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Icy Giant Planet Exploration: Are Entry Probes Essential?

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Abstract

"Flyby, orbit, land" has been the guiding philosophy of planetary exploration. This systematic approach has been highly successful in addressing the most fundamental questions of the origin, evolution, and habitability of the solar system. For the giant planets, entry probes take the place of "landers", since the "land" of the gas and icy giant planets, their solid core, lies some tens of thousands of kilometers beneath their cloud tops, hence impractical to reach. On the other hand, during a planet's accretionary heating phase the volatiles trapped in the core material would have been released, forming the atmosphere, together with the most volatile of the gases, hydrogen, helium and neon, that were captured gravitationally when the core became massive enough. Those atmospheric volatiles would thus be accessible by entry probes deployed to relatively shallow depths in the upper troposphere, allowing the determination of the abundances and isotopes of at least the most critical of the "heavy elements" (mass greater than helium). The heavy elements are key constraints to the formation and evolution models [1]. Entry probes are essential to retrieve their abundances, which are feasible *only* in situ at probe depths. That was the rationale behind NASA's 1995 Galileo probe mission at Jupiter and the Saturn Probe mission in NASA's New Frontier 4 candidate list of science themes. Saturn probe proposals to ESA's Cosmic Vision Program are similarly inspired. In 2015, NASA commissioned an Ice Giant Planets Study to recommend a comprehensive set of science goals and objectives, and further to develop potential mission architectures for accomplishing them in the 2023-2033 decade. The most highly rated mission from that study is an orbiter with a probe to either Uranus or Neptune [2]. While remote sensing observations from the orbiter will yield the composition, structure and the distribution of neutral and charged particles in the magnetosphere and the upper atmosphere, the entry probe will determine the abundances and isotopic ratios of the noble gases (He, Ne, Ar, Kr, Xe), H, C, and possibly N and S. The noble gases are key to discriminating among formation models, and their values from the probe entry location would represent global values as they are unaffected by meteorology, dynamics or chemistry. We will elaborate on these issues and then briefly discuss possible scenario/s for a mission to the icy giant planets, with particular focus on entry probes.

1. INTRODUCTION

All planets in the solar system formed from the primordial solar nebula, but only the giant planets, being so massive, still preserve the original material, while the terrestrial planets have undergone dramatic evolution since the birth of the solar system 4.6 billion years ago. Thus, the giant planets hold the key to the formation of the solar system. The giant planets fall into two categories, the gas giants Jupiter and Saturn, and the icy giants Uranus and Neptune. While much progress has been made toward understanding the formation of the former, especially Jupiter, largely due to extensive spacecraft exploration in the past four decades, the formation of the icy giant planets remains a mystery. The Voyager flybys of Uranus and Neptune, respectively in 1986 and 1989, provided only rudimentary data on their characteristics. Observations from the Earth have yielded some additional data, particularly with the VLA, Hubble and Spitzer. Yet, the information about these planets available to date is far too limited to address the composition, energetics, dynamics and structure of their atmospheres, their interiors and magnetospheres, rings and satellites, and clearly not their formation. An orbiter and probe mission is required to address such fundamental questions, much like the Galileo orbiter probe mission at Jupiter, with an advanced and supplemental payload, including possibly a microwave radiometer as on the Juno orbiter at Jupiter. Only entry probes are capable of making the measurements needed to address the question of their formation and evolution. This paper focuses on the probe component of an icy giant planet mission. First, we will review briefly the current thinking about giant planet formation, followed by what is essential to measure and where, and then discuss a possible mission scenario.

Two main models of the formation of the giant planets have been proposed, the gravitational instability and the core accretion model. According to the former model, gravitational instabilities result in the breakup of cold massive disks into fragments, or clumps that then directly form multiple giant planets, most of which are scattered out. There is no requirement to form a core first. The enrichment of heavy elements observed in Jupiter, as will be discussed later, seems inconsistent with this model, though it has been suggested that heavy elements could have been added later. However, that seems problematic, as the very process of gravitational instability would cause disruption of the disk and remove the required heavy element material as it was distributed into multiple giant planets that were scattered out. An alternative to the disk instability scenario is the core accretion model. According to this model, non-gravitational collisions between submicron-micron size grains of dust, metal, ice and possibly refractory material in the nebula led to larger and larger particles and planetesimals, and eventually the core. When the core became massive enough, i.e. 10-15 Earth Mass (M_E), it was able to accrete the most volatile of the gases, hydrogen, helium and neon (H, He, Ne), from the surrounding nebula to form the giant planet. During the accretionary heating phase the volatiles originally trapped in the core forming solids are released, resulting in the molecular envelope, the atmosphere, comprising those volatiles, together with hydrogen, helium and neon. A number of observational facts, including enrichment of the heavy elements at Jupiter as well as the other giant planets, presence of first solids (millimeter size chondrules and calcium aluminum inclusions) at the very beginning of the solar system, and greater frequency of exoplanets around higher metallicity stars are strong arguments in support of the core accretion model [a detailed discussion of the formation models may be found in Atreya et al. 2018 [1] and references therein].

The core accretion model is generally favored for the formation of the giant planets, but it's a slow process, taking between 1-5 million years (My) to form Jupiter and >50 My to form Uranus and Neptune, if formed at their present orbital distance from the Sun. This could pose a potential problem, as the solar nebula had a finite lifetime of <5My before dissipation. Thus, while the core accretion may be attractive for Jupiter, it does not seem feasible to form the other giant planets by this mechanism. However, models invoking planetary migration have been proposed to get around this problem. Accordingly, all giant planets formed or at least largely completed their formation between 5 and 10 AU, i.e. between the present orbits of Jupiter and Saturn, and then migrated out to their present orbits. In that scenario, formation happens before the solar nebula has dissipated. In the disk instability model, on the other hand, giant planets can form rapidly on the timescale of 100's to 1000's of years, which may seem attractive for Uranus and Neptune, if they indeed formed in place. However, extensive observations of the exoplanets show that planetary migration is commonplace in extrasolar systems, so it is reasonable to assume planetary migration took place in this solar system as well. In that case, there would not be any need to form the icy giant planets at their present orbital distance. It is important to point out also that the solar nebula material required for forming the planets decreases radially away from the Sun, so that there may not be sufficient material available to form the icy giant planets at their present orbits, besides the long time it takes to form them in place. In summary, core accretion is the preferred formation scenario for all giant planets, and the icy giant planets are likely to have started their formation between the orbits or Jupiter and Saturn and then migrated out to their present locations, where the rest of formation took place. That would be a slow process, and would result in far less hydrogen capture because of solar nebula dissipation, thus enriching the heavy elements relative to hydrogen to a much greater degree than Jupiter. The highly enriched C/H in the icy giant planets supports this conclusion. It should be noted, however, that while core accretion is an attractive model, it does require special conditions to prevent the icy giants from growing into gas giants (e.g. [3]).

2. WHAT TO LOOK FOR, AND WHERE?

It is evident from the above discussion that heavy elements ($>^4$He) are key to the formation models. They are expected to be found in the well-mixed atmosphere, which reflects the bulk composition of the atmosphere. As chemical, meteorological and dynamical processes govern the distribution of gases in the stratosphere and the upper reaches of the troposphere, their abundance in those regions does not generally represent their bulk abundance; the exception being the noble gases that not affected by above processes. The region of the atmosphere below which the relative proportion of a given species remains unchanged, i.e. the well-mixed atmosphere, is where its bulk abundance can be determined. The elemental abundance is then derived from the species bulk abundance. Figure 1 illustrates this point for Neptune. Very few molecules have been detected so far in the atmosphere of Uranus and Neptune. In this figure we see that remote sensing in the UV allows the determination of certain hydrocarbons in the upper atmosphere. IR gives information on hydrocarbons in the stratosphere. Radio allows measurements of the electron concentration high in the atmosphere (inset) and temperature in the lower stratosphere. Microwave (e.g. VLA) can sense deeper. Multiple cloud layers are predicted to occur in the troposphere. Thus, the well-mixed atmosphere is

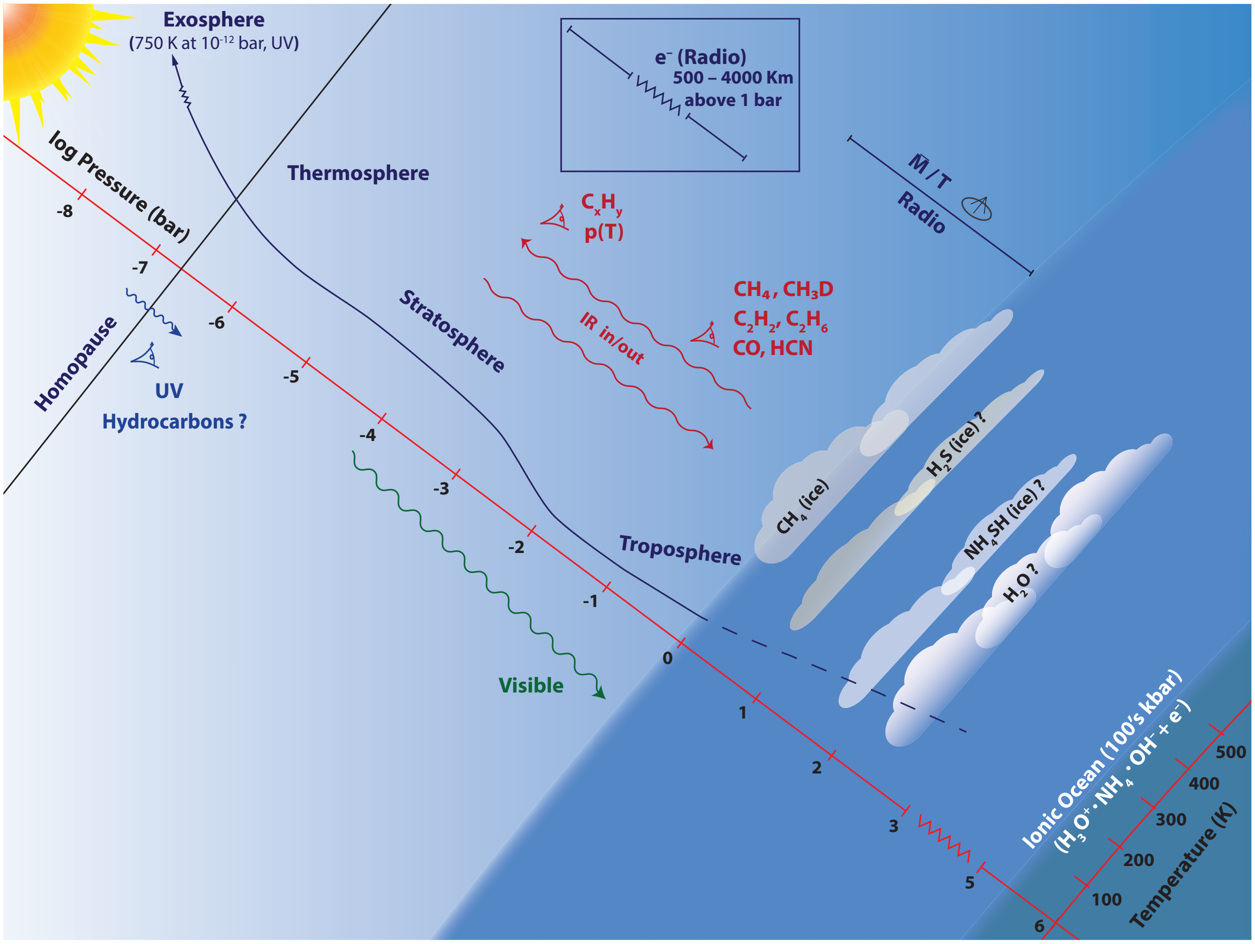

Figure 1. Illustration of the regions of the atmosphere that can be explored using different parts of the solar spectrum and the type of information obtained in Neptune's atmosphere. For example, UV is useful down to the ~10 microbar, whereas radio occultations are good for the ionosphere (inset) and again in the troposphere between ~1-1000 millibar. Only the topmost cloud layer has been inferred from the radio occultation observations done on Voyager. The nature of this cloud and others shown are based on thermochemical models. Maarten Roos-Serote helped with an earlier version of the figure.

expected to be quite deep, below the predicted level of the deepest cloud made up of water.

Figure 2 shows that for Uranus and Neptune only the carbon elemental abundance (from methane, CH_4) has been determined. This figure also shows that many more key heavy elements as well as the He/H ratio, which is important for inferring the interior processes including internal heat, have been determined for Jupiter. The Jupiter values are known largely because of the measurements made by the Galileo probe that entered Jupiter in 1995. Galileo could not determine the bulk water abundance, a proxy for the oxygen elemental abundance, even at 22 bars. This is because, even though that depth is below the predicted water cloud level of 5-10 bars, the probe entered an exceptionally dry spot of Jupiter [6]. The Juno orbiter is designed to map water over Jupiter and measure its abundance in the well-mixed atmosphere. C, N, S, O, and the noble gases He, Ne, Ar, Kr and Xe are yet to be determined for Uranus and Neptune. They require in situ measurements with probes, but to what depth? We will first discuss the requirements for noble gases, starting with helium, followed by the condensible species.

How the giant planets generate internal heat is a fundamental question to understand their interior processes and evolution since the formation of the solar system 4.6 billion years ago. A precise measurement of the He/H ratio in the upper troposphere reflects the extent of He condensation in the interior. That in turn allows an estimate of the contribution to internal heat due to He condensation and subsequent separation of helium droplets from hydrogen. Figure 2 shows the

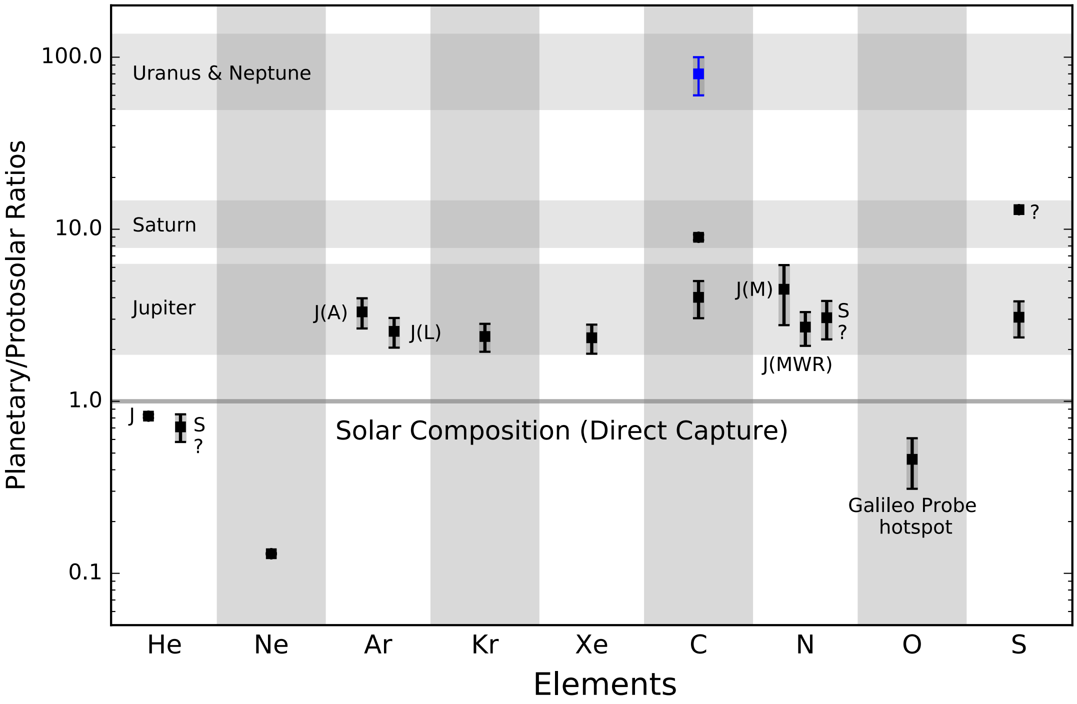

Figure 2. Elemental abundances relative to the protosolar values in the atmospheres of Jupiter, Saturn, Uranus and Neptune. "N" in Jupiter represents values from ammonia (NH_3) abundance measurements made by the Galileo probe mass spectrometer [J(M)] and the Juno microwave spectrometer [J(MWR)], whereas "Ar" values are based on protosolar Ar/H values of Asplund [J(A)] [4] and Lodders [J(L)] [5]. Saturn's He and N are labeled S. Only C/H in CH_4 is measured in Uranus and Neptune. Adapted from Atreya et al. (2018) [1], with permission from Cambridge University Press, where all relevant details and references can also be found.

He/H ratio in Jupiter is approximately 80% of its solar value, implying that 20% of the original helium has condensed in the interior, between 1-3 megabars, according to equations of state. That, in fact, is insufficient to explain Jupiter's large heat balance of ~2, i.e. how Jupiter emits twice as much energy as it absorbs from the Sun. As Jupiter is still undergoing cooling and contraction since the time of formation, the excess heat beyond that due to helium condensation is most likely due to gravitational contraction of the planet. For the icy giant planets, only very crude and indirect estimates of the He/H ratio have been inferred so far from the IR and radio data from Voyager. Direct, in situ measurements, like those done at Jupiter with the Galileo probe, are essential to determine the He/H ratio in the icy giants.

All noble gases, including He, are expected to have uniform mixing ratios below the homopause, which is located at slightly less than a microbar level at Neptune [7] and ~100 microbar at Uranus [8,9]. Thus, all noble gases can be measured in the stratosphere. While that is correct, in principle, the very low abundances of the noble gases, with the exception of He, necessitate making the measurements somewhat deeper, in order to ensure collecting sufficient quantities of the sample for high precision measurements. Mass spectrometers using enrichment techniques are capable of making precise measurements of even the least abundant noble gases, Kr and Xe, together with their isotopes at a few bars of atmospheric pressures, as demonstrated previously on the Galileo probe at Jupiter. That is still a relatively shallow depth for entry probes. It is a different matter for the condensible gases, however, as discussed below.

Figure 3 shows the results of equilibrium thermochemical models of Uranus. The results apply to Neptune with very small adjustments in the pressure-temperature profile. This is because both ice giant planets have very similar temperatures at the 1-bar level, and the temperatures deeper are determined by the adiabatic lapse rate modified by condensation processes. The same cloud layers are expected to form on both planets. Despite Neptune's greater distance from the

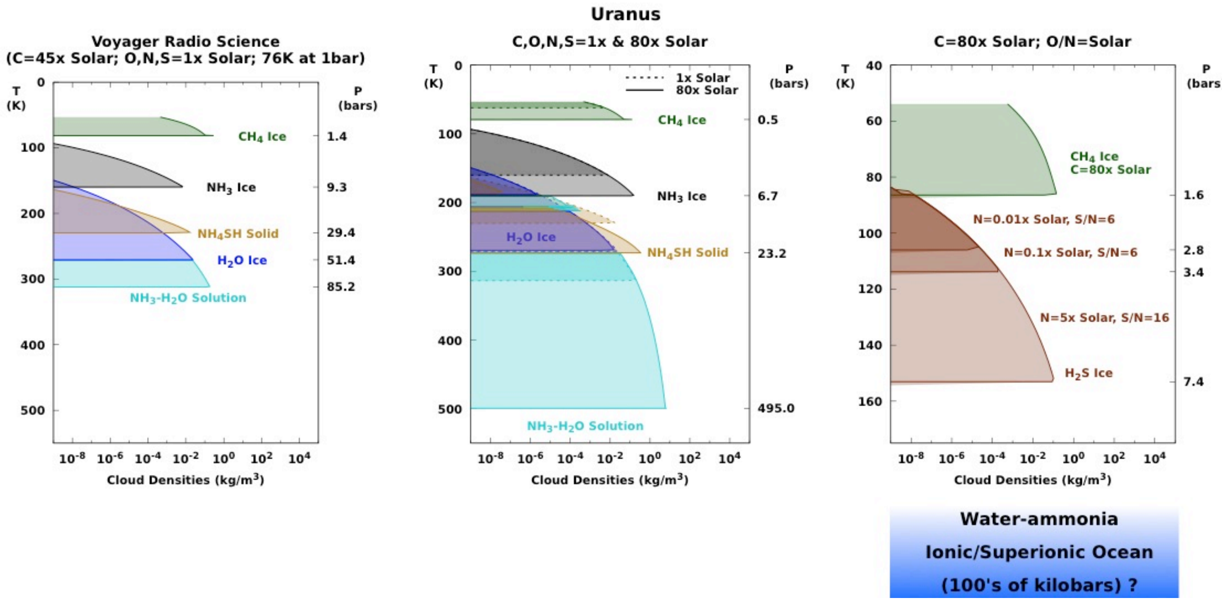

Figure 3. Cloud structure of Neptune predicted by the equilibrium cloud condensation model (ECCM). *Left panel*: assuming p-T and the CH_4 mole fraction from Voyager [10], while all other elements are taken as 1x solar. *Middle panel*: assumes 80x solar for all elements, same as the measured C/H; the deepest of cloud layers, water, forms at 0.5 kilobar level. *Right panel*: Formation of an H_2S ice cloud, with depleted NH_3 of 0.01 and 0.1x solar and S/N enhanced by a factor of 6 and 16. CH_4 ice continues to remain as the topmost cloud layer, with H_2S ice below at ~3 bar level for S/N=6. Notice the absence of H_2O and NH_3 and the NH_4SH cloud layers unlike the cases shown in the other two panels. Cloud densities are upper limits from ECCM, but the cloud bases are robust.

Sun compared to Uranus (30 AU vs. 20 AU), Neptune has nearly the same temperature at 1 bar as Uranus since Neptune's large internal heat compensates for the lower solar energy compared to Uranus whose internal heat is negligible.

Whereas CH_4 does not undergo condensation in the gas giants, Jupiter and Saturn, the very low temperatures of the icy giants would result in its condensation, besides NH_3, H_2S/NH_4SH and H_2O (ammonia, hydrogen sulfide/ammonium hydrosulfide and water, respectively) that condense in the gas giants as well. The left panel of Figure 3 shows the condensation of CH_4 at ~ 1 bar pressure level. Atmospheric p-T and the CH_4 mole fraction used to calculate the methane cloud layer in this figure is the same as that given by the Voyager radio occultation observations [10], which indeed indicate the presence of a cloud layer in the 1-1.2 bar region. The other cloud layers in this panel are calculated using 1x solar proportions of those condensible volatiles for the purpose of illustration only. The deepest cloud layer in that case is made up of water with its base at ~85 bars. While shallow probes may be able to make a measurement of the C elemental abundance from CH_4, besides of course the noble gases, the other heavy elements may not be accessible at those depths. In fact, the well-mixed region may actually be much deeper than the equilibrium condensation levels shown in this figure, as discussed later.

Since the time of Voyager, a number of ground-based observations have attempted to determine the bulk abundance of methane, hence C/H, at Uranus and Neptune. The latest observations yield a C/H=80±20 for both planets [11,12]. If the other heavy elements were similarly enriched, as seen at Jupiter (Figure 2), the cloud structure would be quite different than that shown in the left panel of Figure 3. Such high elemental enrichments would also change the moist adiabatic lapse rate, with significant impact on the atmospheric thermal structure. The resulting cloud layers, shown in the middle panel of Figure 3, indicate the water cloud now forming around the 500-bar pressure level. Even the other clouds besides CH_4 are quite deep. A shallow probe would be unable to determine the well mixed NH_3, H_2S and H_2O hence the N, S, and O elemental abundances in that instance.

3. AMMONIA DEPLETION IN IONIC OCEAN?

Ground-based radio observations using the Very Large Array (VLA) in Socorro, New Mexico, found that

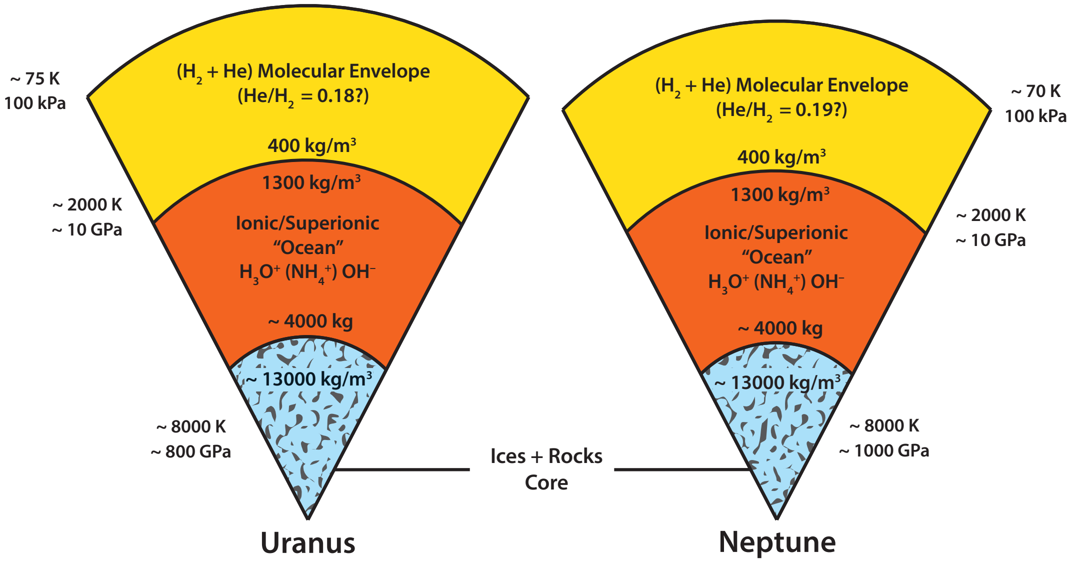

Figure 4. Internal structure of Uranus and Neptune. Models and lab experiments suggest the presence of an ionic/superionic water ocean comprising [H_3O^+ (NH_4^+) OH^-] at pressures ≥10 GPa (≥ 100 kilobar, 2000K) in their interiors.

ammonia was greatly depleted relative to its solar value below its expected condensation level in the atmospheres of Uranus and Neptune [13,14,15]. The derived NH_3 mole fraction in that region was found to be as low as 0.1% of the solar value. Severe depletion in ammonia has also been observed in more recent observations for the upper troposphere [16] with the VLA and the enhanced-VLA (eVLA), though the new observations find that deeper in the troposphere (pressures of tens-of-bars) ammonia is closer to solar. One possible explanation for such a large unexpected depletion in NH_3 is that NH_3 is removed in a cloud of NH_4SH below, but it requires H_2S to be enhanced by a factor of at least 25 relative to solar [14,15], i.e. very low NH_3 but very high H_2S, in contrast with the expected solar H_2S/NH_3 (S/N) ratio of 0.5 [1,17,18]. According to the formation models discussed above, all elements should have similar enrichments in the well-mixed atmosphere, or same as C/H of 60-100 times solar. On the other hand, it is also possible that the abundances of NH_3, H_2S, etc. in the upper troposphere, where the data are presently available, may not represent their bulk abundances in the deep atmosphere.

There are two possible ways NH_3, and possibly H_2S, may be removed in the deep atmosphere – a liquid water ocean at several to tens of kilobars, and an ionic/superionic water ocean much deeper at 100's of kilobars. The former is distinctly different from the condensation of a weak solution of ammonia and water extending to 0.5 kilobar in the middle panel of Figure 3. An investigation into the likelihood of a liquid water ocean between the cloud tops and the H_2-rich deep interior found that Neptune is both too warm and too dry to form such an ocean [19], and the same should apply to Uranus as well. It is also important to point out the solubility of ammonia in water is only 3% at 300 K and drops rapidly at higher temperatures, where the liquid water ocean may form if the conditions were right. Thus, removal of ammonia in a liquid water ocean or the aqueous ammonia solution cloud is unlikely.

The other possibility of removing ammonia is through its loss in an ionic ocean of water in the interior. Molecular dynamics calculations and experiments employing Raman spectroscopy in a laser heated diamond anvil cell show a superionic phase of water forming at temperatures above 2000 K and pressures of 30 GPa ([20], and references therein for associated lab experiments]. Ionic/superionic water would likely take ammonia with it, resulting in the depletion of not only water, but also ammonia at pressures of 100's of kilobars. A plausible composition of such an ionic ocean is $H_3O^+{\cdot}NH_4^+{\cdot}OH^-$, together with free electrons to maintain charge balance in the plasma, as shown in Figure 4 illustrating plausible internal structure of Uranus and Neptune. The relatively large intrinsic magnetic fields of Uranus and Neptune, comparable to the Earth's magnetic field, observed by Voyager [21] may be an evidence of the existence of such an ionic/superionic ocean. As metallic hydrogen, which drives the internal dynamo at Jupiter and Saturn, is not expected to form in the cooler, smaller icy giant planets, the ionic/superionic ocean may be the answer to their intrinsic magnetic fields (another state of water – ionic/superionic ice – is a potential alternative). In summary, the purported ionic/superionic ocean could remove ammonia in the interior of the icy giants, in effect depleting ammonia, water, and possibly H_2S, to varying degrees. Additional lab work and modeling are required to fully understand the characteristics and stability of the ionic/superionic water ocean.

The right panel of Figure 3 shows the effect of depletion of ammonia and water in the deep interior. Two things immediately jump out compared to the other two panels of the figure – absence of the usual water, ammonia and ammonium hydrosulfide cloud layers, and appearance of a hydrogen sulfide cloud layer instead. The base of the H_2S ice cloud ranges between 2.8 and 7.4 bars, depending on the assumptions of the depletion in N and S and the S/N ratio (note than even for the case where N is taken as 5x solar, it is still depleted relative to the expectation from C/H of 60-100). Microwave observations [14,15] had suggested the presence of an H_2S ice cloud at ~3 bars. With the depletion of NH_3 between 0.01-0.1x solar, and assuming S/N=6 in this region, a cloud of H_2S ice cloud indeed forms at ~3 bars, according to thermochemical models (right panel of Figure 3), consistent with previous suggestions. This also implies that detectable quantities of the H_2S gas may be present in the atmospheres of Uranus and Neptune. Though H_2S was previously postulated [14,15], it has now been detected directly in the infrared using the Gemini North telescope [22]. Note that despite the fact that depleted ammonia and elevated S/N (NH_3/H_2S) give rise an H_2S ice cloud, the topmost cloud layer continues to be made up of methane ice (CH_4, right panel, Figure 3), not H_2S, contrary to the assertion of Irwin et al. 2018 [22].

4. HOW DEEP – LESSONS FROM JUNO?

The Galileo probe observations of Jupiter showed that NH_3, H_2S and H_2O were all depleted relative their solar proportions well below their expected condensation levels [6,23]. While NH_3 and H_2S recovered and became super-solar and constant with depth respectively at 8 and 15 bars, H_2O never fully recovered and remained sub-solar even at the deepest level of the Galileo probe measurements (22 bars). It was commonly assumed that the depletion of volatiles seen by Galileo was peculiar to the entry site – a 5-micron hotspot – that was a very dry region with downdrafts. Thus, the prevailing thinking was that had the probe come down into a "normal" region, the volatile depletion seen by the probe would not be present. Juno's arrival at Jupiter in July 2016 has changed all that. With its six microwave radiometer (MWR) channels ranging from 1.37 cm (21.9 GHz) to 50 cm (0.6 GHz), Juno is capable of sensing to at least several hundred bar level with its longest wavelength channel. Figure 5 shows a map of ammonia generated from the MWR data of perijove 1 (more than a dozen perijoves to date show very similar behavior). As can be seen, with the exception of the near equatorial region, ammonia is depleted everywhere, latitudinally, longitudinally, and to much deeper levels than what Galileo observed in its single dry entry site. Juno found that only at pressures of 100+ bars is ammonia well mixed, which is well below its cloud base of 0.7 bars. Though the bulk ammonia abundance found by Juno (~3x solar) is comparable to the lower end of uncertainty of the Galileo probe mass spectrometer value (Figure 2), the structure Juno found in its global distribution is unlike anything seen by Galileo or predicted by any models. Naturally, the question arises - what should one expect at Uranus and Neptune? Atmospheric dynamics drives the depletion of ammonia to great depths seen by Juno, and Jupiter's large internal energy, rather than the solar input, most likely powers that process. The internal energy at Uranus is negligible, but Neptune's heat balance (ratio of the total emitted energy to the absorbed solar energy) is comparable to Jupiter's. Thus, dynamics may be quite sluggish at Uranus and vigorous at Neptune (the strengths of their eddy mixing seem to support that). Note also that the degree of depletion in ammonia abundance relative to solar observed at Uranus/Neptune, a factor of 100 or more, is much greater than a factor of 2-3 found at Jupiter by Juno (Figure 5). Thus, it is not apparent whether dynamics is really what is driving the exceptionally large depletion of ammonia in the upper tropospheres of the icy giant planets, or other factors such as an internal ionic ocean have a controlling role. In the absence of actual data from entry probes, supplemented by appropriate remote sensing observations, it would be premature to draw any firm conclusions.

It is evident from the above discussion that the well-mixed regions of methane, ammonia, hydrogen sulfide and water may be much deeper than their expected condensation levels. If water were 80x solar, as C, the middle panel of Figure 3 shows that the base of the water cloud would be at ~0.5 kilobar, but the actual well-mixed water may not be reached until several-tens of kilobars. Similar conclusions can be drawn for ammonia as well. And, if an ionic ocean exists, that

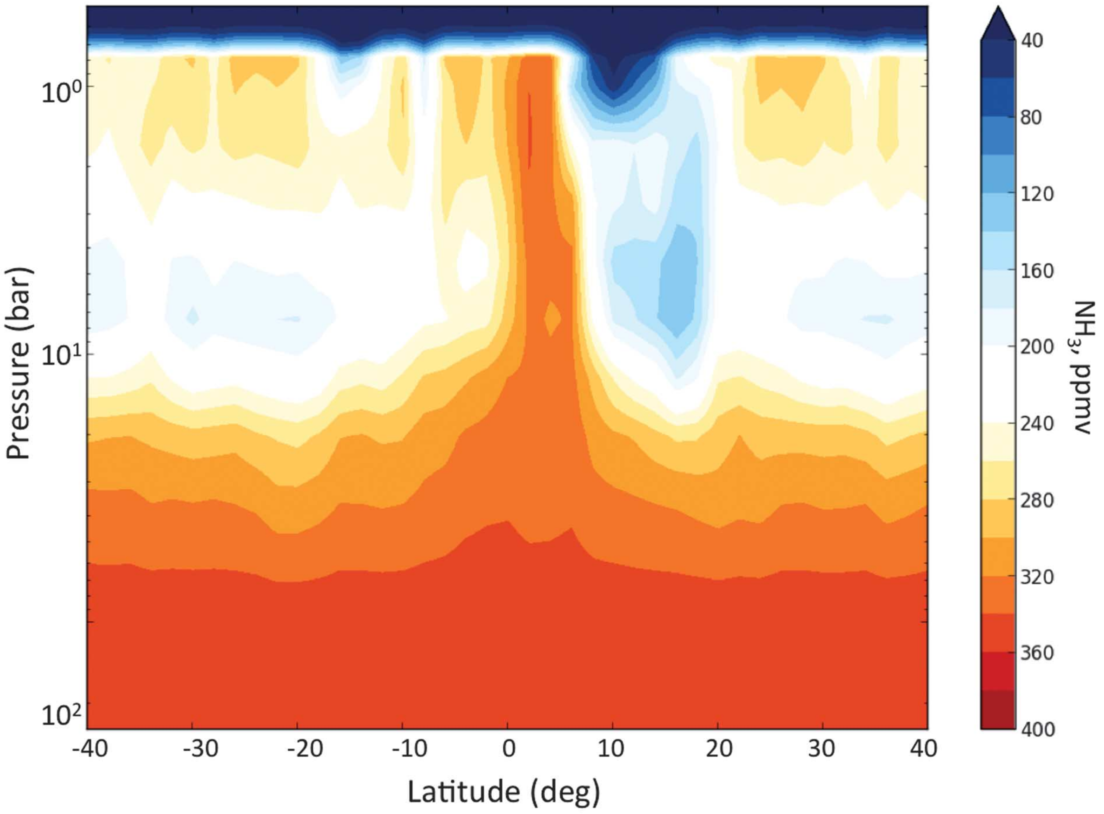

Figure 5. Planetocentric latitude-altitude cross section of ammonia mixing ratio. The thin blue band at the top—near the 1-bar level—is where ammonia is condensing and the mixing ratio is low (<100 ppmv). The high mixing ratio at the equator is interpreted as air that is exchanging with the deep atmosphere at pressures of 100 bars or more, where the mixing ratio is 330 - 370 ppmv. (Figure 3 of Bolton et al. 2017 [24]; reprinted under RightsLink License Number 4396160528029 to coauthor S. K. Atreya of that paper).

region would be below 100's of kilobars for H_2O, NH_3, and probably H_2S.

5. WHAT GOOD ARE SHALLOW PROBES?

The above discussion illustrates that probes to even tens of kilobars cannot guarantee the measurement of well-mixed condensible volatiles, with the exception of methane, which may be achieved at 10's of bars. Current technology does not permit successful probe deployment and operation to kilobar levels. Entry probes can work well to 5-10 bars. Of course, that is too shallow for obtaining any meaningful information on the N, S and O elemental abundances. On the other hand, unlike the condensibles, noble gases, which are key to constraining the formation models, are expected to be uniform all over the planet. They can be measured only with entry probes. Probes to 5-10 bars are adequate for determining their elemental abundances. Figure 6 shows the predicted noble gas ratios relative to solar at Uranus and Neptune for different scenarios of formation. The gravitational instability model is unlikely due to the reasons discussed earlier. He and Ne are not indicated, but they are expected to be close to their solar values. Helium could actually be slightly above solar at Neptune, as allowed within the upper range of uncertainty of the Voyager retrievals, and Ne may be depleted in case there is an appreciable degree of helium condensation in the interior (Ne dissolves in liquid He), which appears unlikely according to current equations of state.

In addition, the isotope ratios of the noble gases can also be measured along with their bulk abundance. They are important to understand the nature of the material that formed the icy giant planets. For example, the noble gas isotopes measured by the Galileo probe showed beyond doubt that the material from which Jupiter formed was of solar composition. Finally, despite the likely depletion of all condensible volatiles to great depths in the icy giants as already seen in NH_3, there is some likelihood of making isotopic ratio measurements

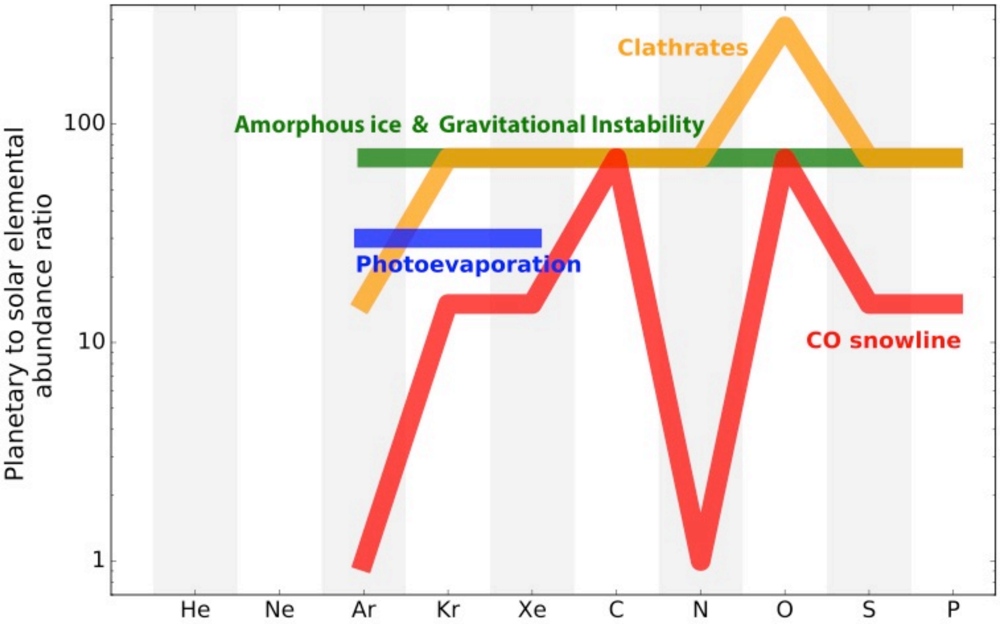

Figure 6. Qualitative differences between the enrichments in volatiles predicted in Uranus and Neptune by the different formation scenarios (calibrations based on carbon (C/H) from the CH_4 data). The resulting enrichments for the different volatiles are shown in green (disk instability model and amorphous ice), orange (clathrates), blue (photoevaporation) and red (CO snowline). In their photoevaporation model, Guillot and Hueso 2006 [25] predict that heavy elements other than noble gases follow the amorphous ice or clathrate predictions. (updated Figure 2 of Mousis et al. 2018 [26], Olivier Mousis, personal communication, 2018; reprinted under RightsLink License Number 4396240462835 to coauthor S. K. Atreya of that paper).

of C (almost certain), N (probable) and S (perhaps), while D/H and $^3He/^4He$ are quite certain. Thus, with the noble gases and the isotopes, there would be sufficient information to constrain the models of the formation of Uranus and Neptune, despite the likelihood that the entry probe may not be able to determine the N, S and O elemental abundances.

Complementary data on the interior and possibly other means for deriving the O/H (perhaps using CO, [27]) would provide additional constraints. Gravity data from Juno, for example, has been very successful in providing valuable information about Jupiter's interior structure. Future missions to the icy giants should explore the possibility of including a Juno-like MWR on the orbiter. Though the well-mixed regions of water and ammonia and hydrogen sulfide on Uranus and Neptune are likely too deep even for the MWR, their vertical mixing ratio profiles and global maps would still be a valuable piece of information for understanding the tropospheric dynamics. [Note, height profiles of methane, which does not have a microwave signature, can only be obtained with the probe.] In addition, the gravity data from spacecraft would be a most desirable complement to the probe data on the noble gases and the isotopes discussed above.

6. IMPLEMENTATION

A comprehensive mission design, architecture and trajectory analysis was performed by the Jet Propulsion Laboratory (JPL) as part of the NASA Ice Giants Science Definition Team study (IG SDT Report [2]). The minimal SDT recommended mission is an orbiter with probe to either Uranus or Neptune. This paper focuses on science that only probes can deliver.

The probe design drew on heritage from the Galileo and Pioneer Venus probes, using current state of the art technologies and instrument designs. The probe is spin-stabilized during its coast to the planet and is powered by primary batteries. Survival heating after probe release and during the 60-day coast period is provided by radioisotope heater units (RHUs). The overall configuration is illustrated in Figure 7.

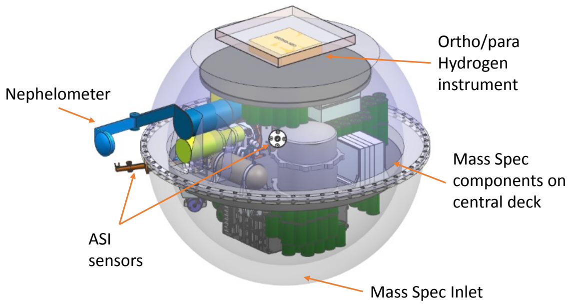

Figure 7. Conceptual design of a probe descent module.

The probe descent module is a truncated sphere, approximately 73 cm in diameter. The descent module is vented, allowing an equalization of pressure inside the probe with the external atmosphere during its descent. Apertures in the probe provide instrument access to the atmosphere. Telecom uses a flat patch antenna on the top of the probe to maintain a communications link with the orbiter during the ~60 minute science mission.

The probe entry system consists of a 45^0 sphere-cone heat shield scaled from Galileo to 1.2 m in diameter, and a spherical backshell with a radius of curvature originating at the vehicle center of gravity (CG). The heat shield uses a 3D weave of blended carbon/phenolic yarns (Heat Shield for Extreme Entry Environment, HEEET) recently developed by Ames Research Center. The backshell TPS is flight proven C-PICA. The mass of the probe at entry is estimated to be ~308 kg.

The probe instrument suite comprises four notional instruments, accommodated as shown in Figure 7:

- Gas Chromatograph Mass Spectrometer (GCMS; based on GSFC heritage design)
- Atmospheric Structure Instrument (ASI; based on Galileo and Huygens instruments)
- Nephelometer (based on Galileo probe design)
- Ortho/Para Hydrogen Experiment (OPH)

A brief summary of the most important elements of a typical Neptune orbiter-probe mission architecture is presented next. A Uranus probe would be similar, though solar electric propulsion (SEP) on the carrier spacecraft would not be necessary for Uranus due to its being significantly closer thereby reducing flight times.

Neptune's distance from Earth and the related interplanetary trip time places lifetime constraints on the mission architecture. Neptune can be further than Pluto, depending upon where Pluto is in its orbit. Early back of the envelope estimates indicate that a flagship class orbiter to Neptune would exceed 1,000 kg dry mass. This mass, coupled with mass of a Neptune atmospheric probe, leads to the conclusion that an SEP-based architecture is required to deliver the spacecraft into orbit and complete the science mission all within the design life of the radioisotope power system. This cannot be achieved with a chemical propulsion alternative. Figure 8 illustrates the SEP mission architecture that can be divided into three mission phases: interplanetary cruise, probe release and Neptune orbit insertion.

The baseline interplanetary trajectory relies on a 25-kW SEP stage powered by 3 NEXT Ion Engines to propel the spacecraft through the inner solar system.

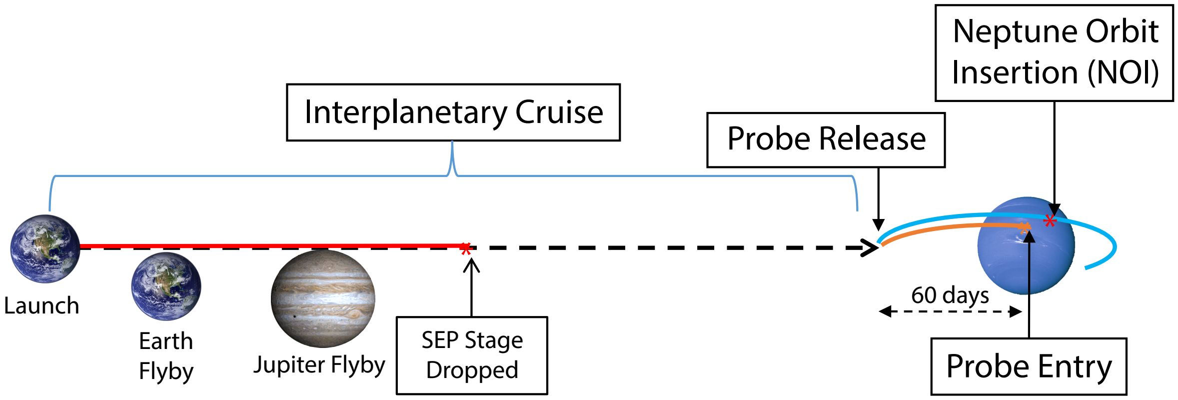

Figure 8. Possible mission concept option: Solar electric propulsion (SEP) mission design architecture.

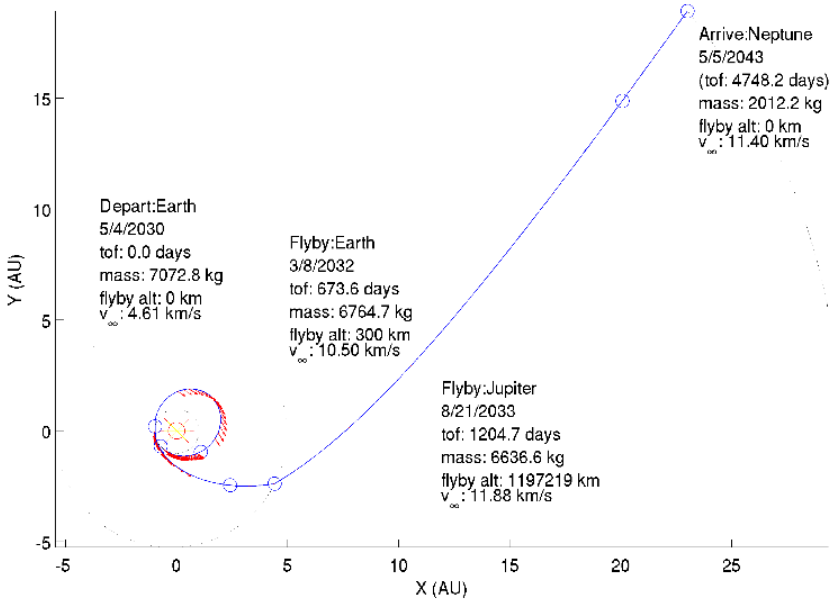

Figure 9. Possible baseline trajectory for a Neptune orbiter-probe mission.

This configuration provides the performance necessary to satisfy the interplanetary flight time constraint and delivered mass requirement. Post-launch, the spacecraft uses the SEP stage to gain momentum, perform an Earth flyby followed by a Jupiter flyby, and transition onto a long coast phase toward Neptune arrival. The SEP stage makes up for the relatively low launch energy through use of high propellant efficiency and continuous thrust arcs. At a range of ~6 AU, where the solar insolation is insufficient for SEP, the stage is jettisoned. Releasing it before Neptune Orbit Insertion (NOI) reduces mass and enables a significant propellant savings. This trajectory is shown in Figure 9.

The probe is released ~60 days before Neptune atmospheric entry. A probe targeting maneuver (PTM) is performed prior to probe release, followed by an Orbiter Divert and Periapsis Targeting Maneuver to achieve the desired conditions for orbit insertion. The probe enters Neptune's atmosphere at an entry flight path angle (EFPA) of -20 degrees. While this relatively shallow EFPA constrains the probe-orbiter telecommunication geometry, it is required to reduce deceleration and heat loads. Due to the relatively low data rate requirements, this geometry is adequate for mission data return. The probe descent to 10 bar lasts for ~1 hr, of which the first ~30 mins represent the entry sequence. Table 1 gives details on the probe entry.

Parameter	Value
Interface Altitude	1000 km
Entry Velocity	22.5 km/s
Entry Flight Path Angle	-20
Max G load	208 G
Stagnation Pressure	11.5 atm.
Cumulative Heat load	109,671 J/cm^2

Table 1. Probe entry parameters.

Following probe relay, the orbiter performs a large orbit insertion maneuver (~2.7 km/s delta v for Neptune, ~2.0 km/s for Uranus) at an altitude of ~1.05 Neptune Radii and enters in a 252-day retrograde orbit. The orbit insertion altitude is chosen to mitigate potential ring crossing issues and to lower the NOI delta v. Figure 10 shows the NOI location, orbiter path, probe approach and probe descent trajectory.

This implementation does not require development of technologies beyond current state of the art. However, there are a number of technologies that, if developed, could have a positive impact on the performance and/or cost of the mission. Aerocapture technology could enable trip times to be shortened, delivered mass to be increased or both. Cryogenic propulsion could have similar but not as pronounced effects as compared to aerocapture. Advanced RPS technologies, with even better specific power than the proposed eMMRTG, such as a segmented modular RTG, could enable more mass or power for instruments or both. Optical communications could dramatically increase the data return from the outer solar system. Advanced mission operations technologies could drive

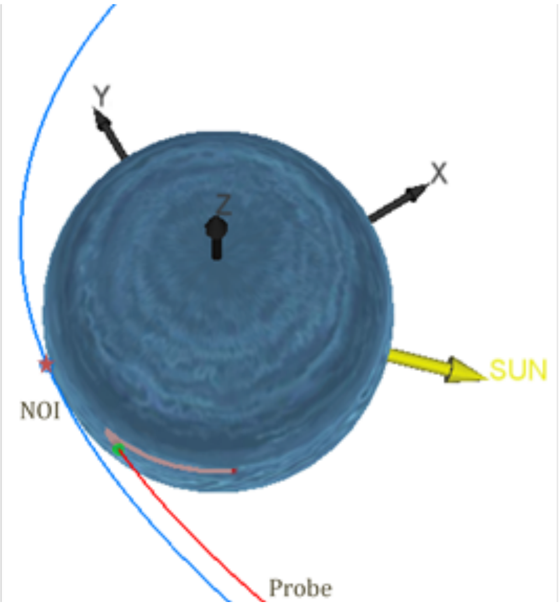

Figure 10. Neptune orbit insertion (NOI) and probe entry.

down cost and permit more autonomous adaptive missions operations.

While not required to enable Icy Giant missions, the availability of SLS would allow:

(a) Reduced flight times and/or increased delivered mass to either ice giant. This allows additional tradeoffs between cost and science return.

(b) Two-planet, two-spacecraft missions on a single launch vehicle. While there is no scientific penalty to launching two-planet missions on different launch vehicles several years apart, there may be programmatic benefits to utilizing a single SLS launch vehicle.

7. SUMMARY AND THE FUTURE

Entry probes are essential for measuring the heavy elements and their isotopes that are key constraints for the models of formation. At Uranus and Neptune, relatively shallow probes to 5-10 bars are capable of determining precisely the abundances of all noble gases including He, Ne, Ar, Kr, Xe and their isotopic ratios, the D/H and $^{13}C/^{12}C$ isotope ratios, and possibly also the $^{15}N/^{14}N$ and $^{34}S/^{32}S$ isotope ratios. Unambiguous measurement of the bulk abundance of water, hence the oxygen elemental abundance, is unlikely with the probe or any other means including microwave either from the orbiter or the ground. In view of the other critical data the probe will make, that is not detrimental. Complementary data from the orbiter payload, especially on the interior, are most desirable to strengthen the conclusions based on the findings from the probe. The probe must include at the very minimum a mass spectrometer and an atmospheric structure instrument. Solar electric propulsion is most suited for an orbiter-probe mission to Neptune, but a purely chemical propulsion based architecture is sufficient for Uranus. The relatively long trip times of ~10 years to Uranus and ~13 years to Neptune can be shortened to half or less and payload mass increased by using cryogenic propulsion, aerocapture, advanced RPS and SLS technologies. These technologies are presently in different stages of development. Icy giant planets are the last unexplored frontiers of the solar system. Their in-depth investigation with orbiter and probe is essential for discovering the missing pieces of the puzzle of the formation of the giant planets in particular and the solar system in general. Finally, the icy giant planets are the best analogs available for understanding the mystery of more than half of the ~4000 confirmed exoplanets that are mini-Neptunes in size. The US NRC's 2011 Vision and Voyages (Planetary Decadal Survey) recommends 3 highest priority flagship-class missions for the 2013-2023 decade [28]. The first two of those are already being implemented (Europa Clipper and Mars 2020), the third priority being a mission to an icy giant planet. That essentially brings the remaining, an icy giant planet mission, to the top of the list for implementation. Considering the importance of the ice giants for the solar system and the extrasolar systems, an icy giant planet mission will likely be a high priority mission in the next Planetary Decadal Survey recommendations of flagship-class missions in the 2023-2033 decade. International partnerships, particularly with ESA and JAXA, are highly desirable for augmenting the science return of such a mission.

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