAM instrument suite (shown above) that have successfully flown on the Mars Curiosity rover: QMS (a) and TLS (b).

sampling inlet for both the QMS and TLS on SPRITE.

The ASI contains several sensors to characterize the Saturn atmospheric structure profile. This includes a three-axis inertial measurement unit (IMU) located in the interior of the probe, and an external boom carrying the pressure inlets, the temperature sensors, and a nephelometer to characterize cloud properties. The IMU provides measurements of the entry and descent accelerations. The pressure/temperature sensors characterize the atmosphere properties during descent, and the nephelometer measures backscattered light to characterize cloud aerosol properties and number densities. Both the entry probe and the carrier-relay spacecraft carry ultrastable oscillators to enable accurate Doppler measurements of the probe radio signal during descent and retrieve the vertical profile of zonal winds.

Finally, the MCI on the carrier-relay spacecraft provides imaging of the cloud-top winds and cloud structure on Saturn several days prior to probe entry. This provides context for the probe in situ measurements.

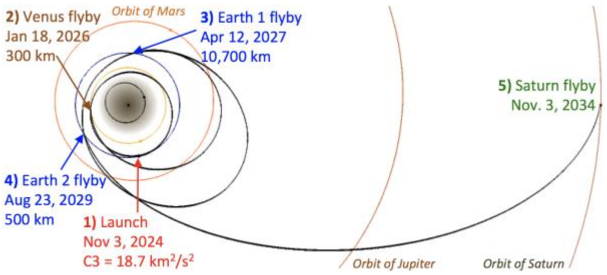

Fig. 4. SPRITE would be launched on an intermediate-low performance launch vehicle, and use a Venus-Earth-Earth gravity assist trajectory for a 10-year cruise to Saturn.

3. Mission Concept Implementation Overview

3.1. Mission Concept Design

The SPRITE concept would target a 21-day nominal launch window in the November, 2024 timeframe. Launch would occur on a low-intermediate performance launch vehicle (e.g., Atlas V 401). After initial checkout on-orbit, SPRITE would embark on a 10-year Venus-Earth-Earth gravity assist trajectory to Saturn (see Fig. 4). Annual checkouts and mission-specific tests, including relay communication tests, validate system performance prior to the Saturn approach and entry.

Thirty days prior to entry, the carrier-relay spacecraft orients to the probe release attitude and releases the probe, and then performs a deflection maneuver two days later to adjust to a flyby (rather than ballistic entry) trajectory. Starting 5.3 days before probe entry, the carrier-relay spacecraft performs 55 hours of context imaging using the MCI. After completing the imaging (more than two days prior to entry), the carrier-relay spacecraft prepares for the probe entry.

On November 3, 2034, the probe would enter the Saturn atmosphere with an atmosphere-relative entry flight path angle of -14 deg. and velocity of nearly 27 km/s. The entry takes approximately seven minutes, during which the probe experiences a peak deceleration of 37.5 g (nominal) and peak heat flux (unmargined) of approximately 1.5 kW/cm_2. Following the Galileo Probe entry and descent concept, a 1.0 m diameter pilot parachute is deployed at Mach 0.9, quickly followed by backshell release and deployment of a 2.6 m diameter main parachute. Once the heatshield is released, the probe then descends beneath the main parachute for the

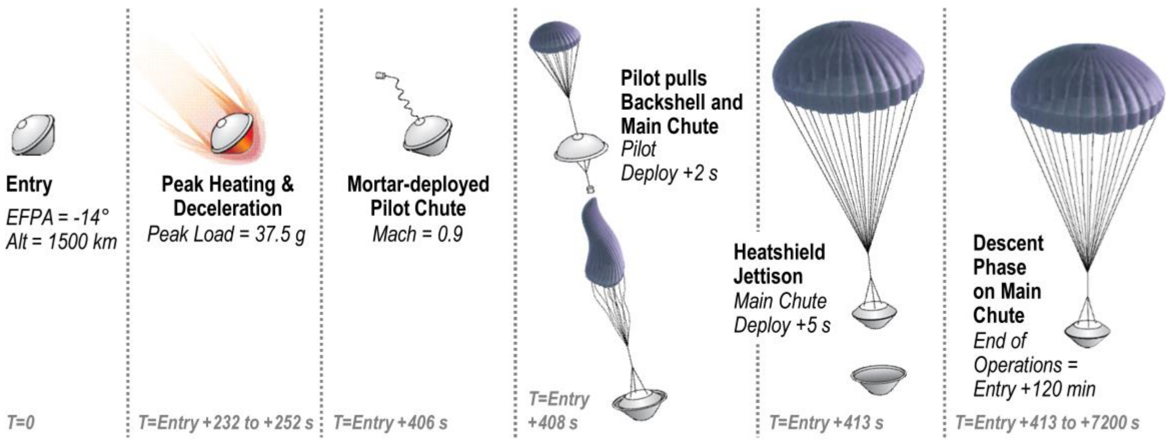

Fig. 5. SPRITE would follow an entry and descent concept similar to that used on the Galileo Probe.

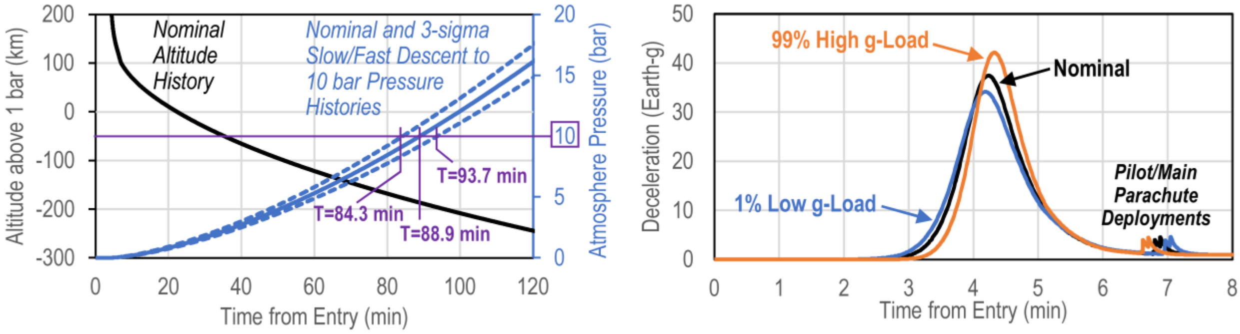

Fig. 6. The SPRITE entry probe would experience a maximum deceleration of 37.5 Earth-g's (nominal), and reaches a pressure of 10 bars approximately 90 minutes after entry.

remainder of the 2-hour long entry and descent phase (see Fig. 5-6).

3.2. Flight System

The SPRITE mission consists of three flight elements: a carrier-relay spacecraft, a descent vehicle, and an aeroshell with entry sensors. The latter two flight elements comprise the entry probe.

The carrier-relay spacecraft (see Fig. 7) is based on a high-heritage design, and utilizes solar arrays and secondary batteries. The telecom subsystem receives the entry probe UHF signal during science operations, and communicates to Earth via X-band. Propulsion is provided by a pressure-regulated mono-propellant system. All subsystems are designed for single-fault tolerance.

The descent vehicle (see Fig. 8) is designed using two main decks, and a sphere-cone shaped aerodynamic fairing (which effectively utilizes the aeroshell volume and provides aerodynamic stability during descent). The QMS and TLS instruments are located on the forward deck, along with avionics and power subsystem components. The aft deck contains parachute attachment lugs, as well as the majority of the telecom subsystem components (e.g., transmitters and UHF patch antenna). A total of 180 $Li\text{-}SOCl_2$ primary batteries provides sufficient energy to power the instruments and vehicle subsystems during the 2-hour science measurement phase, as well as maintain the probe at its survival temperature during the 30-day coast prior to entry. The descent vehicle is designed with high-heritage components, and implements a fault-masking parallel redundancy approach for all subsystems to minimize risk.

The aeroshell (see Fig. 9) encapsulates the descent vehicle and protects it during the entry phase. The 45 deg. sphere-cone heatshield shape is scaled from the Pioneer-Venus probes, whereas the spherical backshell shape is scaled from the Galileo Probe. The NASA-developed Heatshield for Extreme Entry Environments Technology (HEEET)[10] thermal protection system (TPS) material is used for the heatshield; the backshell incorporates the SLA-561V TPS material successfully flown on numerous NASA Mars entry missions (e.g., from Mars Viking to Mars Science Laboratory). The aeroshell flight element also contains the mortar-deployed pilot parachute and the main parachute.

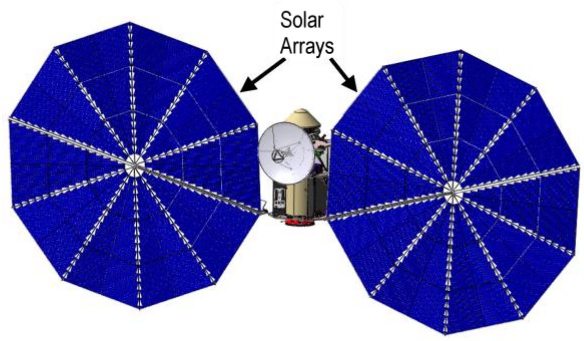

Fig. 7. The carrier-relay spacecraft would be solar-powered. It delivers the entry probe to Saturn, and provides data relay of the in situ science measurements from the probe.

4. Conclusion

The SPRITE mission concept targets key science investigations highlighted as high priority in the most recent Planetary Science Decadal Survey. Deployment of an entry probe into Saturn's atmosphere would provide in situ measurements of elemental abundances and isotopic ratios, and help determine Saturn's role in the formation of the solar system. In situ pressure, temperature, and cloud particle measurements would also provide ground truth of the atmosphere structure below the cloud-tops that limit remote-sensing observations.

These high-priority science objectives are met with a low-risk design based on past mission experience. The entry probe would leverage a similar entry and descent sequence to the Galileo Probe, and employ a single-fault tolerant battery-powered design to enable use of flight-qualified hardware where possible. The solar-powered carrier-relay spacecraft, also single-fault tolerant, would perform a flyby of Saturn during the probe science operations, and relay the data back to Earth.

This combination of low-technical risk mission implementation and high-value science data return would make the SPRITE mission concept instrumental in characterization of the composition of Saturn, as well as its contribution to solar system evolution.

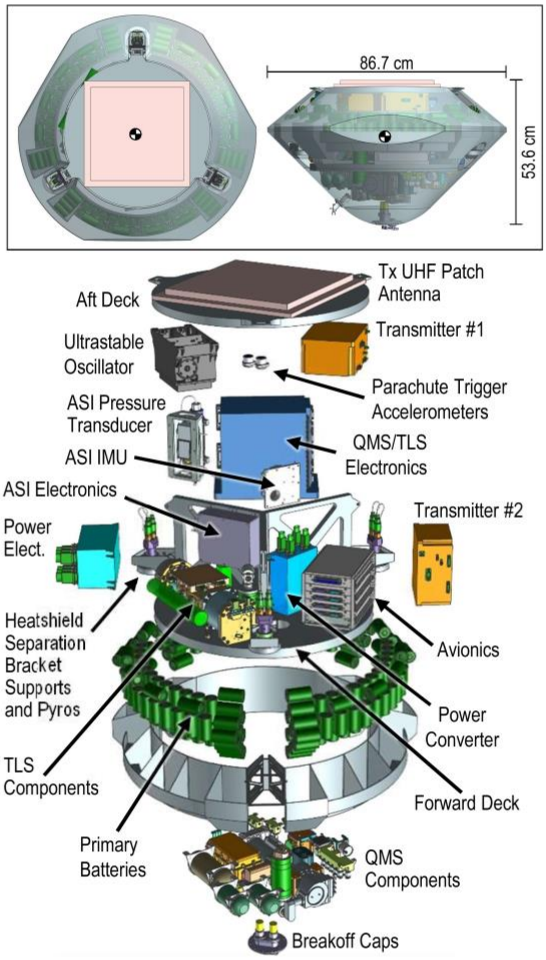

Fig. 8. The descent vehicle would be battery-powered, and a parallel-string redundancy approach would provide a robust capability to obtain and transmit the in situ measurement data back to the carrier-relay

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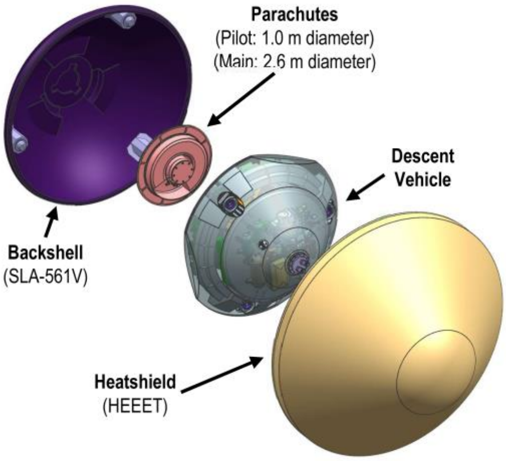

Fig. 9. The aeroshell concept is based on past flight mission designs, and uses the NASA HEEET material for the heatshield TPS.

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