In Situ Probes in the Atmospheres of the Ice Giants

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Abstract This paper describes atmospheric entry and descent probe missions in the atmospheres of the ice giants, Uranus and Neptune, targeting a minimum depth at the 10-bar level. In situ exploration of ice giant atmospheres addresses two broad themes: i) the formation history of the ice-giant planets and their role in the evolution of the solar system, and ii) the structure, dynamics, and processes in their atmospheres. An ice giant probe descending under parachute can measure abundances of key atmospheric constituents, deep thermal structure, dynamics, and processes, with data returned to Earth by a Carrier Relay Spacecraft. An atmospheric probe is an essential element of a possible future NASA Ice Giant New Frontier or Flagship mission.

1. Introduction The gas giant planets, Jupiter and Saturn, and the ice giant planets, Uranus and Neptune, contain most of the non-solar mass of the solar system and have played a significant role in shaping solar system evolution [1], influencing its current structure and affecting delivery of volatiles to the inner (terrestrial) planets [2]. Understanding the formation, evolution, and ultimate location of the giant planets is key to understanding the formation and evolution of the solar system as a whole. To extend knowledge and add additional clarity to the role played by the giant planets in solar system formation and evolution requires *in situ* exploration of the gas and ice giant planets. In particular, noble gases reflect both the location and processes of giant planet formation and subsequent evolution. Additionally, processes in ice giant atmospheres differ significantly from processes in the atmospheres of the gas giant planets. A key example is the predominance of retrograde rather than prograde winds at low latitudes, and the structure, location, and properties of condensate clouds in the significantly colder atmospheres found in the outer solar system. Although remote sensing is capable of making many important measurements of the composition of and processes within planetary atmospheres, remote sensing has limited capabilities to observe the deeper atmosphere beneath the clouds [3].

Atmospheric measurements beyond the reach of remote sensing require entry and descent probes to determine key atmospheric constituents including the abundance of noble gases and isotopes as well as the structure of and processes within the atmosphere beneath the cloud tops. Measurements of noble gas abundances and the ratio of key isotopes must be made *in situ* by a probe carrying a mass spectrometer, possibly including a tunable laser spectrometer and a dedicated helium abundance detector. Since noble gases are expected to be well-mixed, abundance measurements can be made by a relatively shallow probe in the upper atmosphere. Measurements of cloud condensates and condensables requires a vertical profile by a probe descending into the deeper atmosphere, down to 10 bars of pressure or more.

Atmospheric processes including dynamics requires the descent probe to carry an atmospheric structure instrument with sensors for pressure and temperature, electrical properties, as well as an atmospheric acoustic properties to measure speed of sound from which the atmospheric ortho-para H_2 ratio can be found. Other atmospheric processes including the net radiative flux transfer profile of the atmosphere and cloud location, composition, structure, and aerosol properties such as size, number density, and shape requires additional *in situ* instrumentation.

Two themes define the science motivation and instrument requirements for *in situ* exploration of ice giant atmospheres: i) the formation history of the ice giant planets and the role of the ice giants in the evolution of the solar system, and ii) the structure, dynamics, and processes in ice giant atmospheres (Table 1). The details of these goals can be found in our companion white paper [4].

Table 1. Notional Ice Giant Probe Science Traceability Matrix

Science Goals	Science Objectives	Measurement Requirements	Example Instruments	Comments/Notes
Understand the formation of the Ice Giant Planets and their role in the evolution of the solar system	Determine well-mixed atmospheric composition including abundances (relative to H) of He, noble gases, C, N, S, O, and key isotopes	He/H ₂ : $\pm 2\%$ Ne/H, Ar/H, Kr/H, Xe/H: $\pm 10\%$ C/H, N/H, S/H, P/H: $\pm 10\%$ ¹⁵ N/ ¹⁴ N, D/H: $\pm 5\%$ ³ He/ ⁴ He: $\pm 3\%$ Ne, Ar, Kr, Xe isotopes & ¹⁸ O/ ¹⁷ O/ ¹⁶ O, ¹² C/ ¹³ C: $\pm 1\%$	MS/TLS RSE/AtmAbs	Well-mixed H ₂ S, H ₂ O, S, O isotopes, NH ₃ requires deep probe. RSE Atmospheric absorption for profile of microwave absorbers (NH ₃ and H ₂ S); Galileo probe HAD He measurement: $\pm 2\%$
Understand atmospheric circulation, the processes by which energy is transferred outwards from the interior, and the structure of the cloud layers in the Ice Giants	Measure the altitude profile of temperature & pressure	Pressure: $\pm 1\%$, Temperature: ± 1 K	ASI	Required depth ≥ 10 bars
	Measure atmospheric dynamics including winds & waves/tides	Profile of atmospheric dynamics: ± 5 m/s	RSE/DWE	
	Measure speed of sound in atmosphere to determine hydrogen ortho/para ratio	Speed of Sound: $\pm 1\%$	Acoustic Anemometer, ASI, MS/TLS	Ortho-para H ₂ from acoustic anemometer (speed of sound): molecular mass, temperature required
	Determine abundances of key disequilibrium species	CO, PH ₃ , AsH ₃ , GeH ₄ : $\pm 10\%$	MS/TLS	
	Characterize vertical structure, composition, and properties of cloud & haze particles.	Particle optical properties, size distributions, number and mass densities, opacity, shapes, and composition	Nephelometer	
	Determine net atmospheric radiative energy balance; altitude profile of thermal IR & solar visible	Up & down visible flux: $\sim 4\text{-}5$ μm up & down IR flux: $4\text{-}50$ μm ; $\lambda/\Delta\lambda \sim 0.1\text{-}100$ $\Delta\text{Flux} \sim 0.5\text{Wm}^{-2}$: Accuracy $\pm 1\%$	Net Flux Radiometer	Solar uncertain by 2%; Protosolar $\sim$ larger $\rightarrow \pm 5\%$ requirement

ASI: Atmospheric Structure Instrument; **RSE:** Radio Science Experiment; **AtmAbs:** Atmospheric Absorption; **DWE:** Doppler Wind Experiment; **MS:** Mass Spectrometer; **TLS:** Tunable Laser Spectrometer; **HAD:** Helium Abundance Detector

2. Probe Mission Implementation To measure the overall composition, thermal structure, and dynamics of planetary atmospheres requires *in situ* measurements by a probe carrying a Mass Spectrometer, possibly including a tunable laser spectrometer, an acoustic anemometer to measure the ortho-para H₂ ratio from the speed of sound in the atmosphere, a helium abundance detector, and an Atmospheric Structure Instrument to measure the altitude profile of atmospheric temperature vs. pressure. Additional possible instruments include a Nephelometer to characterize cloud structure and aerosol properties, and a Net Flux Radiometer to measure atmospheric radiative energy structure. The probe would target a minimum depth of 10 bars, about 5 scale heights beneath the tropopause with a descent speed largely determined by the instrument capabilities and required sampling periods. Although the probe power, structure, thermal control, and telecommunications will likely allow operations beyond 10 bars, a balance must be found between the total science data volume requirements to achieve the high-priority mission goals, the capability of the probe telecommunications system to transmit the entire science, engineering, and housekeeping data set (including entry accelerometry and pre-entry/entry calibrations) within the descent telecommunications time window, and the probe descent profile allowing the probe to reach 10 bars.

An ice giant atmospheric probe with data returned to Earth by an orbiting or flyby Carrier Relay Spacecraft (CRSC) could be carried as an element of a dedicated ice giant planet system exploration mission. For delivery to the proper entry interface point, the CRSC with probe attached is placed on a planetary entry trajectory, and is reoriented for release of the probe. Prior to release, the probe would be configured for coast, entry, and atmospheric descent. Following probe release, a deflect maneuver is performed to place the CRSC on the proper trajectory to receive the probe descent telemetry. The probe is awakened by the coast timer for sequential power-on, warm-up, and health checks prior to arrival at the entry location. The only data collected during entry would be from the entry accelerometers and possibly instrumentation in the heat shield, including sensors to measure heat shield entry ablation. The end of entry is triggered by the accelerometers initiating the parachute deployment sequence, release of the aeroshell, and the initiation of atmospheric descent-science operations.

Parachute descent begins near the tropopause by deploying a drogue parachute which pulls off the probe aft cover which then extracts and deploys the main descent

parachute. Once under parachute, the probe heatshield is released and the transmit-only descent telecommunications link from the probe to the CRSC is initiated. Probe science collection and relay transmission strategy would be designed to ensure the entire probe science data set is successfully transmitted prior to probe arriving at the targeted depth.

Figure 1. Galileo Jupiter probe entry and descent profile. (Credit: NASA)

The probe descent mission would likely end when the telecommunications link becomes so poor that the link can no longer be maintained due to increasing atmospheric opacity, battery depletion, damaging thermal and/or pressure effects, and changing probe/CRSC geometry due to planetary rotation and CRSC trajectory. The probe descent mission is completed with probe science and engineering data successfully transmitted to the CRSC where multiple copies are stored in redundant on-board memory, together with post-descent context observations. Subsequently, the CRSC reorients to point the High Gain Antenna towards Earth and all stored copies of the probe data are returned. Figure 1 shows the Galileo probe entry, descent and deployment sequence, which could be the basis for a proposed ice giant entry probe mission.

3. Key Measurements and Instruments

Ice giant entry probes need to make several key measurements to constrain better ice giant formation and evolution scenarios and characterize atmospheric processes.

3.1 Atmospheric Thermal Structure from the stratosphere to at least 10 bars would provide context for model-dependent remote sensing measurements, as well as context for other probe measurements of composition, composition gradients, characterization of clouds, and profile of net atmospheric radiative transfer. Testing for the presence of sub- or super-adiabatic lapse rates are key to understanding how internal heat is transported in active atmospheres, and to establish the stability of the atmosphere towards vertical motions. At certain pressures, convection may be inhibited by the mean molecular weight gradient (for instance at ~ 2 bar in Neptune) and it is thus important to measure the temperature gradient in this region.

The altitude profile of atmospheric conductivity helps characterize atmospheric charge separation important to lightning generation within clouds. Measurements of atmospheric conductivity combined with meteorological data and measurements of the physical properties of charged aerosols enables an improved understanding of the role of electrical processes in cloud formation, lightning generation, and aerosol microphysics.

Atmospheric Structure Instrument (ASI) is a multi-sensor *in situ* instrument package to investigate planetary atmospheric thermal structure, including the altitude profile of atmospheric pressure, temperature, and electrical properties. Probe deceleration measurements made during entry can be inverted to provide a profile of upper atmospheric densities. Following aeroshell release, measurements of pressure, temperature, and electrical properties are performed under the parachute by sensors with direct access to the atmospheric flow. The ASI benefits from the strong heritage of the Huygens HASI experiment of the Cassini/Huygens mission [5], and the Pioneer Venus and Galileo ASI instruments [6,7].

3.2 Tropospheric abundances of noble gases He, Ne, Xe, Kr, Ar; C-, N-, S- and P-bearing species, and key isotopes help trace materials in the subreservoirs of the Protosolar Nebula (PSN). The noble gas abundances (relative to hydrogen) should be measured with an accuracy of at least $\pm 10\%$, and the helium abundance accuracy should be at least as good as that obtained by Galileo at Jupiter ($\pm 2\%$). The accuracy of key isotopic ratios should be $\pm 1\%$ to enable direct comparison with other known solar system values. Isotopes of oxygen ($^{18}\text{O}/^{17}\text{O}/^{16}\text{O}$) and carbon ($^{13}\text{C}/^{12}\text{C}$) should also be measured with an accuracy of $\pm 1\%$ to help determine the main reservoirs of these species in the PSN. The isotopic ratios of hydrogen (D/H) and nitrogen ($^{15}\text{N}/^{14}\text{N}$) should be measured with an accuracy of $\pm 5\%$. Abundances of CH_4 , NH_3 , H_2S , and PH_3 should be measured to at least 10-bars with an accuracy equal to the current knowledge of abundances in the PSN ($\pm 10\%$). Disequilibrium species CO and PH_3 abundances can help

bracket the deep H₂O abundance. The measurement of PH₃ is needed to help remove uncertainties in the deep thermal profile caused by the possible inhibition of convection at the H₂O condensation level [3,8,9].

The probe **Mass Spectrometer (MS)** makes *in situ* abundance measurements of the major atmospheric species including the noble gases He, Ne, Ar, Kr, and Xe, noble gas isotopes ³He/⁴He, ²⁰Ne/²²Ne, ⁴⁰Ar/³⁸Ar/³⁶Ar as well as isotopes of Kr and Xe, and key isotopes of C, N, S, and P, including ¹³C/¹²C, ¹⁵N/¹⁴N, ¹⁸O/¹⁷O/¹⁶O and other key isotopes including D/H. [10,11]. The survey capability of the MS makes it capable of measuring unanticipated species, whose presence could provide new discriminators among competing atmospheric processes.

A **Tunable Laser Spectrometer (TLS)** uses ultra-high resolution laser absorption spectroscopy in the near infrared (IR) to mid-IR spectral to complement MS measurements by providing high accuracy measurements of targeted isotopic species such as D/H, ¹³C/¹²C, and ¹⁸O/¹⁷O/¹⁶O. A TLS is part of the NASA Curiosity Mars rover SAM instrument, which measured the isotopic ratios of D/H and of ¹⁸O/¹⁶O in water and ¹³C/¹²C, ¹⁸O/¹⁷O/¹⁶O, ¹³C¹⁸O/¹²C¹⁶O in CO₂ in the Martian atmosphere [12,13].

A **Helium Abundance Detector (HAD)** measures the refractive index of a sample of atmosphere. Since the refractive index is directly related to atmospheric composition, and giant planet atmospheres primarily comprise H₂ and He, the refractive index is a direct measure of the He/H₂ ratio. The Galileo probe HAD [14] used a two-beam interferometer to compare the difference in optical path length through an atmospheric sample and a reference gas, and was able to determine the helium abundance in Jupiter's atmosphere with an accuracy of +/-2% between 2-10 bars.

3.3 Speed of Sound The atmospheric thermal structure and stability can be significantly affected by changes in the ortho-para H₂ fraction as an atmospheric parcel ascends and cools. Measurement of the ortho-para H₂ ratio would help constrain the degree of vertical convection through the atmosphere and the temperature profile through different cloud condensing layers. Additionally, to correctly interpret the thermal profile, stability, and density structure requires the atmospheric ortho-para H₂ fraction be known, with increasing importance for the colder ice giants. The ratio of ortho to para H₂ can be measured by exploiting thermodynamic differences between these two forms of hydrogen which affects the speed of sound. This technique requires that the atmospheric temperature and mean molecular weight be known. The ortho-para H₂ ratio can be found using ultrasonic capacitive transducers to measure the speed of sound as part of a high TRL, compact, energy-efficient and low data volume ultrasonic acoustic anemometer originally developed for Mars [15].

3.4 Doppler tracking of the descent probe provides the profile of atmospheric dynamics including winds, waves, and convection in the troposphere well beneath the region of cloud-tracked wind measurements. As shown by the descent of the Galileo probe into a particularly dry region on Jupiter called a 5-micron hot spot, weather conditions including local winds can significantly affect the structure of clouds and local abundances of atmospheric condensables. An ice giant probe descending from the region of the atmosphere dominated by solar insolation to the deeper, darker atmosphere beyond the reach of the sun's direct influence would be expected to experience changing atmospheric dynamics as solar visible insolation diminishes with depth. Additionally, atmospheric dynamics likely affects compositional gradients in atmospheres, and the respective roles of internal energy and solar visible deposition is not clear.

The **Doppler Wind Experiment (DWE)** utilizes the probe-CRSC radio subsystem comprising both transmit and receive elements mounted on the probe and the Carrier respectively. Accurate radiometric measurements of the received probe signal frequency made by the CRSC-mounted telecommunications link receiver provide the signature of the altitude profile of probe motions along the descent path due to atmospheric winds and waves, turbulence, and aerodynamic buffeting. To generate and measure the stable probe relay signal, the probe and CRSC must each carry an ultrastable oscillator [16].

3.5 Cloud and haze properties. Liquid, solid, and/or ice aerosols play an essential role in cloud structure, cloud processes, and atmospheric energy and thermal structure. Aerosol number densities, shape, size distributions, and composition measurements are needed to understand the dynamics, energy balance, and other processes, together with the structure of ice giant atmospheres. Although remote sensing can provide some aerosol properties, many other important properties require *in situ* direct sampling.

A **Nephelometer** measures scattered visible light within the atmosphere at a number of phase angles to retrieve number density and size distribution of haze and cloud particles to understand the overall character of atmospheric aerosols based on their refractive index and scattering properties. Measurements of scattered light at angles ranging from 20°-170° can characterize aerosols and condensates with size distributions in the 0.2-50 μm range [17,18].

3.6 Net radiative flux differences between downwelling solar visible and upwelling thermal infrared energy from the deeper atmosphere define giant planet meteorology regimes by affecting the altitude profile of atmospheric heating and cooling, resulting in buoyancy differences that are a primary contributor to atmospheric dynamics.

A **Net Energy Flux Radiometer (NFR)** measures both the upward thermal infrared and downward solar visible radiative fluxes to determine the radiative heating (cooling) component of the atmospheric energy budget and to identify the location of cloud layers and opacities. The NFR operates on the day side of the planet to access direct sunlight from 0.1 bar to at least 10 bars to define sources and sinks of planetary radiation, regions of solar energy deposition, and provide additional constraints on atmospheric composition and cloud properties [19].

4. Summary and Perspectives It is expected that one of the next great solar system exploration missions will be a flagship mission to an ice giant planet - Uranus with its unique obliquity and correspondingly extreme planetary seasons, unusual dearth of cloud features and radiated internal energy, tenuous ring system and multitude of small moons, or Neptune with its enormous winds, system of ring arcs, sporadic atmospheric features, and large retrograde moon Triton, likely a captured dwarf planet. Although the ice giants are the last class of planets in the solar system to be explored, they represent the most frequently observed type of exoplanet. To further constrain models of solar system formation and chemical, thermal, and dynamical evolution, the formation, evolution, and processes of ice giant atmospheres, and to provide additional ground truth for improved understanding of extrasolar planetary systems, exploration of one or both ice giants including *in situ* measurements with an entry probe are needed. Additionally, the family of all giant planets offer a laboratory for studying the dynamics, chemistry, and processes of the terrestrial planets including Earth.

In situ exploration is the only means by which deep, well-mixed atmospheres where pristine materials from the epoch of solar system formation can be studied. A descent probe can sample

regions of the atmosphere inaccessible to remote sensing, beneath tropospheric clouds to depths where cosmogonically important species are found. Particularly important are the noble gases, undetectable by any means other than direct sampling. Their absolute as well as relative abundances are needed to understand (i) the properties of the protosolar nebular at the location and epoch of solar system formation, (ii) the delivery of heavy elements to the giant planet atmospheres, and (iii) evidence of possible giant planet migration. An important result from an ice giant entry probe would be the indication as to whether the enhanced heavier noble gas abundances found at Jupiter by the Galileo probe is limited only to Jupiter, or is common to all giant planets, with broad implications for understanding exoplanetary systems. Additional data would include Doppler tracking of a descent probe to determine the vertical wind profile, the thermal structure to determine the structure and stability of the atmosphere, and particle properties to determine the location, density, and properties of the upper clouds. Altogether, measurements of atmospheric chemical and dynamical processes would (i) provide an improved context to understand the chemistries, processes, origin, and evolution of all solar system atmospheres, (ii) enable paradigm-changing understanding of the conditions under which the solar system formed and evolved, and (iii) represent ground-truth measurements to improve understanding of extrasolar planets.

Based on these findings, we recommend including *in situ* probes on future New Frontiers or Flagship class missions to ice giants, either as dedicated probe missions or add-ons to missions with a broader focus.

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