Entry Probe Missions to the Giant Planets

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Abstract

The primary motivation for *in situ* probe missions to the outer planets derives from the need to constrain models of solar system formation and the origin and evolution of atmospheres, to provide a basis for comparative studies of the gas and ice giants, and to provide a valuable link to extrasolar planetary systems. The gas and ice giants offer a laboratory for studying the atmospheric chemistries, dynamics, and interiors of all the planets, including Earth, for it is within the deep, well-mixed atmospheres and interiors of the giant planets that pristine material from the epoch of solar system formation can be found, providing clues to the local chemical and physical conditions existing at the time and location at which each planet formed. Although planetary entry probes sample only a small portion of a giant planet's atmosphere, probes provide data on critical properties of atmospheres that cannot be obtained by remote sensing, such as measurements of constituents that are spectrally inactive, constituents found primarily below the visible clouds, and chemical, physical, and dynamical properties at much higher vertical resolutions than can be obtained remotely. The Galileo probe, for instance, returned compositional data at Jupiter that has challenged existing models of Jupiter's formation. To complement the Galileo *in situ* explorations of Jupiter, an entry probe mission to Saturn is needed. To provide for comparative studies of the gas giants and the ice giants, additional probe missions to either Uranus or Neptune are essential.

I. Current State of Knowledge

Background The atmospheres of the giant planets hold clues to the chemical nature of the refractory materials from which the original planetary cores formed, the surrounding protosolar nebula, and the subsequent formation and evolution of atmospheres. These clues can be derived from the composition, dynamics, and structure of giant planet atmospheres.

There exist a number of different theories of planetary formation that attempt to explain observed patterns of enrichments across volatiles and noble gases. In at least two theories, the enrichment of heavy elements (AMU>4) in the giant planets was provided in the form of solids. The core accretion model [1] predicts that the initial heavy element cores of the giant planets formed from grains of refractory materials in the protosolar nebula. Once these cores grew to 10-15 Earth masses, hydrogen and helium, enriched with heavy elements, gravitationally collapsed from the surrounding nebula onto the central core. Additional heavy elements were subsequently delivered by primordial planetesimals (Solar Composition Icy Planetesimals, SCIP's). However, this theory suffers from the fact that these planetary planetesimals are not seen today.

In the clathrate-hydrate (C-H) model [2], heavy elements are delivered to the giant planets in clathrate-hydrate "cages". Although the C-H theory can account for some of the abundances observed at Jupiter, such as the low abundance of neon (the only noble gas not easily trapped in clathrates), other observed abundances such as water do not closely match the predictions of the C-H model. Another theory suggests that heavy elements were incorporated into the gas accumulated by Jupiter, not in the solids [3]. Guillot and Hueso suggest a scenario comprising a sequence of refinement by settling of grains and loss of gas from the near-Jupiter nebula [4]. To help distinguish between these theories, measurements of heavy element abundances in the deep, well-mixed atmospheres of the giant planets are needed.

Composition Some models of planetary formation predict that the central core mass of the giant planets should increase with distance from the sun, with a corresponding increase in the abundances of the heavier elements from Jupiter outwards to Neptune. Carbon, in the form of methane, is the only heavy element so far measured on all the giant planets. As predicted, Voyager, Galileo, Cassini, and ground-based remote sensing have shown that the ratio of carbon to hydrogen increases from three times solar at Jupiter to 30x solar or greater at Neptune.

In addition to carbon, of particular importance to constraining and discriminating between competing theories of giant planet formation are the deep atmosphere abundances of the heavy elements, particularly nitrogen, sulfur, oxygen, and phosphorus; helium and the other noble gases and their isotopes; and isotope ratios of hydrogen, helium, nitrogen, oxygen, and carbon. Abundances of disequilibrium species such as carbon monoxide, phosphine, germane, and arsine can provide insight into convective and other not easily observable dynamical processes occurring in a planet's deep atmosphere.

Table 1 shows the known and suspected abundances of the heavy elements and several key isotopes at Jupiter, Saturn, Uranus and Neptune [5]. The suspected increase in heavy element abundances for the outer planets is based on the measured increase in carbon and the predictions of the icy planetesimal model of nearly equal enrichment of heavy elements (relative to solar) in the giant planets. However, the specifics of how all the elements vary relative to each other - especially how these relative abundances might vary from Jupiter to Saturn to the ice giants, is diagnostic of accretionary processes because of the range of volatility of their parent molecules.

Table 1 Elemental (relative to H) and Isotopic Abundances (Atreya, 2007), [5]

Element	**Sun**	**Jupiter/Sun**	**Saturn/Sun**	**Uranus/Sun**	**Neptune/Sun**
He	0.09705	.807+/- .02	0.56-.85	0.92-1.0	0.92-1.0
Ne	2.1×10^{-4}	.059+/- .004	?	20-30 (?)	30-50 (?)
Ar	1.7×10^{-6}	5.34±1.07	?	20-30 (?)	30-50 (?)
Kr	2.14×10^{-9}	2.03±.38	?	20-30 (?)	30-50 (?)
Xe	2.10×10^{-10}	2.11 +/- .40	?	20-30 (?)	30-50 (?)
C	2.75×10^{-4}	3.82±.66	9.3 +/- 1.8	20-30	30-50
N	6.76×10^{-5}	4.90±1.87	2.6-5	20-30 (?)	30-50 (?)
O	5.13×10^{-4}	.48±.17 (a)	?	20-30 (?)	30-50 (?)
S	1.55×10^{-5}	2.88±.69	?	20-30 (?)	30-50 (?)
P	2.57×10^{-7}	4.8 (b)	5-10	20-30 (?)	30-50 (?)
Isotope	**Sun**	**Jupiter**	**Saturn**	**Uranus**	**Neptune**
D/H	2.1±.5E-5	2.6±.7E-5	2.25±.35E-5	5.5(+3.5,-1.5)E-5	6.5(+2.5,-1.5)E-5
^{3}He/^{4}He	1.5±.3 E-5	1.66±.05 E-5			
^{15}N/^{14}N	$\leq 2.8 \times 10^{-3}$	$2.3 \pm .3 \times 10^{-3}$			

(a) Jupiter hotspot meteorology [6]

(b) Fletcher, L.N., et al., Icarus, 202, 543–564, (2009). Relative to solar composition of Grevesse et al (2007) [7]

Structure and Dynamics: Transport, Clouds and Mixing Giant planet atmospheres are by no means static, homogeneous, isothermal layers. High-speed lateral and vertical winds are known to move constituents through the atmospheres' complex structures, creating the strongly banded appearance of zonal flows modulated by condensation (clouds), and by vertical and lateral compositional gradients. Foreknowledge of structure and dynamics, even if incomplete, aids in deciding where the most informative composition measurements could be made most reliably. Measurements of structure, dynamics, and composition, in addition to providing understanding of the fundamental processes by which giant planets operate and evolve, help to verify that composition measurements are made under the proper conditions.

As temperatures decrease with increasing distance from the sun, the expected depths of the cloud layers should also increase. At the warmer temperatures of Jupiter, equilibrium models predict three cloud layers: an upper cloud of ammonia (NH_3), a second, slightly deeper cloud of ammonium hydrosulfide (NH_4SH), and deeper still cloud(s) of water ice and/or water-ammonia mixture. At Jupiter, water is the deepest cloud expected, with a cloud-base location predicted to be at depths of 5 to 10 bars for O/H ranging between 1-10x solar [8]. In the colder environs of Saturn, Uranus, and Neptune, water ice and water-ammonia clouds are expected to form much deeper. Thermochemical equilibrium calculations suggest that the base of water ice and ammonia-water solution clouds at Saturn may be at pressures of 10 bars and 20 bars, respectively, for 10x solar O/H. At Neptune with an expected solar O/H ratio of 30-50x, the water and ammonia-water solution clouds could be as deep as ~50-100 bars and 370 bars respectively [5, 9, 10]. Since atmospheric chemistries and diffusion and condensation processes will affect the location and composition of clouds and tend to fractionate constituents above the clouds, the well-mixed state is expected well beneath the clouds.

II. Key Science Questions

As defined by the Outer Planet Assessment Group (OPAG) in 2006, the central theme of outer planet exploration, Making Solar Systems, comprises three basic science goals: Building Blocks, Interior Secrets, and Extreme Environments [11]. To unveil the processes of outer planet formation and solar system evolution, detailed studies of the composition, structure, and dynamics of giant planet interiors and atmospheres are necessary. To fully address the OPAG goal of Interior Secrets, a combination of both *in situ* entry probe missions and remote sensing studies of the giant planets will be needed.

Although some important measurements addressing planetary composition, structure, and dynamics can be accomplished with remote sensing, other critical information is difficult or impossible to access solely via remote sensing techniques. This is the case when constituents or processes of interest, at depths of interest, have no spectral signature at wavelengths for which the atmospheric overburden is optically thin. Additionally, when remote sensing measurements are made it is often difficult to ascertain the precise depth. Entry probes circumvent such limitations by performing *in situ* measurements, providing precise vertical profiles of key constituents that are invaluable for elucidating chemical processes such as those in forming clouds (like NH_3 and H_2S producing NH_4SH clouds), and for tracing vertical dynamics (e.g., the PH_3 profile, where the competing processes of photochemical sink at altitude and supply from depth could give a variety of profiles, depending, for example, on the strength of vertical upwelling). The key science measurements for entry probes therefore focus on those measurements best addressed utilizing *in situ* techniques.

By combining elemental abundances and isotopic ratios on Saturn and one of the ice giants, and comparing with measurements at Jupiter, constraints can be placed on formation models of the gas and ice giants [9]. In addition to composition measurements of the deep atmospheres, probe measurements of atmospheric structure, dynamics, and clouds are also important. Of particular value are measurements of the vertical profile of temperatures at multiple latitudes, although such measurements at a single latitude are still very valuable.

The solar input at Saturn is only about 25% that of Jupiter and 1% that of Earth, and remote sensing shows very little meridional temperature variation at the cloudtops on either Jupiter or Saturn. And although the solar input at Neptune is only about 0.1% that at Earth, the cloud-top jet streams are significantly stronger than at either Jupiter or Saturn. It is not understood how energy of the giant planets is distributed within the atmosphere, how the solar energy and internal heat flux of Saturn and Neptune contribute to the dynamics of the atmosphere, to what depth the zonal wind structure on Saturn and Neptune penetrate, and whether the zonal winds increase with depth as on Jupiter.

The key science questions to be addressed by giant planet entry probe missions are listed below.

- **What was the time scale over which the giant planets formed, and how did the formation process of the ice giants differ from that of the gas giants?**
- **What is the history and distribution of water and other volatiles in the solar system?**
- **What are the processes that have and continue to shape the character of the outer planets, and how do they work?**
- **What can be learned about exoplanets by observing the giant planets of our solar system?**

To address these questions, several specific measurements will be needed, including

- abundances (relative to hydrogen) of heavy elements C, S, N, O, and noble gases He, Ne, Ar, Kr, Xe, key isotopic ratios such as D/H, $^{3}He/^{4}He$, $^{14}N/^{15}N$, $^{12}C/^{13}C$, $^{16}O/^{18}O$, (relative to solar) of Saturn relative to Jupiter, and of the ice giants relative to the gas giants;
- dynamical and thermal structure of the atmosphere beneath the cloud tops, including measurements of net local opacity and radiative divergence (heating), variations in net flux of radiant energy at different wavelengths as a function of depth, and measurements of local winds and waves;
- measurement of disequilibrium species such as PH_3, CO, AsH_3, GeH_4, and SiH_4.

In addition to these *in situ* measurements, knowledge of the core size and mass is needed. Since giant planet seismology results so far are not encouraging, such knowledge is best provided by a gravimetry experiment on an orbiter or flyby spacecraft that can be done at any time before, during, or after the probe mission.

III. Technology needs for future outer planet probe missions

Probes intended for Jupiter, Saturn, Uranus, and Neptune are designed to operate from carrier release through probe approach, atmospheric entry, and descent. During these phases, the probes must tolerate extreme environmental conditions such as entry heating, followed by both low and high temperatures and pressures [12] during descent.

Entry heating, including peak heat flux and heat pulse, is typically mitigated using a suitable thermal protection system (TPS). For planetary probes in general, ablative materials are used. Due to extremely high entry velocities, giant planet probes require the most robust materials such as highly dense Carbon-Phenolic (C-P). Following completion of the Galileo Jupiter probe mission in 1995, NASA decommissioned the Giant Planets Facility at Ames so development and testing capability for high-density ablators at the performance level required for giant planet probes is currently not available. As there are currently no proven alternatives to this “heritage” C-P (HCP), future giant planet entry probe missions must either utilize the very limited remaining stock of HCP (enough for two Galileo-sized entry probes) or develop and test an alternative to HCP. Development of new TPS materials is considered a long-lead item, and will require extensive technology maturation and ground testing. Therefore, **investment should be made in re-establishing the heritage carbon phenolic capability and development of an alternate to the heritage carbon-phenolic, may it be a new batch of C-P or another type of**

highly dense ablator [13].

To enable operation in the extreme pressure and temperature environments of a giant planet's deep (20 - 100 bars) atmosphere, a number of key technologies must be matured. For deep probes, these environments are similar to those experienced by Venus landers, and technologies for giant planet probes would therefore also find use in Venus probe applications. Specifically, a thermally-controlled pressure vessel must protect internal probe components while maintaining structural integrity, including seals, inlets, ports, windows and pass-throughs for external sensors. To increase the payload mass fraction, advances are needed in the technologies of strong and lightweight materials (e.g., composites) for the pressure vessel, and to maintain the probe's interior at moderate temperatures for probe descent times of up to several hours, improved passive thermal control technologies such as thermal energy storage, or phase change materials, and multi-layer thermal insulation are needed [12, 14]. **To enable greater deep probe payload mass fraction for the same entry mass, technology development are needed for lighter pressure vessel and passive thermal insulation and control designs, and to develop components interfacing with the deep extreme environments.**

Future *in situ* studies of planetary atmospheres would be enhanced by networks of small, low-power, lightweight, scientifically-focused probes, separated spatially and possibly temporally. Key technologies include miniaturized, low-power integrated sensors, transmitters and avionics [6, 16].

The atmospheres of the outer planets significantly attenuate microwave signals, greatly affecting the architecture of deep probe communication systems. Improvements in (UHF) antenna design and development of high power, high efficiency transmitters and power amplifiers are needed to provide the large Effective Isotropic Radiated Powers necessary to achieve adequate link margins. To meet the probe energy demands for long descent times into the deep atmosphere without unacceptable increases in battery mass and to minimize power requirements from probe housekeeping, science, and communication operations, **investment is needed in low power logic and power conditioning electronics, and in high energy density battery technologies** [15]. For deep probes, novel communication strategies should also be explored, such as Multiple Descent Module Data Relay systems [17].

IV. Mission Recommendations

<u>Giant Planet Probe Missions</u>

Jupiter is the only giant planet to have been studied *in situ*. To provide improved context in the results of the Galileo probe studies of Jupiter, and to provide for additional discrimination among theories of the formation and evolution of the gas giants and their atmospheres, it is essential that the Galileo Jupiter probe studies be complemented by similar studies at Saturn. For an understanding of the formation of the family of giant planets, both ice giants and gas giants, and, by extension, the entire solar system, probe missions to the ice giants Uranus and Neptune are also essential. Both observationally (measured carbon abundances) and theoretically (atmospheres forming from some combination of accreting nebula gas, degassing of core material, and influx of SCIPs, etc.), there is every reason to expect the atmospheric composition of the ice giants will be greatly different from that of Jupiter or Saturn.

It is recognized that all the giant planets represent excellent targets for future probe explorations, and if special opportunities are presented, the order in which specific giant planets are explored is of lesser importance than the value of the science that can be returned from missions to any of these targets.

Saturn Probe

A Saturn *in situ* mission, a mission of exceptionally high scientific value, is recommended as the highest priority giant planet probe mission. The goals of Saturn probe science can be accomplished with either deep (20-100 bar) entry probes alone, or shallow (<20 bar) probes complemented by Juno-type remote sensing with microwave radiometers (MWR) from a flyby carrier or orbiter for determination of water vapor [5, 18]. For risk mitigation and to sample a diversity of environments, a dual-probe mission – one equatorial and one mid-latitude – is most desirable.

The key measurement of a Saturn probe mission is composition of the well-mixed atmosphere below the cloud layers, including the heavy elements O, C, N, and S, the noble gases He, Ne, Ar, Kr, Xe and their isotopes, isotope ratios $^{14}N/^{15}N$, $^{12}C/^{13}C$ and D/H, and disequilibrium species such as CO, PH_3, AsH_3, GeH_4 as tracers of internal processes. He sedimentation is thought to be a major energy source at Saturn and a measurement of the He abundance in Saturn's atmosphere would put the theory for the cooling of all giant planets on firmer footing [19].

It should be stressed that other than oxygen (in the form of water), all of these species can be accessed and measured by entry probes at depths less than 10 bars for Saturn. Retrieval of oxygen abundances will require either deep probes or Microwave Radiometry. This is not a serious drawback, as even at Jupiter (for different reasons) no reliable measurement of O was obtained from Galileo. Complementary data on the deep winds, atmospheric pressure vs. temperature structure, and cloud location, composition and structure, and measurements of net radiative flux as a function of depth and wavelength are highly desirable.

With far fewer technology issues and relatively less expensive than probe mission to other destinations, a Saturn Probe(s) mission with MWR on a flyby carrier is the highest priority and most feasible near-term mission.

Neptune and Uranus Probes

A probe mission to one of the ice giant planets is strongly recommended. Since ice giant regions of well-mixed water and ammonia are expected at depths of kilobars to (possibly) hundreds of kilobars, probes into these truly extreme environments are not currently feasible and orbiter-based microwave radiometry at practical wavelengths is not expected to be particularly useful [1,2]. Shallow probes, a far less challenging engineering problem, will retrieve abundances of most heavy elements other than oxygen and nitrogen, and will make atmospheric structure and dynamics measurements below the levels significantly influenced by sunlight. Ice giant shallow probes will measure noble gas and methane abundances and will help unravel important atmospheric chemistries and processes that are currently not well understood. This, in turn, will help constrain the bulk oxygen, nitrogen, and sulfur abundances.

An ice giant probe(s) mission is strongly recommended. As both Uranus and Neptune are high-priority targets, studies will be needed to determine the best near-term ice giant destination.

Return to Jupiter

A single or multiprobe return to Jupiter should be considered soon after water and ammonia data from Juno have been received and analyzed. Despite the measurements available from the

Galileo probe and the expected measurements of water abundance from Juno microwave measurements, a probe mission to Jupiter is still needed since measurements of deep atmospheric composition, clouds, and dynamics at spatially separated locations are essential for unambiguous understanding of the formation of Jupiter and the origin of its atmosphere. These measurements will also provide "ground truth" for the microwave remote sensing. Results from Juno will dictate the optimum number, location, and depth of *in situ* probe explorations.

Cost

The estimated cost of most giant planet probe missions will likely exceed the current cost cap of New Frontiers class of missions, although a single shallow probe mission to Saturn with MWR on a flyby might fall within the NF cost cap. It is strongly recommended that a new small flagship class of missions be considered by the Decadal Survey for the next decade. Such missions would be particularly effective for conducting explorations of outer solar system objects beyond the capabilities of New Frontier missions, at costs well below that of full flagship missions.

To realize cost savings to NASA and the international community, and to maximize science return, it is essential that multinational partnerships be vigorously pursued.

V. Recommendations for Point Studies

It is strongly recommended that several point studies be undertaken to address key issues in preparation for future *in situ* giant planet explorations.

Thermal Protection Systems It is recommended that a study be performed to reestablish the heritage carbon phenolic heat shield capability for Saturn, Jupiter, and ice giant entry probe missions using the Galileo heritage rayon and the heritage manufacturing process. This study will assess the cost and time needed to close the current gaps in manufacturing, material conversion process from raw rayon to flight ready heat shield, design and analysis capabilities, and test capability to qualify and certify the heat shield. The study will provide data, based on a time line and budget for technology readiness, to determine which destinations are more attractive from cost and time constraints and risk tolerance.

Microprobes It is recommended that a study be conducted to assess the probe size trade space between microprobes and Galileo-sized probes as a function of potential science return from these mission elements. One of the key drivers for this study is the mass fraction of the TPS as a function of probe size and optimizing the probe shape to minimize the TPS mass (which translates directly into science mass). It is important to understand what can be accomplished with small probes using miniaturization and low power technologies, and what the savings is in cost and mass, and the impact on mission risk.

Saturn Shallow Probes To assess overall feasibility and cost, it is recommended that a study be undertaken to re-examine the payload trade space for Saturn shallow probes, and to identify an optimized payload that can provide the highest science return with minimized instrumentation.

Uranus / Neptune It is recommended that the Decadal Survey Giant Planets Panel evaluate the relative scientific merits of exploration missions including probes to Neptune and Uranus. The Panel should develop a strategy for soliciting community input and consensus on destination priorities for ice giant missions in the overall context of giant planet exploration.

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