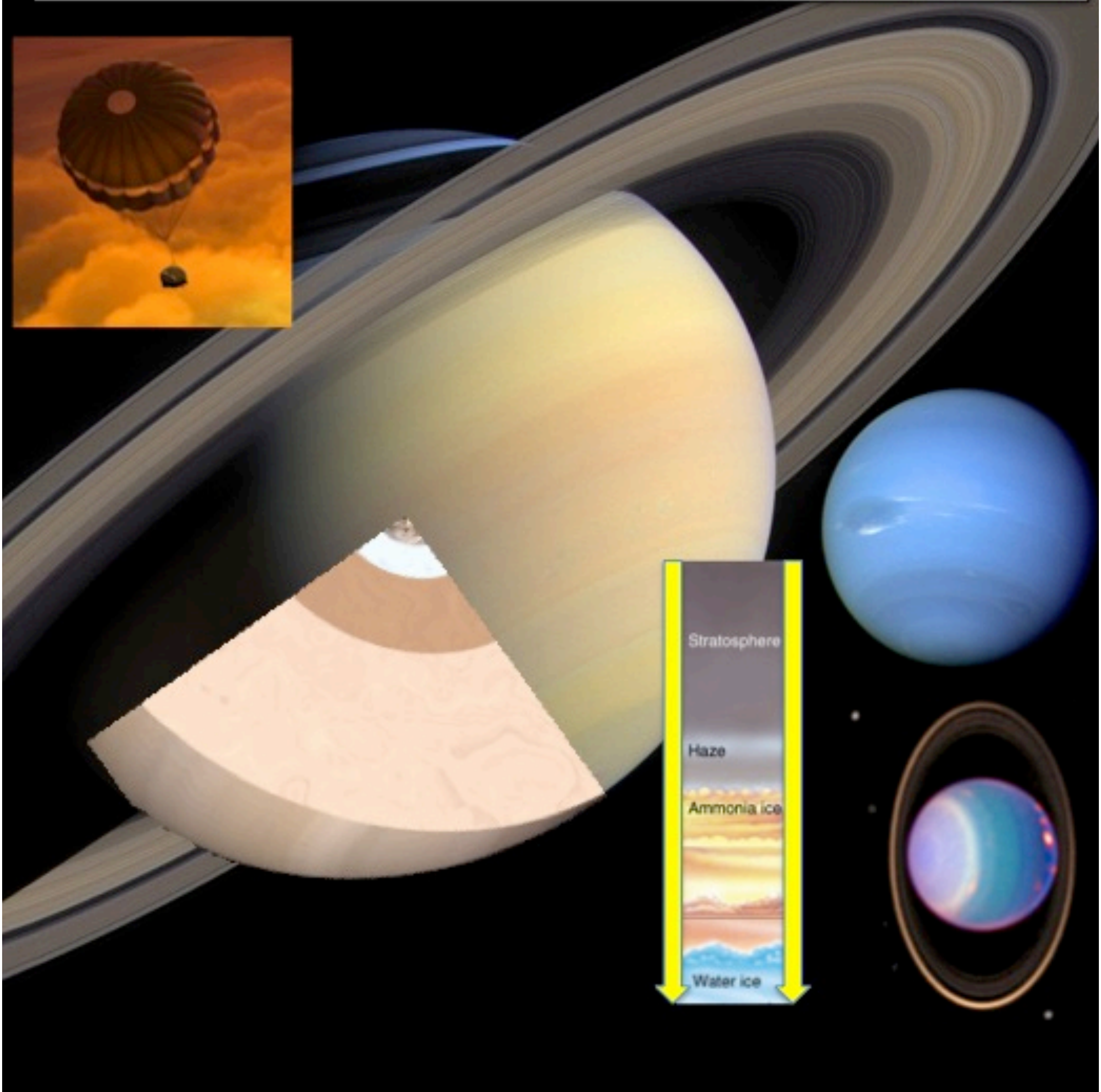
IN SITU EXPLORATION OF THE GIANT PLANETS
and an Entry Probe Concept for Saturn

A White Paper Response to ESA's Call for L-Class Science Themes



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In Situ Exploration of the Giant Planets and an Entry Probe Concept for Saturn

WHITE PAPER RESPONSE TO ESA CALL FOR LARGE-CLASS SCIENCE THEMES

Executive summary

Comparative studies of the elemental enrichments and isotopic abundances measured on the four giant planets would provide unique insights into the processes at work within our planetary system at the time of giant planet formation, providing an invaluable ***window onto the earliest evolutionary stages of our diverse solar system***. In situ measurements via entry probes remain the only reliable, unambiguous method for determining the atmospheric composition from the thermosphere to the cloud-forming regions of their complex weather layers. Furthermore, in situ experiments can reveal the properties of planetary atmospheres (temperatures, densities, composition, clouds, winds, waves and mechanisms responsible for energy, momentum and material transfer across different atmospheric layers) to ***provide 'ground truth' for orbital remote sensing***. Following the orbital reconnaissance of the Galileo and Cassini spacecraft, and the single-point in situ measurement of the Galileo probe to Jupiter, we believe that in situ measurement of a second giant planet (either Saturn or an ice giant) should be an ***essential element of ESA's future cornerstone missions***, providing the much-needed comparative planetology to reveal the origins of our outer planets. This ***quest to reveal the origins of our solar system and the nature of planetary atmospheres*** drives to the heart of ESA's Cosmic Vision, and has vast implications for the origins of planetary systems around other stars. Furthermore, such a mission would ***build on ESA's successful heritage*** following the Huygens lander on Titan, and kick-start technology development for the in situ exploration of other planetary bodies (e.g., Venus). This White Paper presents the top-level science questions for in situ exploration of a giant planet, and in the last section we focus on ***an entry probe for Saturn as the logical next step*** beyond the Galileo probe to Jupiter and the Cassini orbital exploration of Saturn. The development of giant planet entry probe technology within Europe will pave the way for future collaborative efforts with NASA, who are pursuing their own studies of thermal protection requirements at a variety of planetary targets, and will also build upon ESA's Concurrent Design Facility reports into entry probe mission scenarios and previous Cosmic Vision concepts (KRONOS, Marty et al., 2009) for the in situ exploration of Saturn.

1. Motivation and background

Giant planets contain most of the mass and the angular momentum of our planetary system and consequently they must have played a significant role in shaping the architecture of our planetary system and the evolution of the smaller, inner worlds. Furthermore, the formation of the giant planets affected the timing and efficiency of volatile delivery to the Earth and other terrestrial planets (Chambers and Wetherill 2001). Therefore, understanding giant planet formation is essential to understand the origins and evolution of the Earth and other terrestrial planets capable of maintaining life in the form of complex organisms. The origins of the giant planets, their influence on planetary system architectures, and the plethora of physical and chemical processes at work within their atmospheres, make these destinations crucial for future exploration. ***This White Paper advocates in situ exploration of giant planets to address questions at the heart of ESA's Cosmic Vision.*** There is a fundamental difference between the interiors of Jupiter and Saturn and those of Uranus and Neptune. Because Jupiter and Saturn have massive envelopes essentially composed of hydrogen and helium and a relatively small core, they are called ***gas giants***. Meanwhile, data indicate that Uranus and Neptune also contain hydrogen and helium atmospheres but unlike Jupiter and Saturn, their H_2 and He mass fractions are smaller (5 to 20%). They are called ***ice giants*** because their density is consistent with the presence of a significant fraction of ices/rocks in their interiors. Despite this apparent grouping into two classes of giant planets, the four giants likely exist on a continuum, each a product of the particular characteristics of their formation environment. Comparative planetology of the four giants is therefore essential to reveal the formational, migrational and evolutionary processes at work in the early solar nebula***. This White Paper describes the science themes to be addressed by the future probe exploration of the giant planets of our Solar System. In this context, we outline the importance of in situ exploration of*** Saturn in the spirit of the previous ESA Cosmic Vision concept KRONOS (Marty et al. 2009) as a counterpoint to Galileo's in situ exploration of Jupiter, in addition to the science themes to be addressed ***by future probe exploration of an ice giant.***

Remote-sensing observations have always been the favoured approach of astronomers for studying the giants of our Solar System. However, the efficiency of this technique has some limitations when used to study the bulk atmospheric composition crucial to the understanding of planetary origins, namely due to degeneracies between temperatures, clouds and abundances in shaping the emergent spectra. A remarkable example of these restrictions is illustrated by the exploration of Jupiter, where key measurements such as the determination of the noble gases and helium abundances have only been made in situ by the Galileo probe. These measurements revealed unexpected results concerning the Ar, Kr and Xe enrichments with respect to their solar abundances, which suggest that the planet accreted icy planetesimals formed at temperatures possibly as low as 20-30 K to allow the trapping of these noble gases. Another remarkable result was the determination of the Jovian helium abundance obtained by a dedicated instrument aboard the Galileo probe (von Zahn et al. 1998) with an accuracy of 2%. Such accuracy on the He/H_2 ratio is impossible to derive from remote sensing, irrespective of the giant planet being considered, and yet precise knowledge of this ratio is crucial for the modelling of giant planet interiors and thermal evolution. The Voyager mission has already shown that these ratios are far from being identical, which presumably result from their evolution. An important result also obtained by the mass spectrometer aboard the Galileo probe was the determination of the $^{14}N/^{15}N$ ratio, which suggested that nitrogen present in Jupiter today originated from the solar nebula essentially in the form of N_2 (Owen et al. 2001). The mass spectrometer aboard Galileo unfortunately did not make measurements at levels deeper than 22 bars, precluding us from determining the H_2O abundance at levels representative of the bulk oxygen enrichment of the planet. Furthermore, the probe descended into a region depleted in certain volatiles and gases by unusual 'hot spot' meteorology (Orton et al. 1998; Wong et al. 2004), so may not be representative of the planet as a whole.

Nevertheless, the Galileo probe provided a giant step forward our understanding of Jupiter, but one can wonder if these measurements are really representative or not of the whole set of giant planets of the solar system. ***In situ exploration of more than one giant is the only way to address this crucial question for planetary science***. In situ exploration of giant planet atmospheres addresses two broad themes, each of which we will explore in turn:

A. ***Formation history of our solar system investigated by comparing bulk elemental enrichments and isotopic ratios;***
B. ***Atmospheric processes (dynamics, waves, circulation, chemistry and clouds) from the upper atmosphere to below the cloud tops.***

Both themes have relevance far beyond the leap in understanding gained about an individual giant planet – the stochastic and positional variances produced within the solar nebula, the depth of the zonal winds, the propagation of atmospheric waves, the formation of clouds and hazes, disequilibrium processes of photochemistry and vertical mixing are common to all planetary atmospheres, from terrestrial planets to gas and ice giants, to brown dwarves and hot extrasolar planets. ***To progress beyond the Galileo probe findings, we now require a point of comparison.*** This could either be a second gas giant, to test theories of the joint origins of the two largest planets, or one of the ice giants, to assess their compositional differences compared to Jupiter. Despite the wealth of remote sensing data returned by the Cassini spacecraft for Saturn, several key questions still require an in situ probe to answer. ***This White Paper advocates any giant planet mission that incorporates elements of in situ exploration, whether for an ice or a gas giant. This paper also focuses on the description of a Saturn probe scenario because such a mission will appear the next natural step beyond Galileo's in situ exploration of Jupiter, and the Cassini spacecraft's orbital reconnaissance of Saturn.*** Moreover, many of the scientific questions outlined below remain valid additions to the cases for Uranus and Neptune orbital exploration (see White Papers by Arridge et al., Masters et al.). In the following, we detail why in situ exploration is vital to understand giant planet formation and atmospheric processes from the thermosphere to deep below the clouds, and we state the case specifically for a Saturn probe as a vital comparison to the Galileo results. We also provide examples of approach phase science that could enhance the scientific return of any in situ mission.

2. Primary Science Themes

Theme A: Planet Formation and the Origin of the Solar System

Giant planets formed 4.55 Gyr ago, from the same disk of gas and solids that formed the Sun and eventually the entire Solar System. A significant fraction of their mass is composed of hydrogen and helium, the two lightest and most abundant elements in the Universe. Disks dominated by hydrogen and helium are almost ubiquitous when stars appear, but their lifetimes do not exceed a few million years. This implies that the gas giants Jupiter and Saturn had to form rapidly in order to capture their hydrogen and helium envelopes, more rapidly than the terrestrial planets which took tens of millions of years to attain their present masses, and retained only negligible amounts of the primordial gases as part of their final composition. Due to formation at fairly large radial distances, where the solid surface density is low, the ice giants Uranus and Neptune had longer formation timescales (slow growth rates) and did not manage to capture large amounts of hydrogen and helium before the disk gas dissipated. As a result, the masses of their gaseous envelopes are small compared to their ice/rock cores. A ***comparative study of the properties of these giant planets thus gives information on spatial gradients in the physical/chemical properties of the solar nebula as well as on stochastic effects that led to the formation of the Solar System.***

Data on the composition and structure of the giant planets, which hold more than 95% of the non-solar mass of the Solar System (Marty et al. 2009), remain scarce, despite the importance of such knowledge. The formation of giant planets is now largely thought to have taken place via the core accretion model in which a dense core is first formed by accretion and the hydrogen-helium envelope is captured after a critical mass is reached (e.g. Mizuno 1980; Pollack et al. 1996). Once accounting for planet migration (e.g. Lin and Papaloizou 1986; Ward 1997), such a model can explain the orbital properties of exoplanets, although lots of unresolved issues remain (e.g. Ida and Lin 2004; Mordasini et al. 2012). However, an alternative scenario for the formation of giant planets remains the disk instability model (e.g. Boss 1997, 2001), in which they form from the direct contraction of a gas clump resulting from local gravitational instability in the disk. In principle, measurements of bulk elemental enrichments and isotopic ratios would help us to ***distinguish between these competing formation scenarios***.

Formation and evolution models indicate that the total mass of heavy elements present in Jupiter may be as high as 42 *Earth-masses* (hereafter EM) whereas the mass of the core is estimated to range between 0 and 13 EM (Saumon and Guillot 2004). In the case of Saturn, the mass of heavy elements can increase up to 35 EM with the mass in the envelope varying between 0 and 10 EM and the core mass ranging between 0 and 20 EM (Helled and Guillot 2013). The masses of heavy elements are found to be in the 10.9-12.8 and 12.9-15.2 EM ranges for Uranus and Neptune, respectively (Helled et al. 2011). Direct access to heavy materials within giant planet cores to constrain these models is impossible, so we must use the composition of the well-mixed troposphere to infer the properties of the deep interiors. ***Remote sounding cannot provide the necessary information*** because of a lack of sensitivity to the atmosphere beneath the cloudy, turbulent and chaotic weather layer. These questions must be addressed by in situ exploration.

The availability of planetary building blocks (metals, oxides, silicates, ices) is expected to vary with position within the original nebula, from refractories in the warm inner nebula to a variety of ices of water, CH_4, CO, NH_3, N_2 and other simple molecules in the cold outer nebula. Turbulent radial mixing, and the evolution of the pressure-temperature gradient in the disk could have led to distinct regions where some species dominated over others (e.g., the water-ice snow line or N_2 over NH_3). Furthermore, both inward and outward migration of the giants during their evolution could have provided access to different material reservoirs at different epochs. A giant planet's bulk composition therefore depends on the timing and location of planet formation, subsequent migration and the delivery mechanisms for the heavier elements. By measuring a giant planet's chemical inventory, and contrasting it with measurements of (i) other giant planets, (ii) primitive materials found in comets and asteroids, and (iii) the abundance of our parent star and the local interstellar medium, can reveal much about the ***conditions at work during the formation of our planetary system***. Furthermore, comparison to the compositions of the larger ensemble of extrasolar giant planets would place our own planetary origins in a broader context.

Galileo at Jupiter: To date, the Galileo probe at Jupiter (1995) remains our only data point for interpreting the bulk composition of the giant planets. Galileo found that Jupiter exhibited an enrichment in carbon, nitrogen, sulfur, argon, krypton and xenon compared to the solar photospheric abundances, with some notable exceptions – water was found depleted, may be due to meteorological processes at the probe entry site; and neon was depleted, possibly due to rain-out to deeper levels (Niemann et al. 1998, Wong et al. 2004). In any case the oxygen abundance in Jupiter remains an enigma. The Juno mission, which will arrive at Jupiter in 2016, may provide an estimate of the tropospheric O/H ratio. Interestingly, the nitrogen isotope composition of Jupiter is similar within errors to the protosolar nebula value (Marty et al. 2011) whereas the N isotope composition of comets is very different (enriched in ^{15}N by a factor of two). Explaining the high abundance of noble gases requires either condensing these elements directly at low temperature in the form of amorphous ices (Owen et al. 1999), trapping them as clathrates in ices (Gautier et al. 2001; Hersant et al. 2008; Mousis et al. 2009, 2012) or photoevaporating the hydrogen and helium in the protoplanetary disk during the planet's formation (Guillot and Hueso 2006). The Galileo measurements at Jupiter also include a highly precise determination of the planet's helium abundance, crucial for calculations of the structure and evolution of the planet. Figure 1 represents fits of the volatile enrichments measured at Jupiter in the context of two different formation models, both being based on the hypothesis that Jupiter's building blocks formed from a mixture of rocks and crystalline ices but postulating a different oxygen abundance in the formation zone of Jupiter in the primordial nebula. While the quality of the matching of the volatile abundances is fairly similar, these two scenarios provide different predictions of the oxygen abundance in Jupiter. These calculations illustrate the strong connection between the formation circumstances of the planet and its bulk composition, and similar measurements for Saturn or an ice giant would enable comparison of their formation mechanisms to Jupiter.

Saturn Probe: Because of the absence of in situ measurements, the noble gas abundances are unknown in Saturn. However there is some indication for a non-uniform enrichment in C, N and S. Hersant et al (2008) suggest that ground-based and space-based (Cassini) observations are well fitted if the atmospheric carbon and nitrogen of the planet were initially mainly in reduced forms at 10 AU in the solar nebula. Alternatively, Mousis et al. (2009) find that it is possible to account for the volatile enrichments in Saturn in a way that is consistent with those measured at Jupiter if the building blocks of the two planets shared a common origin. ***A determination of the oxygen abundance on Saturn via in situ exploration would distinguish between these scenarios***. Furthermore, ***a determination of***

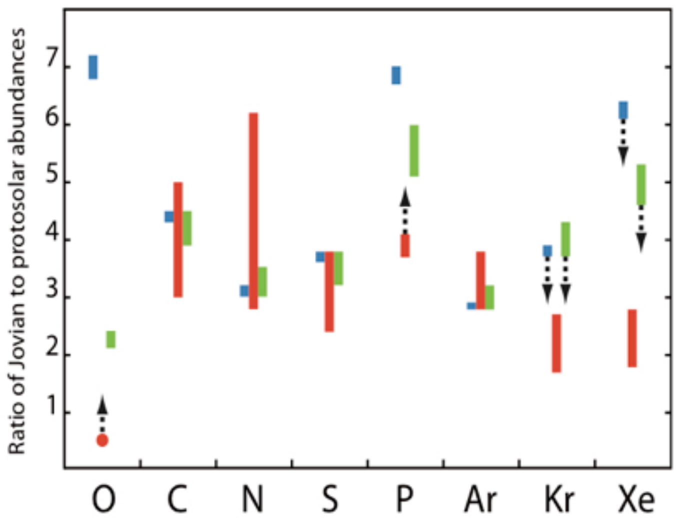

Figure 1. Ratio of Jovian to protosolar abundances (Mousis et al. 2012). Red bars and the red dot correspond to observations made by the Galileo probe. Green and blue bars correspond to calculations based on an oxygen abundance that is 0.5 and 1 times the protosolar value in the feeding zone of Jupiter, respectively. The corresponding oxygen abundances are predicted to be about 2 and 7 times protosolar in the Jovian atmosphere. Arrows pointing up correspond to the possibility that the measured oxygen and phosphorus abundances are lower than their bulk abundances, and arrows pointing down to the possibility that planetesimals could be impoverished in krypton and xenon (Pauzat et al. 2013).

noble gases is indispensable to understand the formation conditions of Saturn. On one hand, Hersant et al. (2008) predict that Ar and Kr should be solar in Saturn while Xe could be supersolar, whereas Mousis et al. (2009) find that all these species should be significantly supersolar. In addition, a determination of the volatile enrichments in Saturn could also provide a constraint on its rotation period, which will help to better infer its internal structure (Helled and Guillot 2013; Nettelmann et al. 2013). Moreover, as Saturn's atmosphere is believed to be depleted in helium as a result of H/He phase separation and subsequent helium rain, a precisely measured He/H_2 value of Saturn's atmosphere is crucial for probing the theoretical H/He demixing phase diagram, which is impossible with current laboratory technology for high-pressure physics. Helium-rain has long been predicted to occur in Saturn as an explanation for its high luminosity. Therefore, an entry probe measurement of the helium abundance is required to resolve this riddle.

Ice Giant Probes: Compared to the two gas giants, only a small amount of the solar nebula gas appears to have been accreted by Uranus and Neptune (about 3.6 EM for Uranus and 4.2 EM for Neptune; Helled et al. 2011), implying that elemental enrichments and isotopic ratios could vary significantly from the gas to the ice giants, indicative of their different formational mechanisms. Hersant et al. (2004) have calculated that Ar and Kr should be solar in the hydrogen envelope, while the Xe enrichment would be oversolar by a large factor. Therefore comparative measurements of noble gases in Saturn and the ice giants, for comparison to the Galileo probe results, should provide a firm representation of the theory of volatile enrichments with respect to the Sun. A very interesting peculiarity of the composition of Uranus and Neptune is that microwave observations have revealed a very large oversolar S/N ratio (Gulkis et al. 1978). This has been interpreted as resulting from the formation of NH_4SH clouds in the troposphere from the combination of NH_3 in H_2S, but it should be noted that models fitting the microwave spectra leave room for significant ambiguity, which will only be resolved by in situ sampling. For Saturn and the ice giants, a precise determination of the He/H_2 is necessary for constraining the models of interiors of Uranus and Neptune and their cooling history since formation (i.e., to explain their intrinsic luminosities). Following the in situ exploration of Saturn, we propose that the second priority for giant planet exploration features ***future bulk compositional measurements of an ice giant***, in tandem with orbital exploration, to reveal why their evolution diverged so substantially from that of the gas giants. Table 1 shows the measured abundances of the heavy elements (relative to solar) and several key isotopes at Jupiter, Saturn, Uranus and Neptune. On the three latter planets, reliable data concerning elemental abundances are much more limited, due to the absence of situ measurements and substantial ambiguities in the remote sensing data.

Element	**Jupiter/Sun**	**Saturn/Sun**	**Uranus/Sun**	**Neptune/Sun**
He	0.8[a]	0.6–0.9[a]	0.92–1[a]	0.9–1.0[a]
Ne	0.59[a]	?	?	?
O	0.3–0.7[b] (*)	?	?	?
C	3–5[b]	8.8–9.6[c]	20–30[a]	30–50[a]
N	2.8–6.2[b]	?	?	?
S	2.4–3.8[b]	?	?	?
P	3.7–4.1[b]	8.9–13.5[c]	?	?
Ar	2.8–3.8[b]	?	?	?
Kr	1.7–2.7[b]	?	?	?
Xe	1.8–2.8[b]	?	?	?
Isotope	Jupiter	Saturn	Uranus	Neptune
D/H	2.6 +/-0.7E-5[a]	2.3 +/-0.4E-5[a]	4.4+/-0.4 E-5[d]	4.1+/-0.4E-5[d]
^{3}He/^{4}He	1.7 +/-0.0E-5[a]	?	?	?
^{15}N/^{14}N	2.3 +/-0.3E-3[a]	?	?	?

Table 1. Elemental abundances (relative to solar) and isotopic ratios measured in Jupiter, Saturn, Uranus and Neptune. [a] Atreya (2007), [b] Mousis et al. (2012), [c] Mousis et al. (2009), [d]Feuchtgruber et al. (2013), (*) this value is probably a lower limit.

Measurement Requirements for Constraining the Origins of Saturn and Ice Giants

The “ideal” measurement requirements are:

- **The atmospheric fraction of He/H_2 with a 2% precision on the measurement;**
- **The elemental enrichments in cosmogenically abundant species C, H, O, N and S C/H, N/H, S/H and O/H should be sampled with a precision better than +/- 10%.**
- **The isotopic ratios in hydrogen (D/H), oxygen (^{18}O, ^{17}O and ^{16}O), carbon ($^{13}C/^{12}C$) and nitrogen ($^{15}N/^{14}N$), to determine the key reservoirs for these species (e.g., delivery as N_2 or NH_3 vastly alters the $^{15}N/^{14}N$ ratio). $^{13}C/^{12}C$, $^{18}O/^{16}O$ and $^{17}O/^{16}O$ should be sampled with a precision better than +/- 1%. D/H, $^{15}N/^{14}N$ should be analyzed in the main host molecules with a precision order of +/- 5%.**
- **The abundances and isotopic ratios for the chemically inert noble gases He, Ne, Xe, Kr and Ar, provide excellent tracers for the materials in the sub-reservoirs existing in the proto-solar nebula. The isotopic ratios for He, Ne, Xe, Kr and Ar should be measured with a precision better than +/- 1%.**
- **The elemental enrichments in minor species delivered by vertical mixing (e.g., P, As, Ge) from the deeper troposphere. P/H, As/H and Ge/H should be sampled with a precision better than +/- 10%.**

The depth of probe penetration will determine whether it can access the well-mixed regions for key condensable volatiles. In the case of Saturn, a shallow probe penetrating to 5-10 bar would sample ammonia and H_2S both within and below their cloud bases, in the well-mixed regions of the atmosphere to determine the N/H and S/H ratios, in addition to noble gases and isotopic ratios. This would not be the case for Uranus and Neptune, where a shallow entry probe must focus on noble gas enrichments and isotopic ratios. Such a probe would be able to sample condensable volatiles such as methane (condensing in the 1-2 bar region) and ammonia/H_2S above or possibly within their cloud bases (condensing in the 5-10 bar region), but would not reach the well-mixed tropospheres of the ice giants. Shallow entry probes would be unlikely reach the deep hypothesised water clouds on any giant planet, so that the deep O/H ratio would remain elusive unless accompanied by remote sensing experiments on an carrier spacecraft capable of probing these depths (e.g., the Juno microwave radiometer, currently en route to Jupiter). Of all these targets, a deeper entry probe on Saturn, penetrating to the 20-30 bar level, might reach the water cloud base to permit a precise measurement of Saturn’s O/H ratio, providing a strong ***argument for targeting Saturn as the next destination for in situ exploration beyond the Galileo and Juno investigations of Jupiter***. Nevertheless, measuring elemental abundances (in particular He, noble gases and other cosmogenically-common species) and isotopic ratios using a shallow entry probe on Saturn or an ice giant would provide a vital comparison to Galileo’s measurements of Jupiter, and crucial ‘ground-truth’ for the remote sensing investigations of the Cassini spacecraft.

Theme B: Planetary Atmospheric Processes

Planetary atmospheres constitute our only accessible gateway to the processes at work within the deep interiors of the giant planets, and yet we must extrapolate from this thin, dynamic region over many orders of magnitude in pressure, temperature and density to infer the planetary properties deep below the clouds. Remote sensing provides insights into the complexity of the transitional zone between the external environment and the fluid interior, but there is much that we still do not understand. In situ measurements are the only method providing ground-truth to connect the remote-sensing inferences with the environmental conditions below the clouds, and yet this has only been achieved twice in the history of outer solar system exploration, via the Galileo probe for Jupiter and the Huygens probe for Titan. In situ studies provide ***access to atmospheric regions that are beyond the reach of remote sensing***, enabling us to study the dynamical, chemical and aerosol-forming processes at work from the thermosphere to the troposphere below the cloud decks. The scientific objectives are summarised in Figure 2 and have relevance to both Saturn and the ice giants, but any of these targets would provide a fascinating comparison to the results of the Galileo probe at Jupiter. In this theme, we demonstrate how in situ sampling addresses two crucial questions:

- ***What processes are at work in planetary atmospheres, shaping the dynamics and circulation from the thermosphere to the deep troposphere?***
- ***What are the properties and conditions for cloud formation as a function of depth and temperature in planetary atmospheres?***

Meteorology and Dynamics

Giant planets are natural planetary-scale laboratories for the study of geophysical fluid dynamics without the complicating influences of terrestrial topography, yet remote sensing only provides access to limited altitude ranges, principally via visible and infrared observations in the upper troposphere just above the condensate clouds and within the tropospheric hazes; and secondly in the mid-stratosphere near the 1-mbar level via mid-infrared emissions. Regions below the top-most clouds and in the middle/upper atmosphere are inaccessible, limiting our knowledge of the vertical variations of temperatures, densities, horizontal and vertical winds and waves, compositional profiles and cloud/haze properties. A probe would be able to measure continuous profiles of these parameters during descent. Temperatures and densities in the upper atmosphere could be determined via the deceleration caused by atmospheric drag, connecting the high temperature thermosphere at nanobar pressures to the middle atmosphere at microbar and millibar pressures (e.g., Yelle et al. 2004). An atmospheric structure instrument, (e.g., Galileo/ASI, Seiff et al. 1998) would measure temperatures, pressure and densities throughout the descent to the clouds, sampling both the radiatively-cooled upper atmosphere and the convectively-cooled troposphere, precisely constraining the static stability, radiative-convective boundary (i.e., how far down does sunlight penetrate?) and the levels of the tropopause, stratopause, mesopause and turbopause. Thermal structure measurements of Saturn or an ice giant could be directly compared to those on Jupiter to ***understand the energetic balance between solar heating, thermal cooling, latent heat release, wave heating and internal energy*** for driving the complex dynamics of all the different atmospheric layers on the giants, and how this balance differs as a function of distance from the Sun.

Perturbations of the temperature structure due to vertical propagation of gravity waves are expected to be common features of the stably stratified middle atmospheres. Wave activity is thought to be a key

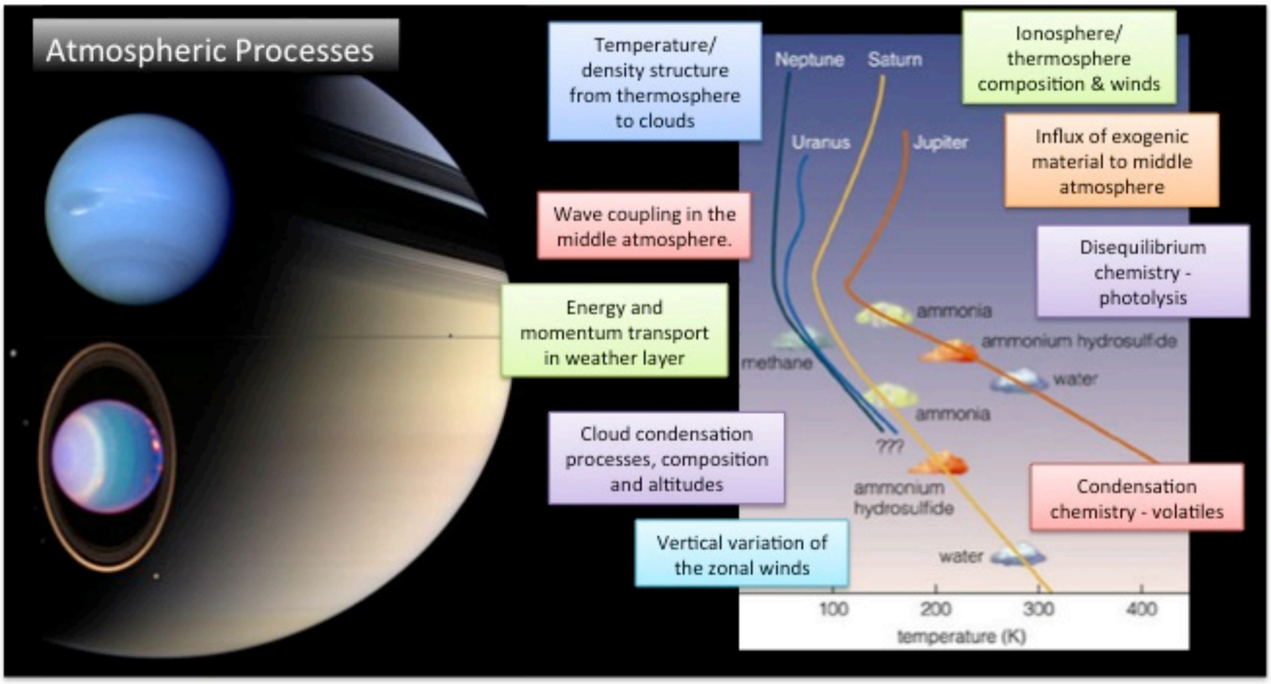

Figure 2. Examples of the vertical temperature structures of the giant planets, highlighting the scientific themes to be addressed via in situ remote sensing. Vertical profiles of temperature, density, radiant flux, chemical and aerosol composition will all be acquired during the descent of an entry probe from the upper atmosphere to depths within and below the cloud-forming regions.

coupling mechanism between the convective troposphere (e.g., gravity waves and Rossby/planetary waves radiated by rising plumes and vortices) and the stable middle/upper atmosphere, being responsible for transporting energy and momentum vertically through the atmosphere. Energy and momentum transfer via waves serves as a source of both heating and cooling for the hot thermospheres, whose temperatures far exceed the expectations from solar heating alone, although the precise origins of the heating source has never been satisfactorily identified (e.g., Hickey et al., 2000; Yelle et al. 2009). The periodicity of gravity waves measured by the Galileo probe on Jupiter has allowed us to reconstruct the zonal wind profile from the lower thermosphere to the upper troposphere (Watkins and Cho 2013), permitting identification of the turbopause (where molecular and eddy diffusion become comparable and gravity waves break to deposit their energy), above which the atmosphere separates into layers of different molecular species. ***Understanding the propagation, periodicity and sources of wave activity on the giant planets will reveal the properties of the background medium and the coupling of the 'weather layer' to the middle atmosphere***, and facilitate direct comparison with Jupiter.

In situ exploration would also allow us to tackle one of the most enduring mysteries for the giant planets – ***what powers and maintains the zonal winds responsible for the planetary banding, how deep do those winds penetrate into the troposphere, and what are the wind strengths in the middle atmosphere?*** Remote sensing of temperature contrasts (and hence wind shears via thermal wind relationships), or inferences from the properties of atmospheric plumes at the cloud-tops (e.g., Sanchez-Lavega et al. 2008) cannot directly address this question, but in situ measurements of the vertical variation of winds on Saturn or an ice giant may help distinguish between shallow and deep models for this zonal organisation of the atmospheric flows. The Galileo probe's Doppler Wind Experiment (DWE, Atkinson et al. 1998) reported that jovian winds were at a minimum at the cloud tops (where most of our understanding of zonal winds and eddy-momentum fluxes originates from), and increased both above and below this level. In the deep atmosphere, DWE demonstrated that the winds increased to a depth of around 5 bars, and then remained constant to the maximum probe depth of around 20 bars. Similar measurements on Saturn could ***sample the transition region between two different circulation regimes*** - an upper tropospheric region where eddies cause friction to decelerate the zonal jets and air rises in cloudy zones, and a deeper tropospheric region where the circulation is reversed, eddy pumping is essential to maintain the jets and air rises in the warmer belts (e.g., del Genio et al. 2009; Fletcher et al. 2011). A single entry probe to either a mid-latitude belt or a zone would sample both regimes, albeit at different altitudes. Multiple entry probes would be highly desirable for any of the four giant planets, but is beyond the scope of the present white paper. Reconciling these two views of tropospheric circulation on Saturn would have implications for all of the giants, and provide crucial new information to solve a mystery left by the Cassini spacecraft. Alternatively, the measurement of the vertical variation of winds on an ice giant would ***establish the fundamental similarity or difference between circulation patterns on gas and ice giants***. Finally, direct measurements of winds in the middle atmospheres of any of these targets would establish the reliability of extrapolations from the jets in the cloud tops to the stratosphere in determining *the general circulations of planetary stratospheres.*

Composition and Clouds

In Theme A we demonstrated the need for reliable measurements of bulk elemental enrichments and isotopic ratios to study the formation and evolution of the giant planets. However, vertical profiles of atmospheric composition (both molecular and particulate) are essential to ***understanding the chemical, condensation and disequilibrium processes at work.*** Jupiter's atmospheric composition (e.g., Atreya et al. 1999) was measured by the Galileo probe's mass spectrometer (Niemann et al. 1998), optical interferometer (specifically for a refractive index measurement to determine the helium abundance, von Zahn et al. 1998), net flux radiometer (NFR) and nephelometer (NEP), between pressures of 0.5 and 20 bar. The attenuation of the probe signal as it moved deeper into the atmosphere also revealed the density and composition. These instruments revealed an unexpectedly dry region of the jovian troposphere, depleted in clouds and volatiles, which was consistent with ground-based observations of the probe entry into a warm cyclonic vortex (e.g., Orton et al. 1998). For this reason, the compositional profiles measured by Galileo are not thought to be globally representative, leading to a desire for ***multiple entry probes for different atmospheric regions in future, more ambitious missions.*** Nevertheless, a single atmospheric entry probe for Saturn or an ice giant would provide an intriguing counterpoint to Galileo's sampling of Jupiter's unusual meteorology.

A poor understanding of cloud and haze formation in planetary atmospheres of our solar system may be the key parameter limiting our ability to interpret spectra of extrasolar planets and brown dwarfs (e.g., Marley 2013). Although equilibrium cloud condensation models, combined with the sedimentation of condensates to form layers, have proven successful in explaining the broad characteristics of the planets (methane ice clouds on ice giants, ammonia ice clouds on gas giants), they apparently fail rather spectacularly in predicting the location, extent and microphysics of the observed cloud decks. The Galileo probe results defied expectations of equilibrium condensation by revealing clouds bases at 0.5, 1.3 and 1.6 bar, plus tenuous structure from 2.4-3.6 bar and no evidence for a deep water cloud (West et al. 2004). Ammonia ice on Jupiter has only been spectroscopically identified in small, localised regions of powerful convective updrafts (e.g., Baines et al. 2002). The spectral signature of pure ammonia ice is likely obscured by a coating or mixing with other products, such as photolytically produced hydrocarbons, hydrazine or diphosphine (e.g., Sromovsky et al., 2010; West et al., 2004). The spectral properties of these mixtures are poorly known, rendering cloud remote sensing highly ambiguous. The only way to resolve these questions is by ***in situ sampling of the clouds and hazes formed in a planet's atmosphere***, using instruments designed to measure the particle size distributions, radii, number densities, mass densities, optical depth and size properties. Combined with the vertical profiles of condensable volatiles (e.g., CH_4 on the ice giants; NH_3, H_2S and H_2O on all the giants) and photochemically-produced species (hydrocarbons, hydrazine, diphosphene), this would give an estimate of the composition of giant planet condensation clouds and upper atmospheric hazes for the first time. Precise determination of bulk atmospheric composition is made difficult since all species in the upper troposphere are affected by fractionation and mixing. However, Saturn's atmosphere provides the most accessible cloud decks for this study (condensates of NH_3 and H_2O are locked away at considerably higher pressures on the ice giants), the most useful comparison to remote sensing data (e.g., from Cassini) and the most similar composition to Jupiter for a full understanding of gas giant clouds.

Volatiles are removed from the gaseous phase both by condensation, and by photolytic destruction. Indeed, all the giant planets exhibit a rich chemistry due to the UV photolysis of key atmospheric species. Their stratospheres are dominated by the hydrocarbon products of methane photolysis (e.g., Moses et al. 2005), and their tropospheres by the photolysis of residual saturated ammonia and phosphine dredged from their deeper interiors by vigorous atmospheric mixing (e.g., Fletcher et al. 2009). Additional trace species in the troposphere (GeH_4, AsH_3, CO) provide constraints on the ***strength of atmospheric mixing*** from deeper, warmer levels below the clouds; unusual chemical products (HCN, HCP, CS) ***reveal coupled chemistry*** due to lightning activity or shock chemistry due to planetary impacts; and oxygenated species in the high stratosphere (CO, CO_2, H_2O) reveal the ***strength of exogenic influx*** of materials (comets, interplanetary dust, e.g., Harrington et al., 2004) into the upper atmospheres. Sensitive mass spectrometry of these species, combined with probe measurements of atmospheric temperatures and haze properties, could ***reveal the processes governing the soup of atmospheric constituents on the giant planets.*** Once again, Saturn's trace species are expected to be the most accessible, as volatiles and disequilibrium species (e.g., PH_3 and NH_3) have so far eluded detection on the ice giants.

This rich chemistry extends into the thermospheres of the giants planets, where gaseous constituents are ionised by solar EUV radiation at mid-to-high latitudes and by charged-particle bombardment in the circumpolar regions. At lower altitudes where solar UV rays and charged particles do not penetrate, ionization by cosmic rays may become important (Capone et al. 1979). Photoionisation of CH_4 can lead to CH^+, CH_2^+ and CH_4^+ ions that react efficiently with molecular hydrogen to form CH_3^+ and CH_5^+ ions. At lower altitudes CH_3^+ ions can react with acetylene and methane to produce hydrocarbon ions containing more carbon atoms. The dissociative recombination of these species then leads to neutral hydrocarbons (Kim and Fox 1994) and thus starts a very complex hydrocarbon chemistry leading to e.g., benzene. Isotopic ratios measured in these ionic species could reveal their formational pathways. In situ measurements of this ion-neutral chemistry using mass spectrometers capable of distinguishing ions and isotopes of very similar masses would ***revolutionize our understanding of upper atmospheric chemistry***, with capabilities far beyond that of the Galileo probe. ***The possibility to identify ions and neutrals with high masses and to determine their abundances will allow a vastly improved understanding of important processes like the formation of aerosols and, subsequently, generation of haze and clouds.***

Measurement Requirements for the atmospheres of Saturn and ice giants

Although the science case differs slightly for Saturn and the ice giants due the accessibility of certain species (e.g., methane condensation on the ice giants versus ammonia on the gas giants, and the improved detectability of tropospheric trace species on Saturn), we summarise the requirements for atmospheric science as follows:

- **Determine the thermal and density profile from thermosphere to troposphere, and the balance between different energy sources controlling atmospheric dynamics and structure;**
- **Measure the strength of the winds as a function of altitude and the importance of wave perturbations on atmospheric structure;**
- **Sample and determine the properties of cloud and haze layers as a function of depth (e.g., methane and hazes on ice giants; NH_3, NH_4SH and N- and P-bearing hazes on Saturn);**
- **Measure the vertical profiles of chemical products, disequilibrium species and ions to understand vertical mixing and atmospheric chemistry.**

3. Ancillary Science Themes: Approach Phase & Carrier

In Section 2 we demonstrated the specific scientific case for in situ measurements by an atmospheric probe for Saturn or an ice giant. The measurement requirements specified above should be considered as essential for any giant planet entry probe mission. However, a mission flying to one of these targets presents a substantial opportunity for secondary science during the approach and flyby phases. In the following sections, we describe a subset of science themes related to the in situ atmospheric experiments: Doppler seismology to ***probe the existence of a planetary core*** and supplement Theme A (Origins); ***atmospheric electricity to support the in situ exploration of the weather layer*** in Theme B (Atmosphere); and suggestions for ***in situ sampling of material associated with the rings and inner magnetosphere of Saturn*** to study the connectivity between the planet and its immediate magnetospheric environment. A detailed trade study would be conducted for any future mission proposal to assess their feasibility, but this provides a taste of the opportunity that the giant planet probe mission represents.

Doppler Seismology Approach

As mentioned in Theme A, the present internal structure of giant planets is the result of their formation and evolution. Unveiling this internal structure would give unprecedented constraints both on the formation scenario and on the physics controlling its evolution. After decades of fruitless attempts, the seismology of giant planets is finally providing very exciting results. Ground-based observations demonstrated the existence of acoustic modes of ~30cm/s amplitude and frequencies between 1 and 3 mHz on Jupiter (Gaulme et al.

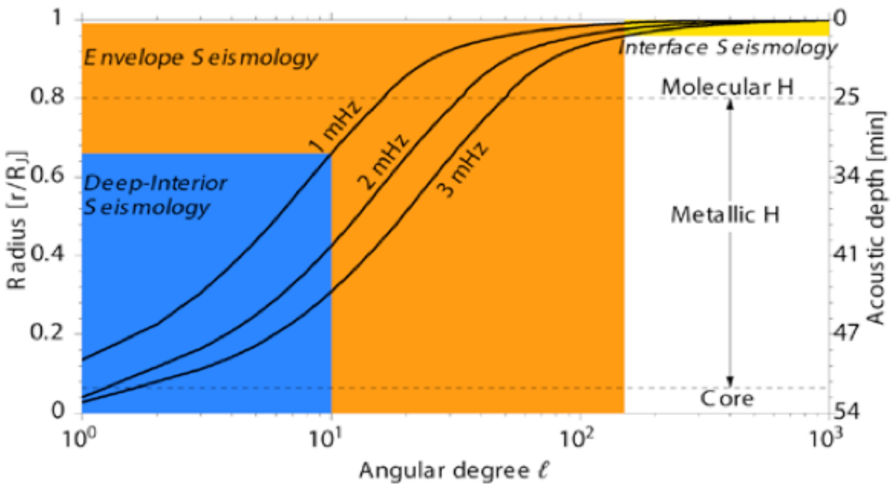

Figure 3. Internal turning point of acoustic oscillations as a function of the degree, for different frequencies in the expected, and observed range of excited modes (here calculated for Jupiter). It shows the zone inside the planet that can be explored following the angular resolution:R/10 in blue, R/150 in orange, higher resolution in yellow (local seismology).

2011), consistent with expectations (e.g., Vorontsov et al. 1976; Bercovici and Schubert 1987). Observations of stellar occultation by Saturn's rings, made by the Cassini spacecraft, exhibited density waves structures that can only be explained as a consequence of some of Saturn's oscillations modes resonating in the rings (Hedman and Nicholson 2013). This result was also predicted (Marley and Porco 1993). These discoveries are extremely exciting because they announce a revolution in the study of the interiors of these planets similar to that experienced for the Sun with solar seismology (e.g., Christensen-Dalsgaard 1996). Unfortunately, the data that can be acquired now, or even in the future, from the ground remains insufficient to get the full reward of the techniques.

Seismology requires ***continuous observations of spatially resolved global modes for period of weeks, or months***. A ***spacecraft approaching a planet would provide a long enough observing period of several months, with resolution sufficient to detect all modes with degree l>10, sounding precisely the central part of the planet, particularly the core.*** As the probe get closer, the observing time decreases, but the number of observed modes increases with the square of the inverse of the distance, giving access to the whole internal structure and rotation. At close distance, time-travel analysis (local seismology) will give estimation of the temperature and motions just below the surface that will help to understand the conditions found by the entry probe. At the same time, the same instrument would also provide a monitoring of the surface in the visible domain as well as instantaneous Doppler velocity maps, allowing the study of the global and detailed dynamics of the atmosphere, even in absence of clouds for tracking, and separation between waves and winds. In conclusion, the addition of a Doppler seismometer to the planetary probe carrier would provide complementary information on both origins and atmospheres for the in situ measurements of the probe.

Lightning and Atmospheric Electricity

The in situ exploration of a giant planet weather layer will provide new insights into the cloud-forming processes below the levels normally visible to remote sensing (Theme B). Lightning flashes most likely exist in the atmospheres of all gas planets (Yair et al. 2008), and the Galileo Probe lightning and radio emission detector (LRD) used a magnetic antenna to detect signals of lightning from Jovian clouds with an electric dipole moment change about 100 times that of terrestrial lightning (Rinnert et al. 1998). The existence of lightning in Saturn's atmosphere has been proven by Voyager and Cassini measurements of radio emissions (Fischer et al. 2008) and direct optical flash observations (Dyudina et al. 2010). The thunderstorms tend to appear infrequently at the equator and in the "storm alleys" at the latitudes of 35° north and south. The flashes originate from a depth of 125-250 km below the 1-bar level, most likely in the water clouds. So far, Saturn lightning radio emissions have only been measured above the ionospheric cutoff frequency (~1 MHz). Measurements in the VLF region (3-30 kHz) can reveal the unknown spectrum at lower frequencies, where lightning radio emissions are expected to be strongest and to be able to propagate over thousands of kilometers below the ionosphere. Another unique and new measurement for gas planets concerns Schumann resonances in the TLF (<3 Hz) and ELF regions (3-300 Hz), which should be excited by lightning in their gaseous envelopes (e.g. Sentman 1990). It has been suggested that such a measurement could even constrain the water abundance on giant planets (Simões et al. 2012), and it would be very useful in conjunction with conductivity measurements throughout the descent of the probe.

Ring Science

The ring systems of Jupiter, Saturn, Uranus and Neptune show diverse physical and dynamical properties. The rings of Jupiter and Saturn have vertical corrugations likely due to recent impact events (Showalter et al. 2011; Hedman et al. 2011) while direct observations of impacts on Saturn's rings (Tiscareno et al. 2013) have constrained the impact flux in the outer solar system. For all the ring systems, timescale problems suggest either a relatively recent origin or a continuous source of material from nearby satellites. Results from the Cassini-Huygens mission have revolutionised our understanding of Saturn's rings, having provided the opportunity to study in detail the closest example of an astrophysical disk as it evolves (Cuzzi et al. 2010). Key discoveries include (i) observations of "propellers" in Saturn's A ring (Tiscareno et al. 2006) and their orbital migration (Tiscareno et al. 2010), (ii) the detection of self-gravity wakes (Colwell et al. 2006) and (iii) observations of objects forming in the F ring (Beurle et al. 2010) and colliding with it (Attree et al. 2012). Despite its success, the Cassini mission cannot address the question of the physical appearance and composition of ring particles and the exact nature of their localised clustering in self-gravity wakes, which are crucial to determining the origin and lifetime of the rings.

Voyager images and recent Keck observations reveal that Saturn has a major interaction between its atmosphere and ring-dominated inner magnetosphere. Charged water particles bound to magnetic field lines “rain” down on to the ionosphere of Saturn from the rings, causing the appearance of dark bands in Saturn's upper atmosphere (Connerney 1986). In the dark regions, the influx of charged water products reacts with the ionosphere (Jontof-Hutter and Hamilton 2012a, 2012b; O’Donoghue et al. 2013). This “ring-rain” must act to alter the chemistry and temperature of Saturn's atmosphere, but current and future telescopes cannot gather the required light to study this unique interaction much further. ***In situ measurements of this material flux are absolutely essential in order to understand how the atmosphere responds to its planetary ring system raining into it.*** Our understanding of the evolution and lifetime of the rings as well as the influence of the rings on the upper atmosphere will be enhanced by both the carrier and in situ phase of this mission.

Magnetic dynamo, magnetosphere and radiation environment

The relative orientations of the rotation and the magnetic dipole axis and the direction of the solar wind flow lead to important differences in all the planetary magnetospheres in our Solar System (Russell and Dougherty 2010). Jupiter and Saturn have giant magnetospheres shaped by a broad diversity of internal plasma sources and the fast planetary rotation. Uranus and Neptune (see the white papers by Arridge et al. and Masters et al.) have unusual asymmetric magnetospheres that result from the significant tilt between the planetary magnetic dipole and the rotation axis, and the existence of significant multipolar magnetic fields.

Saturn's rich magnetospheric environment is unique in the solar system. It strongly interacts with all other components of the saturnian system: the planet, its rings, numerous satellites (icy moons and Titan) and various dust, neutral and plasma populations. In the innermost regions of this System, the main rings are a very strong absorber of energetic particles so that Saturn’s main radiation belts stop exactly at the outer edge of the main rings. A second radiation belt has however been discovered planetward of the D ring (Krimigis et al. 2004). The saturnian magnetosphere is shaped by a nearly axisymmetric intrinsic planetary magnetic field, the rotational and magnetic axis of Saturn being almost aligned, but a strong modulation related to a longitudinal asymmetry of yet unknown nature was detected in SKR emissions (Carbary and Mitchell 2013). Very close magnetic field measurements are needed to construct a more complete intrinsic magnetic field model, with more high degree moments being better resolved, and decipher the unique dynamo that may operate at Saturn (Cao et al. 2012). Accurate measurements of the magnetic field very close to Saturn's atmosphere and thus unfiltered by the ring is a key to both the composition and conductivity of Saturn's interior.

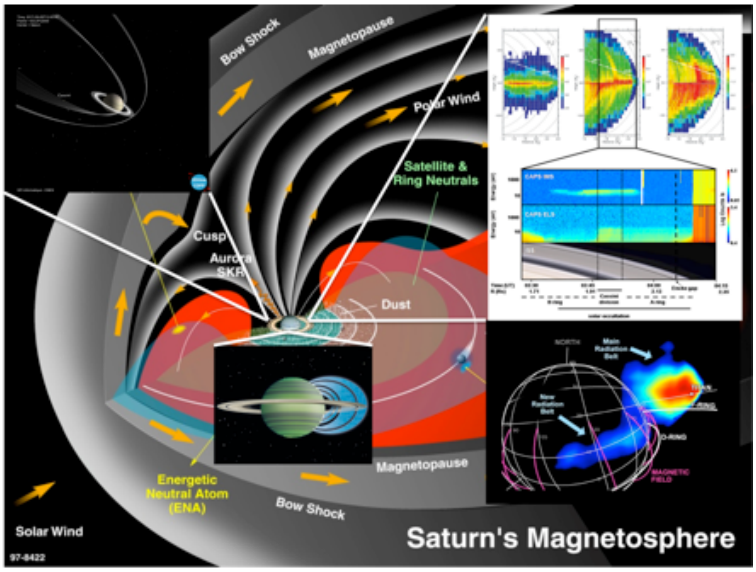

Figure 4. Saturn’s magnetospheric regions and processes. Bottom left inset ring ‘rain’ onto Saturn’s low-latitude ionosphere (O’Donoghue et al. 2013); Bottom right inset new radiation belt observed in ENA (Krimigis et al. 2005); Top left inset Cassini proximal orbits (3DView/CDPP); Top right inset ring ionosphere and exosphere (André et al. 2008).

The Cassini-Huygens mission has been expanding our understanding of the Saturn system since 2004. Juno-like inclined proximal orbits at the end of the Cassini Solstice mission in 2016-2017 will provide the opportunity to study in-depth the interaction between the rings, ionosphere and magnetosphere, and the formation of the ring atmosphere/ionosphere and its coupling to Saturn's ionosphere (Spilker et al. 2009). On the other hand, taking advantage of an instrumented carrier for a Saturn probe would enable us to ***obtain in situ magnetospheric observations in the innermost unexplored regions of Saturn's magnetosphere***. These unique observations would complement the ones obtained by Cassini at the end of its mission (including the very close magnetic field measurements) and, by analogy, refine our understanding of magnetized protoplanetary disks.

4. Mission Architectures

The primary science objectives described in Section 2 can be addressed by an atmospheric entry probe that would descend under parachute, and start to perform *in situ* measurements in the stratosphere as soon as feasible after parachute deployment and continue in the troposphere down to a minimum of 10 bars. The 10 bar value is just a representative value. Future proposals would conduct a careful study of the trade-offs between the science return and the added complexity of a probe than could operate down to higher pressures to determine the deep oxygen abundances. Accelerometry measurements would also be performed during the entry phase to probe the upper layers of the atmosphere prior to starting *in situ* measurements under parachute. A spacecraft carrier would be required in order to bring the probe to its target planet. The range of possible carriers include:

- **A carrier (carrier option 1) that would detach prior to probe entry, follow the probe path and destroy itself when entering the atmosphere;**
- **A fly-by carrier (carrier option 2) that would release the probe several months prior to probe entry and deflect its trajectory to be used for both probe data relay and for performing flyby science;**
- **An orbiter, which would provide a similar configuration to that of the Galileo orbiter/probe mission. The carrier would be placed in orbit after the probe relay is over and would perform**

The mission architecture would depend on the chosen target, taking into account the orbital science that has already been performed by Cassini, but it remains to be done at Uranus or Neptune.

__Saturn mission reference case:__
Taking the reference case of a future mission to Saturn to describe a mission architecture concept, in addition to the entry probe, we do not consider an orbiter/probe configuration and briefly address the different mission architectures with the two carrier options. A mission architecture with the carrier option 1, if the carrier is instrumented properly, would allow performing approach science and *in situ* pre-entry science. In this architecture, the probe data transmission would solely rely on a Direct-to-Earth link. As an alternative, if the carrier would be separated early enough prior to probe entry and slowed enough to be delayed by a couple of hours, it could also be used as a probe radio relay. A mission architecture with the carrier option 2, would provide the capability to perform approach science (for months) and flyby science (for a few days) in addition to being used as the probe radio relay. It would also allow many retransmissions of the probe data to reduce risk. Alternative technologies, such as the solar photonic sail or solar wind electric sail (Janhunen et al. 2010, 2013), could be potentially used for the propulsion of the spacecraft.

__Entry atmospheric probe:__ An entry probe to Saturn, Uranus or Neptune, would in many respects resemble the Jupiter Galileo probe. The concept was further developed for Saturn in the KRONOS mission proposal (Marty et al. 2009). Concept probe studies to the giant planet have been studied by ESA in

2010[1]. As an example, the KRONOS probes had a mass of ~330kg, with a 220kg deceleration module (aeroshell, thermal protection system, parachutes and separation hardware) and a 117kg descent module, including the science instruments and subsystems). A representative payload for the Saturn probe that would allow addressing the measurement requirements identified for themes A and B are shown in Table 2.

Table 1. Measurement requirements identified for themes A and B.

Instrument	Measurement	Science Theme
Helium Abundance Detector	Accurate He/H_2 ratio	A
Mass Spectrometer	Elemental & chemical composition	A
	Isotopic composition	A
	High molecular mass organics	B
Atmospheric Structure Instrument	Pressure, Temperature, Density, molecular weight profile	B
Highly sensitive accelerometer	High altitude Atmospheric structure (during entry phase)	B
Doppler Wind Experiment	Measure winds, speed and direction	B
Nephelometer	Cloud structure	B
	Solid/liquid particles	B
Net flux radiometer	Thermal/solar energy profiles	B
Lightning detector	Detect lightning, measure energetic particles	B

[1] http://sci.esa.int/science-e/www/object/index.cfm?fobjectid=47568

Table 2. Measurement requirements identified for *in situ* pre-entry science.

Instrument	Measurement	Science Theme
Camera	Probe entry	Context
Camera	Ring particles, close structure and size	Ring
Lightning detector	Low Frequency emissions (VLF, possibly TLF and ELF) water abundance	B
Fourier Spectro Imager	Doppler seismology	A/B
Spectrometers (IR/ UV)	Temperatures, Clouds and Chemical composition	B/Rings

Table 3. Measurement requirements identified for carrier/flyby science.

Instrument	Measurement	Science Theme
Camera	Probe entry	Context
Lightning detector	Low Frequency emissions (VLF, possibly TLF and ELF) water abundance	B
Fourier Spectro Imager	Doppler seismology	A/B
Spectrometers (IR/UVIS)	Temperatures, Clouds and Chemical composition	B/Rings
Magnetometer	Magnetic dynamo, magnetosphere and radiation environment	Ancillary

Carrier: The carrier (either for option 1 or 2) may benefit from subsystems developed for JUICE. In addition to studying specific carrier architectures, it is suggested to look into an approach similar to the one that allowed to develop MEX and VEX based on Rosetta by studying how the carrier design would benefit from the re-use of JUICE elements.

Power generation: It is believed that all mission architectures proposed can be solely designed on batteries and solar power, pending LILT qualification extension to 9 AU conditions. The probe will be powered with primary batteries as were the Galileo and Huygens probes. The carrier, in both options 1 and 2, would be equipped with a combination of solar panels, rechargeable batteries (option 1) and possibly a set of primary batteries for the phase that will require a high power demand. Nuclear power would be considered for the carrier only if available solar power technology would not work.

Interplanetary trajectory and entry zone of the probe: Many trajectory options have been identified, using both direct and gravity-assisted transfers to Saturn, and more would be identified in subsequent studies. Trajectory selection would consider all the trajectory options, the selected carrier option, and the launch vehicle capabilities available at the time. Different trajectories may be envisaged for carrier options1 and 2. Concerning the entry zone, mid latitudes should be a safer destination for the probe. Volatile-depleted regions are probably located at the cyclones in both poles and may be at the storm-alley (region of low static stability able to develop updrafts and downdrafts). More generally, the peaks of westward jets can be unstable based on the stability of the wind system and eastward jets (particularly the anticyclonic branch of eastward jets) and might be good locations to retrieve the deep values of volatiles at higher levels in the atmosphere (Read et al. 2009).

International collaboration: One of the key probe technologies, which would be new for Europe industry, is the heat shield material for an entry probe into a giant planet. Careful trade-offs would have to be made for either development of this new technology within Europe or establishing collaboration with an international partner that may have this technology readily available. In particular, recent NASA studies have been made concerning the thermal protection requirements for a Saturn entry probe. International collaboration may also be looked at for other mission elements, including the ground segment.

5. Conclusions

In this White Paper, we have shown that the in situ exploration of the giant planets of the Solar System can address two major science themes: ***the formation history of our Solar System and the processes at work in the atmospheres of giants***. We advocate that any giant planet mission incorporating elements of in situ exploration, whether for the gas or ice giants, should form an essential element of ESA's future cornerstone missions. ***We describe the concept of a Saturn probe as the next natural step beyond Galileo's in situ exploration of Jupiter, and the Cassini spacecraft's orbital reconnaissance of Saturn***. Two missions designs are envisaged and derived from the KRONOS concept previously proposed to ESA. Both scenarios envisage the ***transport of the probe to Saturn via a spacecraft carrier*** that would detach either a few months before or just prior the probe entry. The first scenario would enable some in situ pre-entry science whereas the second scenario would allow both pre-entry and flyby science (ring science, Doppler seismology, magnetosphere science). In situ exploration builds on ESA's successful heritage with Cassini-Huygens, and paves the way for ESA leadership in future international collaboration in outer solar system exploration.

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