IPPW-9 #105

Scientific Value of a Saturn Atmospheric Probe Mission

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Abstract Atmospheric entry probe missions to the giant planets can uniquely discriminate between competing theories of solar system formation and the origin and evolution of the giant planets and their atmospheres. This provides for important comparative studies of the gas and ice giants, and to provide a laboratory for studying the atmospheric chemistries, dynamics, and interiors of all the planets including Earth. The giant planets also represent a valuable link to extrasolar planetary systems. As outlined in the recent Planetary Decadal Survey, a Saturn Probe mission - with a shallow probe - ranks as a high priority for a New Frontiers class mission [1].

Atmospheric constituents are needed to constrain theories of solar system formation and the origin and evolution of the giant planets, and can be accessed and sampled by shallow entry probes. Many of these important constituents are spectrally inactive or are beneath an optically thick overburden at useful wavelengths, and therefore are not accessible by remote sensing, such as from Cassini. A small, scientifically focused shallow entry probe mission can make the critical abundance measurements of key constituents, and can measure depth profiles of atmospheric structure and dynamics at a significantly higher vertical resolution than can be achieved by remote sensing techniques alone.

The Galileo mission began the detailed study of the solar system's two major gas giants by dropping an entry probe into the atmosphere of Jupiter and deploying an orbiter around Jupiter. Detailed gravitational and magnetic field measurements of Jupiter, along with a determination of the deep oxygen abundance will be made by the Juno mission in 2016-17. In the same period the Cassini Saturn Orbiter will begin a set of Juno-like orbits to make comparable measurements of Saturn. A Saturn entry probe would complete the quartet of Missions needed to comprehensively and comparatively study the two planets [2]. Keeping the Scientific mission highly focused with a minimal science payload enables an outer planet mission that fits within existing program budget caps while still addressing unique and critical science. Fundamental measurements made from a small and scientifically focused Saturn Entry probe include abundances of the noble gases He, Ne, Ar, Kr, and Xe, abundances of key isotopic ratios $^4He/^3He$, D/H, $^{15}N/^{14}N$, $^{18}O/^{16}O$, and $^{13}C/^{12}C$, and detection of disequilibrium species such as CO, PH_3, AsH_3, and GeH_4. These are diagnostic of deeper internal processes and dynamics of the atmosphere along the probe descent path. Abundances of these key constituents, as well as carbon, which does not condense at Saturn, sulfur, which is expected to be well-mixed below the 4 to 5-bar ammonium hydrosulfide (NH_4SH) cloud, and gradients of nitrogen below the NH_4SH cloud, and oxygen in the upper layers of the water and water-ammonia solution cloud, can be measured by a shallow entry probe descending through 5 or 10 bars. A shallow Saturn probe is capable of obtaining the key noble gas and isotopic abundances, plus vertical abundance profiles for other constituents not accessible to an orbiter mission. In concert with the results from Galileo, Cassini, and Juno, these measurements are critical to enabling a full comparison of composition and dynamical processes on Jupiter and Saturn. A better understanding of the structure of the gas and ice giants in our solar system will ultimately aid future studies of exoplanets, as well.

Decadal Survey 2013-2022 Every ten years, NASA and NSF request the National Research Council to review the status of planetary science in the United States and to help develop a comprehensive strategy to continue advances in the field through the coming decade. Drawing extensively on input from the planetary science community, the report presents a program with the potential to yield revolutionary new discoveries [1]. The recommendations of the recently released United States National Research Council's Planetary Science Decadal Survey "Vision & Voyages for Planetary Science in the Decade 2013-2022" articulates three overarching goals for giant planet system exploration. Supporting each goal are key Science Objectives and Science Questions, many of which are addressed by Saturn probes.

	Overarching Goal # 1 Giant Planets as Ground Truth for Exoplanets - Explore the processes and properties that influence giant planets in the solar system.						**Overarching Goal # 2** Giant Planet's Roles in Promoting a Habitable Planetary System				**Overarching Goal # 3** Giant Planets as Laboratories for Properties and Processes on Earth			
Science Objectives	**Understand Heat Flow and Radiation Balance in Giant Planets**				**Investigate the Chemistry of Giant Planet Atmospheres**		**Search for Chemical Evidence of Planetary Migration**		**What are the sources, sinks and evolution of organic material?**		**Investigate Atmospheric Dynamical Processes in the Giant Planet Laboratory**			
Science Questions	What mechanism has prolonged Saturn's thermal evolution?	Does helium rain play a role in reducing the H/He in Saturn's molecular envelope?	Why and how does the atmospheric temperature and cloud composition vary with depth and location on the planet?	Which processes influence the atmospheric thermal profile, and how do these vary with location?	How did the giant planet atmospheres form and evolve to their present state?	What are the current pressure-temperature profiles for these planets?	How and why do elemental and isotopic abundances vary as a function of distance from the Sun?	How and why do abundances of heavy elements and isotopes, noble gases, and the ratios of D/H and H/He differ between the two classes of giant planets?	What is the nature of atmospheric processes on Titan that converts small organic gas phase molecules in the upper atmosphere into macromolecules and solid haze particles?	What is the source of the organic material in the plumes of Enceladus?	What processes drive the visible atmospheric flow and how do these processes couple to the interior structure and deep circulation?	What are the sources of vertically propagating waves that drive upper atmosphere oscillations and do these sources play a role on all planets?	How does moist convection shape tropospheric stratification?	What are the natures of periodic outbursts such as global upheaval on Jupiter and infrequent great white spots on Saturn?

The NRC's Planetary Science Decadal Survey included a Saturn entry probe mission to the list of recommended high priority science missions for NASA's New Frontiers Program. Two levels of science objectives were recognized by the Decadal Survey Giant Planets Panel:

Tier 1 Objectives focus on Saturn's composition and thermal structure to 5-10 bar, including to

- determine the noble gas abundances and isotopic ratios of H, C, N, and O in Saturn's atmosphere;
- determine the atmospheric structure at the probe descent location.

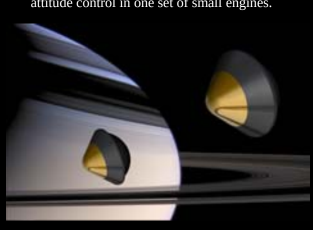
Tier 2 Objectives whose priorities are somewhat lower than the Tier 1 objectives including to

- determine the vertical profile of zonal winds as a function of depth at the probe entry location(s);
- determine the location, density, and composition of clouds as a function of depth in the atmosphere.
- determine variability of atmospheric structure and the presence of clouds in two locations;
- determine the vertical water abundance profile at the probe descent location(s);
- make precision isotope measurements for light elements (e.g., S, N, O) in atmospheric constituents.

Entry System The Galileo Jupiter entry probe in 1995 provides significant heritage for the Saturn probe conceptual design, with several key differences. Saturn entry speeds of 26-28 km/s are significantly less challenging than Galileo's 47.4 km/s entry, with a corresponding decrease in the TPS mass fraction. Existing facilities can test under Saturn entry conditions, so other sources of carbon phenolic can be tested to replace Galileo-heritage carbon phenolic. With 10 bar temperatures of about 280K, no extreme environment system designs are needed. Early design studies conclude that the probe mass , including the aeroshell, would be 200-230 kg, significantly less than the Galileo Probe's 340 kg.

Telecommunications The Saturn probe telecomm system can use UHF hardware at lower frequencies where atmospheres of giant planets are much more transparent to radio signals than at the Galileo Probe's L-band. An Electra-Lite transmit system on the probe can send 8-10 W RF through a patch antenna on the probe's upper face. At a range of 80,000 km, a second Electra-Lite system on the CRSC can receive 500 bps from the probe through a 2x2 patch array antenna with adequate margin.

Propulsion and Trajectory For the trajectory options examined, the mission ΔV budgets ranged from ~200 m/s to nearly 3 km/s. Larger ΔV's require expensive bi-propellant main engines, smaller ΔV's could use simpler mono-propellant systems, and the smallest can combine ΔV and attitude control in one set of small engines.



Electric Power The Carrier Relay Spacecraft (CRSC), carrying the probe to the Saturn system prior to probe release, could be powered by either an Advanced Stirling Radioisotope Generator (ASRG)-based or a solar-based electric power subsystem producing ~250 W average. An ASRG-based system would be lighter and cost less than a solar-based system, but is subject to the availability of Pu^{238} and could be affected by other programmatic issues. Solar arrays are affected by uncertainties in the low-intensity, low-temperature performance of current technology individual (LILT) cells. Even cells from the same production batch require larger than usual margins in array sizing, resulting in large (85 m^2), heavier, and more expensive arrays that require more structure mass and more propellant.

Science Payload Two instrument packages are needed for the entry probe to achieve Tier 1 Science Objectives: a composition instrument such as a Neutral Mass Spectrometer (NMS), and an Atmospheric Structure Instrument (ASI) comprising pressure and temperature sensors, and accelerometers. The NMS (2-150 Daltons with a resolution of 0.3 Daltons) is Galileo-heritage but with advances in power efficiency (25 W average) and mass (8kg). The ASI is a package of multiple pressure and temperature sensors, and entry and descent accelerometers. The reduced data provides atmospheric temperature and pressure as a function of depth. With a very simple suite of sensors, the ASI has a mass of ~1.2 kg and average power of ~6 W.

Including an ultrastable oscillator (USO) on both ends of the telecomm system will allow Doppler measurements of the atmospheric dynamics, including a vertical profile of the zonal winds to ~1 m/s and detection and characterization of atmospheric waves, convection, and turbulence.

Giant Planet Science – Comparative Planetology Theories of planetary formation attempt to explain patterns of volatile and noble gas enrichments in the giant planets. The Core Accretion Model [3] predicts that the initial heavy element cores of the giant planets formed from grains of refractory materials in the protosolar nebula, with additional heavy elements subsequently delivered by primordial Solar Composition Icy Planetesimals. In the Clathrate-Hydrate (C-H) model [4], heavy elements are delivered to the giant planets in clathrate-hydrate "cages", and can account for some Jupiter abundances observed such as the low abundance of neon, the only noble gas not easily trapped in clathrates. However, other observed abundances (e.g., water) do not closely match the predictions of the C-H model. Other theories suggest that heavy elements were incorporated into the gas accumulated by Jupiter and not in the solids [5], and Guillot and Hueso suggest a scenario comprising a sequence of refinement by settling of grains and loss of gas from the near-Jupiter nebula [6].

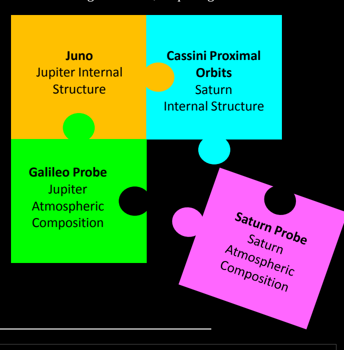
Comparative studies of the gas and ice giant planets provide the opportunity to discriminate between competing theories of giant planet formation, to test hypotheses regarding the processes by which volatiles (such as water) and organics were delivered to the giant and terrestrial planets, and to help establish time scales for planetary formation and protoplanetary disk evolution. Comparative planetology of gas giants is therefore a high priority objective for solar system formation and evolution studies [1,7].

A meaningful comparison of gas giants Jupiter and Saturn requires knowledge of elemental and isotope composition in the well-mixed atmospheres of both planets, and knowledge of gross interior structure to provide context for understanding compositional differences between the planets [8,9]. This data set goes beyond the capabilities of a single mission, requiring the combined results from multiple missions to enable truly meaningful comparisons.

With the exception of oxygen in the form of water, the Galileo probe provided measurements of elemental and isotope abundances at Jupiter. NASA's Juno mission is en route to Jupiter to make needed measurements of interior structure. Together with measurements of ammonia and oxygen, measurements of Jupiter's internal structure by Juno will complete the comparison data set for Jupiter.

The interior structure of Saturn can be provided by the Cassini Proximal Orbit mission. To complete the full Saturn data set, the elemental and isotope composition of Saturn's well-mixed atmospheres is also needed [1]. Measurements of the elemental and isotope composition in the well-mixed atmospheres of Saturn comparable to that achieved by the Galileo probe at Jupiter requires *in situ* instruments carried by a Saturn entry probe.

Without the Saturn composition and interior structure data set, it would be impossible to make comparisons adequate for unambiguous models of planet and planetary system formation, thereby precluding development of a fundamental understanding of giant planet and planetary system formation processes not only in our own solar system, but also in exoplanetary systems.



Summary Entry probe missions to the giant planets are needed to constrain models of the formation and evolution of the solar system and atmospheres, to provide a basis for comparative studies of the giant planets, and to provide a valuable link to extrasolar planetary systems. A Saturn probe mission would complete the quartet of data sets needed for a full comparative study of the gas giants, and to provide the contextual foundation for understanding the respective roles of the gas and ice giants in the origin, and chemical and dynamical evolution of the solar system. Critical measurements for a Saturn entry probe include the composition and structure of the atmosphere to 10 bars, goals that are easily accomplished with a probe carrying a composition instrument and an Atmospheric Structure Instrument. With an atmosphere that presents no significant extreme environmental issues, an entry that is challenging but significantly less difficult than experienced by Galileo at Jupiter, and with a radiation and synchrotron noise environment that is benign compared to Jupiter, no technical barriers to achieving the goals of a Saturn probe mission exist. The 2012 Planetary Science Decadal Survey lists a Saturn probe as a high priority mission for NASA in the decade 2013-2022.

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This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA.