# Synegistic Probe-Orbiter Science and Measurements for Understanding the Formation and Evolution of the Icy Giant Planets


**Sushil K. Atreya(1), Olivier Mousis(2), Kim R. Reh(3), Tarun Kumar(1) and Pranika Gupta(1)**

(1)Planetary Science Laboratory, Climate and Space Sciences and Engineering, Univ. of Michigan, Ann Arbor, USA

(2)Laboratoire d'Astrophysique de Marseille, France

(3)Caltech Jet Propulsion Laboratory, Pasadena, California USA



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## ABSTRACT


The Galileo Probe was designed to measure the abundances of the heavy elements (mass >helium) and helium in Jupiter since they are key to understanding the planet's formation and heat balance. Broadly speaking, the same formation scenarios are expected to apply to the Icy Giant Planets (IGP), Uranus and Neptune; hence their elemental abundances are crucial also. However, bulk of the C, N, S, and O bearing molecules are sequestered in condensible volatiles whose well-mixed regions in the atmospheres of the IGPs are extremely deep compared to Jupiter, preventing their direct *in situ* measurement. On the other hand, the noble gases − He, Ne, Ar, Kr and Xe – can provide the most robust constraints to the formation scenarios. Moreover, being non-condensible and chemically inert, they are expected to be uniformly mixed all over the planet, unlike the condensibles whose distribution is governed by dynamics, convection and purported deep oceans. Although the noble gases should be well-mixed everywhere below the homopause, measurements at and below the 1-bar level are needed, considering their low mixing ratios, except for He. That depth also gets around any potential cold trapping of the heavy noble gases at the tropopause or adsorption on methane ice aerosols. A single entry probe deployed to relatively shallow pressure levels of 5-10 bars at any location would yield robust determination of the abundances and isotopic ratios of the noble gases. Multiple entry probes would help in understanding the dynamics of condensible volatiles. A measurement of CO from orbit, along with other disequilibrium species has the potential of estimating the O elemental abundance. Microwave radiometry from orbiter and the Earth have the potential of measuring the depth profiles of $NH_3$ and $H_2O$, which would be important for understanding the atmospheric dynamics and weather in the deep atmosphere. Combined with the above data and the data on the interior and the magnetic field from orbiter, the probe results on the noble gases would provide even more robust constraints to the formation, migration and the evolution models of the Icy Giant Planets.


## ICY GIANTS — THE MISSING PIECES OF THE SOLAR SYSTEM FORMATION PUZZLE

- Though giant planets, IGPs belong in a class of their own, distinct from the gas giants.
- Comparative planetology of IGPs and gas giants is essential to understand the formation and evolution of the giant planets, in particular, solar system in general, and by extension, exoplanets, bulk of which are Uranus-Neptune size.

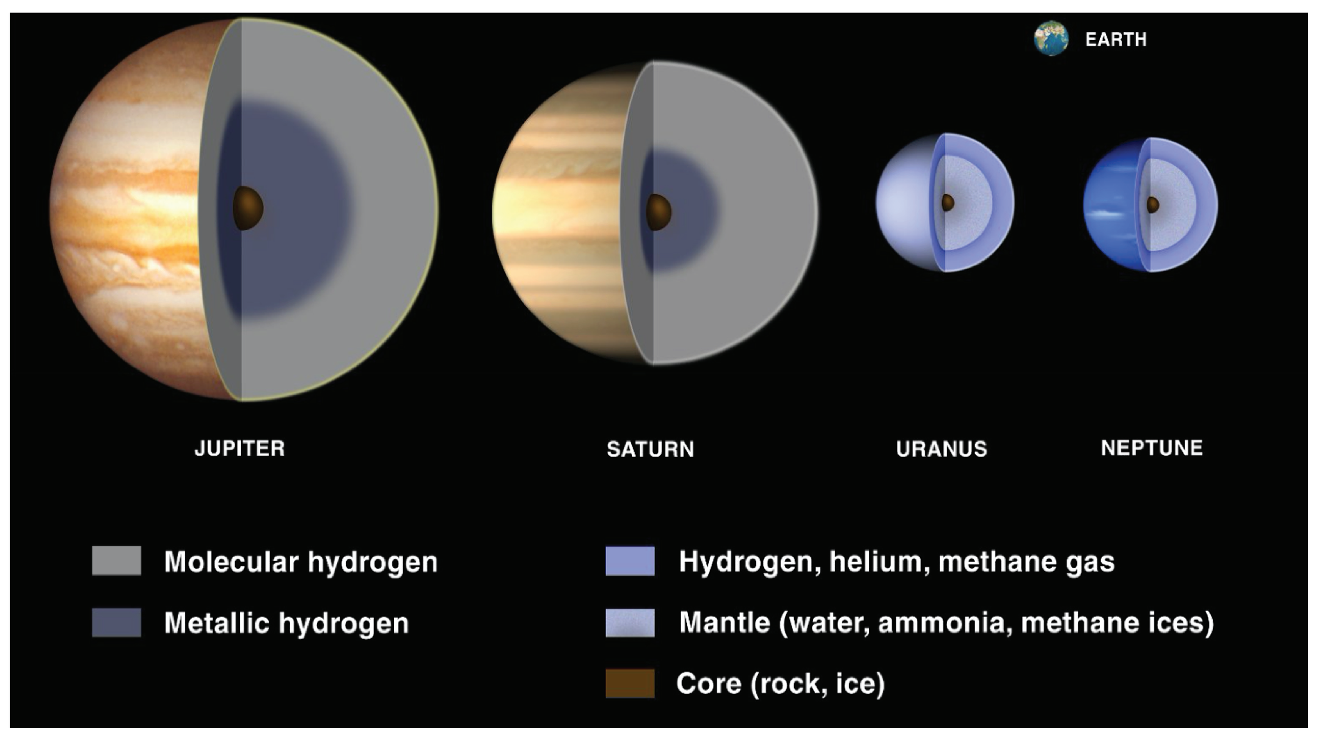


**Figure 1**. Comparison between the composition and internal structure of the gas giants (Jupiter and Saturn) and the icy giants (Uranus and Neptune). [Credit: Tristan Guillot].

## *IN SITU* AND REMOTE SENSING ESSENTIAL

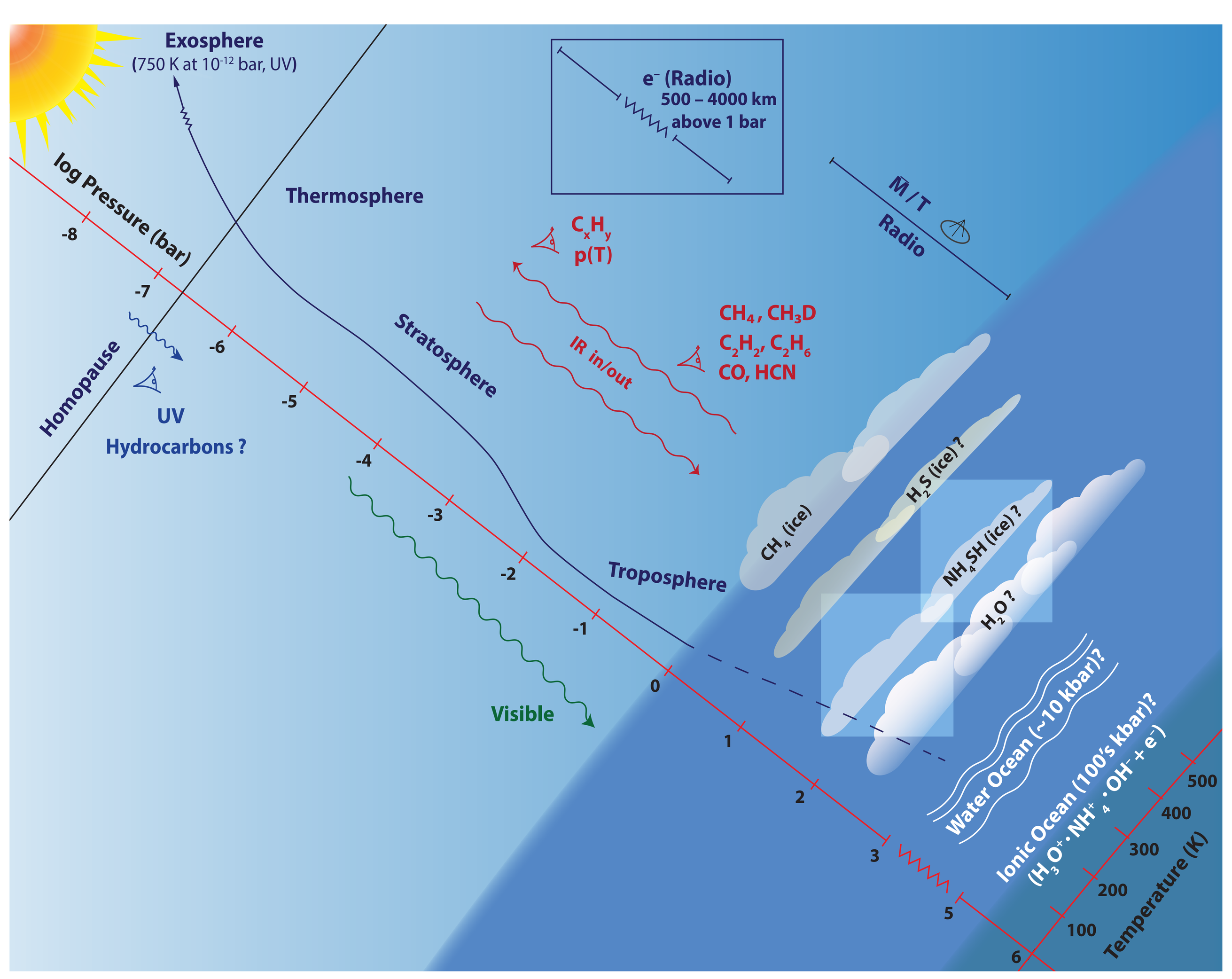


**Figure 2**. Regions of Neptune's atmosphere that can be explored by remote sensing, in situ entry probes, and the type of information obtained. Topmost cloud layer of methane ice is based on data from Voyager's radio occultation observations, other Cloud compositions are based on thermochemical models. [After Atreya et al. 2020; Maarten Roos-Serote helped with an earlier version of the graphic].

## ONLY C/H KNOWN IN THE IGPs

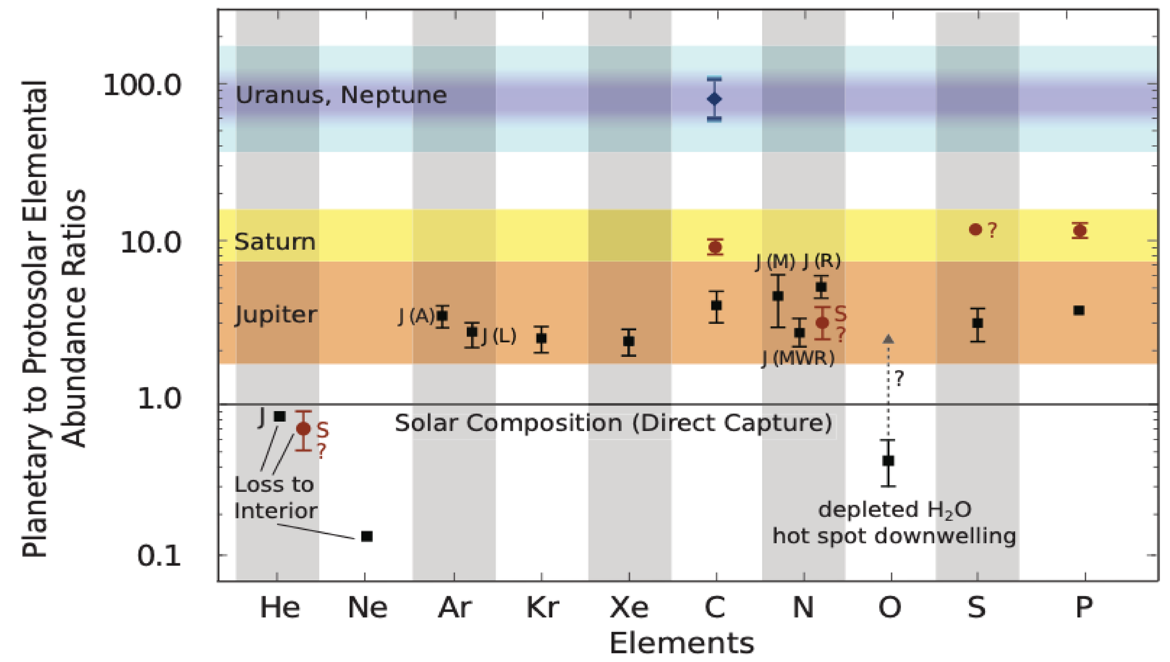


**Figure 3**. Elemental abundance ratios in the atmospheres of Jupiter, Saturn, Uranus and Neptune relative to the protosolar values. Only C/H is determined for Uranus and Neptune from ground-based observations down to ~1 bar level, but could be greater in the deeper atmosphere. Jovian values are from measurements made by the Galileo probe, except for $NH_3$, which is also by Juno. Saturn's He and N are labeled S. [Atreya et al. 2020].

## IGPs WATER IS TOO DEEP FOR ANY PROBES

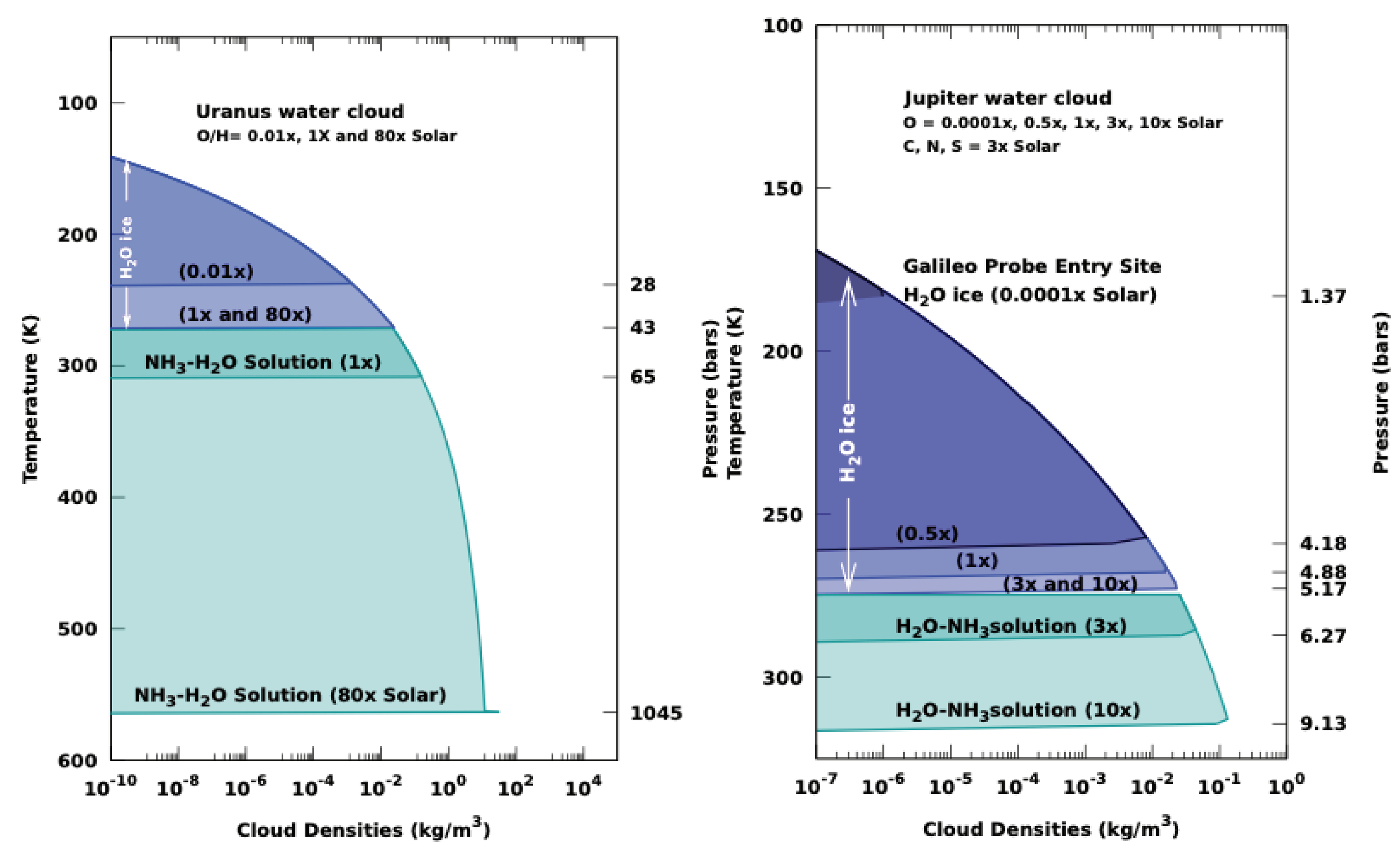


**Figure 4**. Comparison of the depth of a water cloud on Uranus and Jupiter under thermochemical equilibrium conditions, with different O/H ratios, i.e. abundances of well-mixed water, relative to the solar value [Atreya et al. 2020]. Cloud bases are robust; densities are upper limits. On Jupiter, the water cloud would form at ~6 bar level if the global O/H is similar to that in the equatorial region [Li et al. 2020], which is ~3x solar like the other heavy elements. On Uranus, it would form at a kilobar level for O/H = C/H = 80x solar. In fact, the depth of the $H_2O$ cloud at IGPs may be even deeper due to deep ocean dynamics inferred by Juno at Jupiter [Bolton et al 2017], a water ocean at ~10 kilobar level or even an ionic ocean at 100's of kilobar level. These oceans may also remove $NH_3$ and perhaps some $H_2S$, thus preventing the determination of O, N and S. In fact, the VLA observations find $NH_3$ depleted by up to a factor of 1000 relative to solar down to at least 50 bars. That would permit $H_2S$ to prevail to the upper troposphere, since it would not be scavenged by (depleted) $NH_3$. As a result, an $H_2S$ ice cloud would form between 1-3 bars., but no $NH_3$ and little $NH_4SH$ cloud, if any, unlike Jupiter. A $CH_4$ ice cloud forms above the $H_2S$ ice cloud at IGPs, but the well-mixed methane, hence C/H is likely much deeper.

## NOBLE GASES ARE KEY TO THE FORMATION MODELS OF THE IGPs

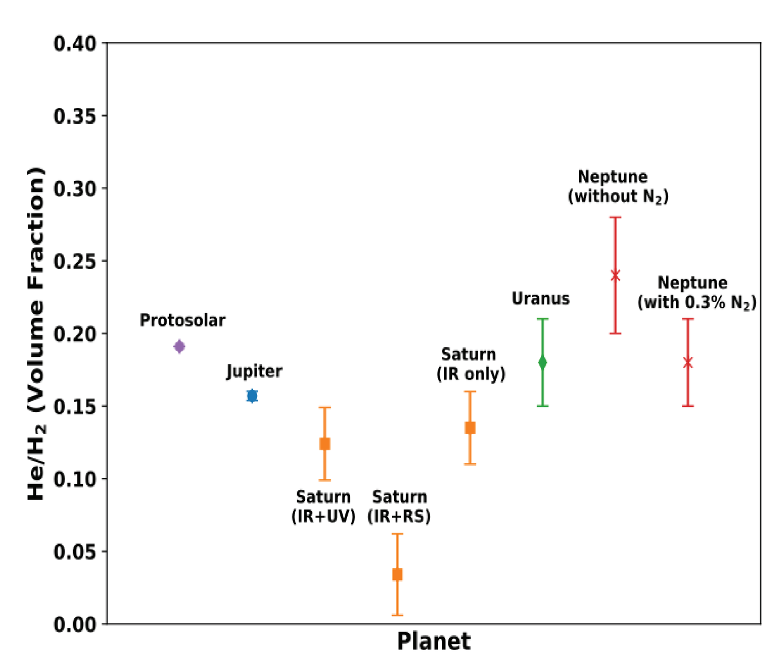


**Figure 5**. He/$H_2$ ratio in the atmospheres of the giant planets and the Sun. The value at the IGPs from Voyager flybys is too uncertain to constrain models of heat balance, interior processes and planetary formation, and requires entry probes, as Galileo at Jupiter. [Atreya et al. 2020].

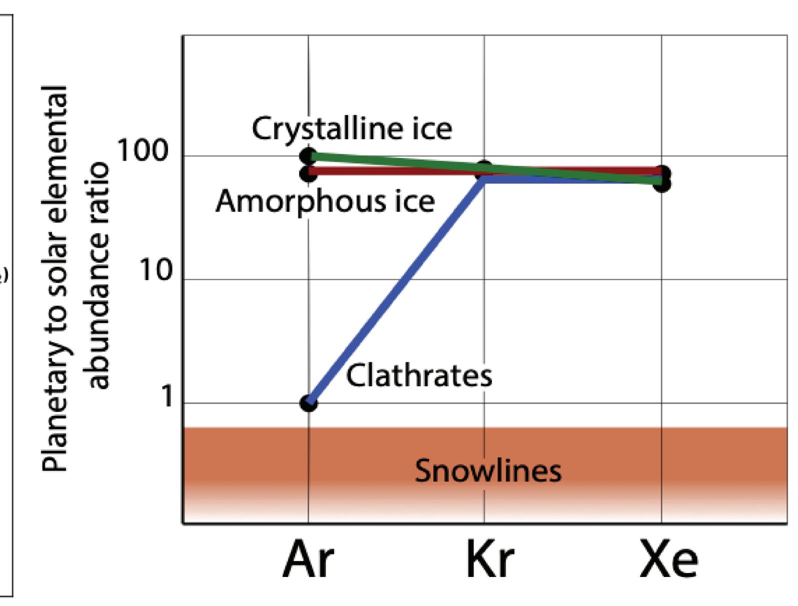


**Figure 6**. Predicted qualitative differences in the enrichments of volatiles in Uranus and Neptune for different formation scenarios. The resulting enrichments of the heavy noble gases, Ar, Kr and Xe, are shown in green (crystalline ice), brown (amorphous ice), blue (clathrates), and shaded brown (snowlines). [Mousis et al. 2020].

## ICY GIANT PLANET EXPLORATION WITH PROBE AND ORBITER CONCEPTS

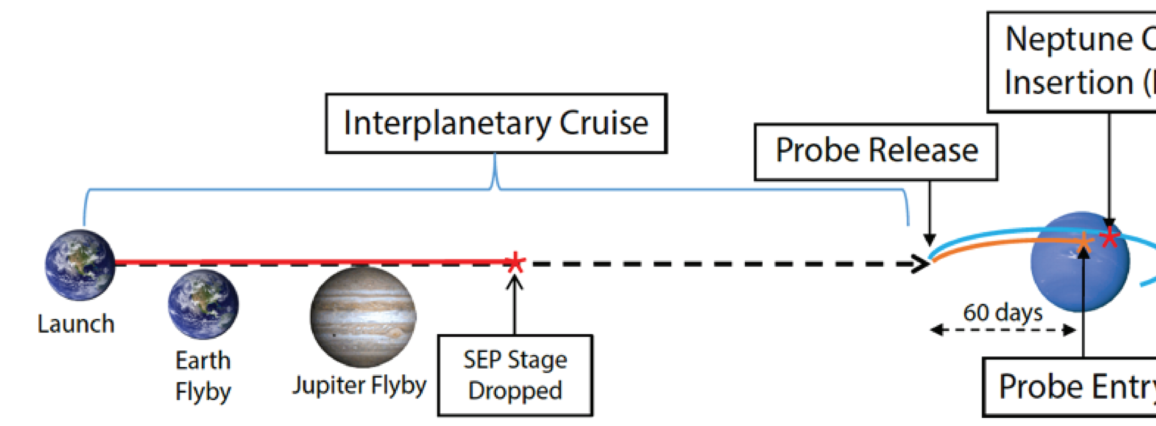


**Figure 7**. Possible scenario for a typical Neptune mission: Solar electric propulsion (SEP) architecture. [Credit: NASA/JPL].

The main elements of a typical Neptune mission on conventional launch vehicle are launch, followed by gravity assist at Earth and Jupiter, SEP jettison at ~6 AU, probe release ~60 days prior to Neptune orbit insertion, probe mission for ~1 hour, and the orbital phase. Uranus mission concept is similar. SEP is mission enabling for Neptune, but not Uranus. Table 1 below shows a typical mission to either Uranus or Neptune has a cruise duration of ~12 years from launch to orbit insertion. Best mass margin and JGA require launch no later than 2030-2034 for Uranus and 2029-2030 for Neptune (2031 with SLS). Dual spacecraft mission can be enabled by an SLS launch, as shown in Figure 9. [Credit: NASA/JPL].

**Table 1.** Orbiter-Class Mission: Launch-no-later-than Dates [Credit: NASA/JPL].

| | | Uranus | Neptune | Dual |
|---|---|---|---|---|
| Best Launch Years (JGA) | | 2030-2034 | 2029-2030 | 2031 |
| Launch Class | S/C Propulsion | | | |
| Delta IV-H | Chemical | 2035 | 2029 | n/a |
| | SEP | Any | 2030 | n/a |
| SLS-Block1B | Chemical | Any | 2031 | n/a |
| | SEP | Any | Any | 2031 |
| Delta IV-H | SEP | | Any | n/a |
| *Color code(b) | | TOF < 12 yrs | TOF < 13 yrs | |
| (TOF is interplanetary portion only) | | | TOF < 20-25 yrs | |

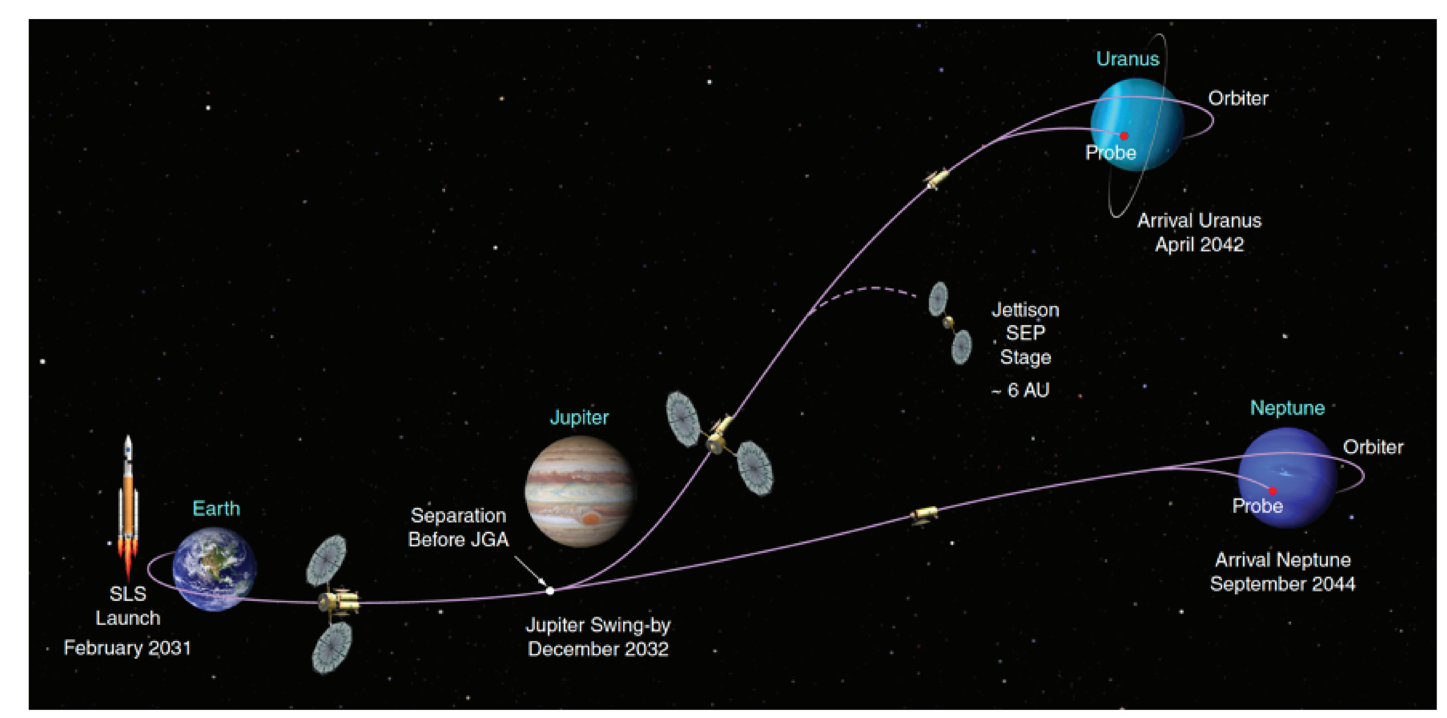


**Figure 8**.Dual-spacecraft, dual-planet mission scenario. [Credit: NASA/JPL].

## CONCLUSIONS

- Only entry probes are capable of making the measurements critical to constraining the models of the origin, migration and evolution of the icy giant planets.
- Those data include the abundances and isotopic ratios of the key noble gas and certain heavy elements.
- Orbiter observations, especially on magnetic field, interior and deep dynamics, are essential complements to the *in situ* probe data.
- Mission enabling technologies exist today to carry out an orbiter probe mission. Mission enhancing technology developments are underway, however.

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