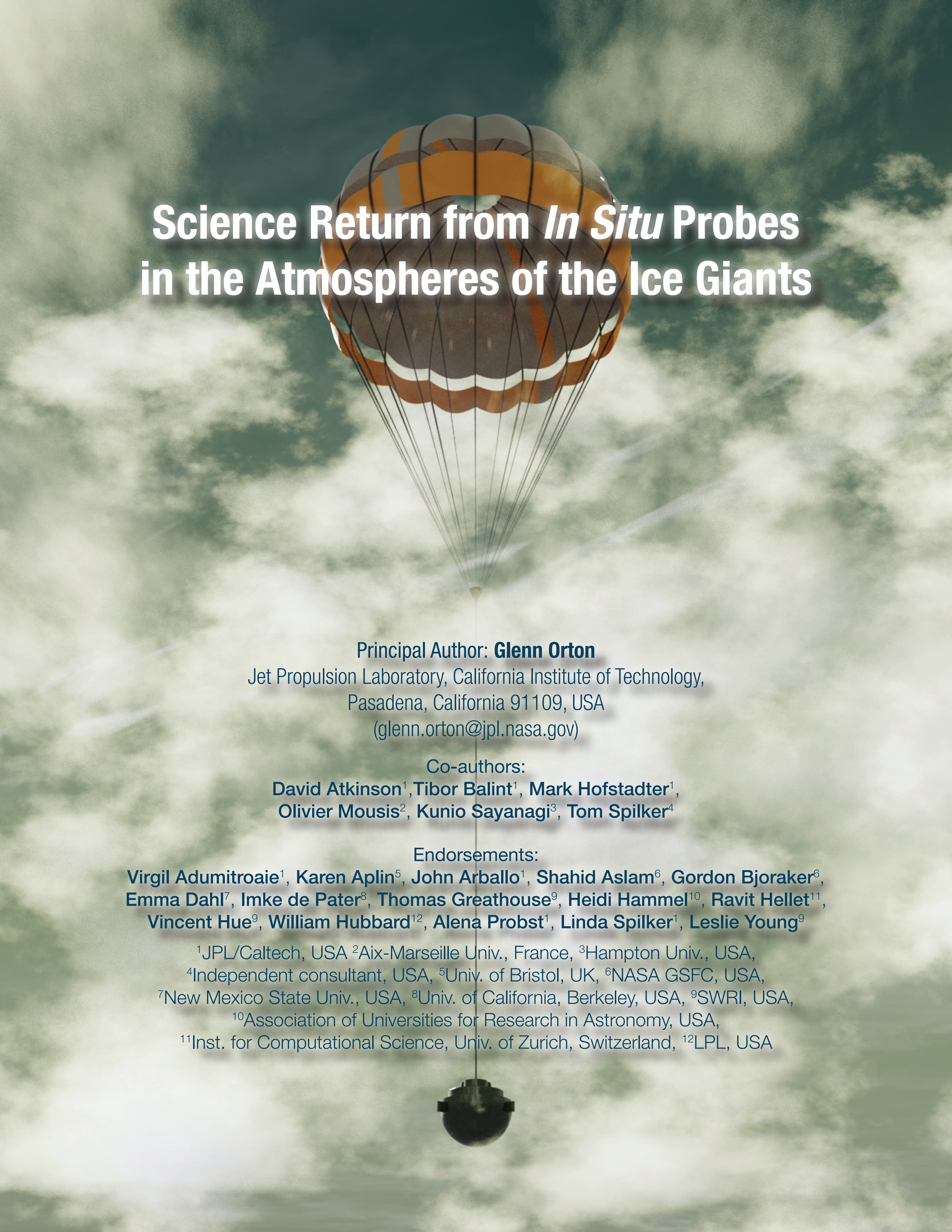

Science Return from *In Situ* Probes in the Atmospheres of the Ice Giants

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Abstract

We describe the main scientific goals that can be addressed uniquely by direct probes into the atmospheres of Uranus and Neptune. The Galileo Jupiter descent probe demonstrated the potential for unexpected science return: measurements of key abundances, including those of helium and other noble gases, possibly only *in situ*. We advocate for measurements that will put the Galileo probe results into a broader context. Atmospheric entry probes targeting the 10-bar level would yield unique insight into (i) the formation history of the outer planets and that of the Solar System, and (ii) the various processes at play in planetary atmospheres. An *in situ* probe or probes would focus on key measurements of atmospheric composition, structure, and dynamics.

1. Introduction

The giant planets contain most of the non-solar mass of the Solar System and have played a major role in shaping the evolution of the Solar System as a whole [1], including the delivery of volatiles to the terrestrial planets [2]. Thus, understanding their origin is a key to unlocking our understanding of the formation, evolution, and current structure of the entire Solar System. Although giant-planet composition is predominantly hydrogen and helium, Uranus and Neptune have a smaller mass fraction of those constituents than Jupiter and Saturn. Uranus and Neptune are considered Ice Giants because their composition is consistent with interiors possessing significant fractions of icy and rocky material. Sending probes into the Ice Giants extends our knowledge of the range of giant-planet compositions currently known in great detail only for Jupiter from the Galileo Probe [3]. In particular, only a probe can measure the noble gases, providing key information on Ice Giant formation and evolution. Atmospheric processes in Uranus and Neptune also represent a big departure from those in Jupiter and Saturn, e.g. the dominance of retrograde rather than prograde winds at low latitudes and additional condensate clouds in their significantly colder atmospheres. These processes can be studied to some extent by remote sensing, but important details remain hidden either below the clouds or by limitations inherent in remote sensing. Studies of the deeper-atmospheric processes are an important key to the conditions in the large fraction of exoplanets whose masses are in the same range as those of Uranus and Neptune [4]. The time for such exploration is now: a joint NASA–ESA Ice Giant Study Science Definition Team (SDT) [5] identified 2030–2034 as the optimal launch window for Uranus and 2029-2030 for Neptune, both within the time frame addressed by the 2023-2032 Decadal Survey.

2. Science themes

2.1. When, Where and How Did the Ice Giants Form?

The short lifetimes of protoplanetary disks implies that the gas giants Jupiter and Saturn formed rapidly in order to capture their envelopes of hydrogen and helium [6,7,8]. Their larger distances from the Sun allowed Uranus and Neptune to have longer formation time scales before the gas disk dissipated [9,10]. This resulted in the masses of Ice Giant gaseous envelopes being relatively small compared with their ice/rock cores. Thus, a comparison of the composition of the Gas and Ice Giants provides information on the spatial gradients within the solar nebula and constraints on planetary migration [11, 12] during and following the epoch of formation. Direct measurements by entry probes into the Ice Giants will help discriminate among Solar System formation models.

Composition The composition of the outer planets provides direct evidence on the formation, evolution history, and interiors of the outer planets. Measuring heavy element, noble gas and isotopic abundances reveals the conditions and processes leading to the formation of planetesimals that fed the forming planets [3,13,14]. The Galileo probe into Jupiter's atmosphere achieved a ground-breaking advance [15, 16, 17, 18, 19, 20, 21], where the He/H_2 ratio was determined with a relative accuracy of 2% [21], along with the abundances of several heavy elements and noble gases [20,21, 22]. With the notable enrichments of Ar, Ke and Xe over solar abundances, the strong depletion of Ne was a surprise. This depletion has been attributed to the process of He rain

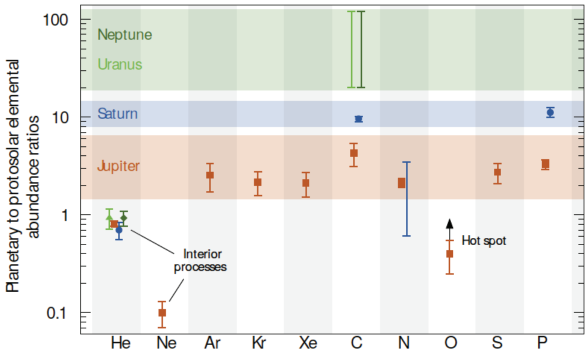

Figure 1. *Enrichment factors (with respect to the protosolar value) of noble gases and heavy elements in the outer planets relative to solar. (See [4] for references).*

in Jupiter [24]. Depletion of He and Ne is not expected in Uranus and Neptune because their deeper interiors are mostly made of ices, implying that He does not rain out in either planet. *In situ* measurement of Ice Giant atmospheres would test those assumptions and diagnose the high-pressure behavior of H/He. The uniform enrichment observed in Galileo probe data (Fig. 1) tends to favor the *core accretion* scenario for Jupiter [7,25]. Even the most fundamental measurement of the bulk composition to the 2% level of the Galileo probe would provide valuable ground truth.

Understanding the interior structures of Uranus and Neptune is inextricably tied to their formation. Gravity-field data suggest possibly very different interiors from Jupiter and Saturn [26]. Direct access to heavy materials in outer-planet cores is impossible, so the composition of the well mixed troposphere must be used. Atmospheric entry probes can access the appropriate depth.

Isotopic Measurements Measurement of isotopic ratios represents a rich source of information to constrain formation scenarios in detail, D/H in particular. The D/H ratio in Jupiter's atmosphere is estimated to be ~5%-10% larger than the protosolar value, possibly a result of mixing of nebular gas with deuterium-rich ices during formation. The deuterium enrichment is similar in Uranus and Neptune [27], with its value suggesting that significant mixing occurred between the protosolar H_2 and the H_2O ice accreted by both planets. If the D/H ratio in H_2O ice is cometary, then 68%–86% of the heavy components consist of rock and 14%–32% is made of ice, values suggesting that both Uranus and Neptune are comprised of more rock and ice, assuming that the planets have been fully mixed [27]. Alternatively, it has been suggested [28] that, if Uranus and Neptune formed at the carbon monoxide line in the protosolar nebular (PSN), then the heavy elements accreted by the two planets would mostly consist of a mixture of CO and H_2O ices, with CO being the dominant species. This scenario assumes the accreted H_2O ice presents a cometary D/H ratio and allows the two planets to remain ice-rich and O-rich while providing an H/D ratio consistent with the observations. Deeper probing of these atmospheres would allow an investigation into the possibility of a change in isotopic fractionation with depth. The measurement of the D/H ratio should be complemented by a precise measurement of $^3He/^4He$ to provide additional constraints on the protosolar D/H ratio, which still remains uncertain. It is derived from $^3He/^4He$ measurement in the solar wind, corrected from changes occurring in the solar corona and chromosphere subsequent to the Sun's formation from which the primordial value of $^3He/^4He$ is subtracted [29]. This primordial $^3He/^4He$ is currently derived from the ratio observed in meteorites or in Jupiter's atmosphere. Measurements of $^3He/^4He$ in Uranus or Neptune would verify the corresponding value in Jupiter as well as complement the scientific impact of the protosolar D/H determination.

The $^{14}N/^{15}N$ ratio has large variations as measured in different planetary bodies. Genesis solar-wind samples [30] suggest a $^{14}N/^{15}N$ value that is consistent with remote sensing [31] and *in situ* [22] measurements made of ammonia in Jupiter and a lower limit derived from ground-based mid-infrared observations of NH_3 in Saturn. The Jupiter and Saturn measurements suggest that primordial N_2 was most likely the main reservoir of the present NH_3 complement in giant-planet atmospheres [6, 32, 33]. But if Uranus and Neptune are mostly made of rocks and ices [25], they may share the same composition as comets. The strong depletion of N in Comet 67P/Churyumov–Gerasimenko [34] confirms that N_2 is only a minor nitrogen reservoir compared to NH_3 and HCN [35] and probably also other comets [36]. If Uranus and Neptune have been accreted from the same building blocks as comets, then we would expect an Ice Giant $^{15}N/^{14}N$ ratio in them to be close to cometary values, thereby providing insights regarding the origin of the primordial nitrogen reservoir in both planets. One would expect that isotopic measurements of carbon, oxygen and noble-gas isotopic ratios would reflect their primordial values. Only small variations of the $^{12}C/^{13}C$ ratios have been observed across the Solar System. *In situ* measurements of this ratio in Uranus and Neptune would confirm whether this ratio is also similar to the telluric one.

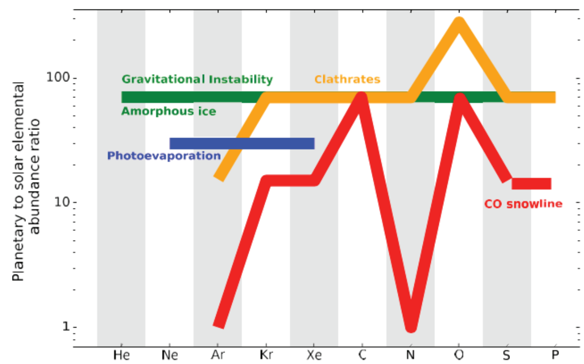

Figure 2. *Qualitative differences between the enrichments in volatiles predicted in Uranus and Neptune predicted by the different formation scenarios (calibrations based on the carbon determination).*

Formation Models and Enrichment Patterns in Ice Giants Measurements of the volatile abundances are key to deciphering the conditions around Ice Giant formation in the PSN. Such measurements can confirm or refute individual formation models (Fig. 2).

» The *gravitational instability model* involves the photoevaporation of giant-planet envelopes by a nearby OB star and settling of dust grains before mass loss. O, C, N, S, Ar, Kr and Xe should all be enriched by a similar factor relative to their protosolar abundances in this model [37].

» The *core accretion and amorphous ice model* also predicts homogeneous enrichments of O, C, N, S, Ar, Kr and Xe because their low-temperature trapping efficiencies are similar in amorphous ice [3,38], if there is no process leading to relative fractionation differences between them.

» The *core accretion and clathrate model* implies trapping efficiencies that strongly vary from one species to another [39], with amounts that vary as a function of trapping temperatures and scenarios for the availability of crystalline water to achieve full or only partial clathration [13, 33, 40].

» In the *photoevaporation model*, Ar, Kr and Xe were homogeneously adsorbed at low temperatures on the surface of amorphous icy grains, and the disk lost H_2 and He due to photoevaporation. These icy grains migrated toward the region where the giant planets were being formed and subsequently released their trapped noble gases due to increasing temperature. These noble gases would have been supplied in supersolar abundance from the PSN gas to the forming giant planets. The noble-gas enrichments should be smaller than those resulting from accretion of solids [41].

» The *CO snowline model* suggests that Uranus and Neptune were both formed at the location of the CO snowline in a stationary disk [28]. Due to diffusive redistribution of vapor, the PSN CO snowline formed both planets from C- and O-rich solids but N-depleted gas. Ar is depleted just as much as N in these atmospheres. However, Kr, He, S and P should be supersolar in the envelopes of the two Ice Giants, but lower than C and O abundances, which are very high [28].

2.2 How Do Physical and Chemical Processes Maintain the Current Atmospheric State?

In situ exploration of the atmospheres of Uranus and Neptune would also provide direct sampling and a ground-truth baseline for a plethora of physical and chemical processes in their atmospheres.

Zonal Winds Unlike Jupiter's and Saturn's alternating prograde and retrograde zonal winds as a function of latitude, Uranus and Neptune have broad retrograde jets [42]. These differences form the subject of intensive research, with models unable to reproduce properties of the wind systems without carefully adjusting multiple parameterizations. Juno gravity-sensing [43,44] suggests that the winds may extend 3,000 km below the cloud tops in Jupiter, with Cassini [45] implying 9,000 km in Saturn, and a reanalysis of Voyager-2 data on Uranus and Neptune [26] suggesting 1,000 km. Modeling the winds in Uranus and Neptune may also be complicated if the horizontal distribution of volatiles is inhomogeneous, resulting in "humidity" winds [46] due to the enriched state of volatiles compared with Jupiter and Saturn. *In situ* measurements of the vertical wind shear with depth would provide unique insights into the mechanisms responsible for wind generation The vertical wind shear measured by Galileo conformed to few previous expectations. Only through knowledge of the vertical distribution of winds and condensables will any detailed understanding of the roles of solar heat flux and moist convection be constrained [47].

Temperature Structure Measuring temperatures in the upper atmospheres of Uranus and Neptune is possible from remote sensing of thermal emission but with a vertical resolution that is generally no better than a full atmospheric scale height. Higher-resolution measurements are available from radio-occultation experiments, but those depend on knowledge of the vertical variability of mean molecular weight. But the vertical distribution of highly enriched volatiles vs temperatures represents a fundamentally degenerate problem. Only entry probes can determine these quantities accurately, thereby providing a ground-truth to compare with remote-sensing retrievals. For both Uranus and Neptune, models of globally averaged temperatures [48, 49] differ from radio occultation results [50,51], requiring *in situ* determination of a temperature profile and vertical distribution of mean molecular weight. Furthermore, remote-sensing is limited to pressures not much greater than 1 bar. For Uranus and Neptune, considerable uncertainty is due to the uncertainty in the gradient of molecular weight caused by methane condensation and the resulting inhibition of moist convection in the atmosphere [52, 53, 54] that may be sub-adiabatic, dry adiabatic or superadiabatic. These conclusions have profound consequences for interior and evolution models, atmospheric dynamics and the interpretation of abundance measurements for disequilibrium species. Measurements of the temperature profile to pressures of ~10 bars will clearly include the 2-bar methane condensation level. Finally, measurements of the stratospheric temperature profile in the Ice Giants will provide a detailed characterization of gravity-wave propagation that could help resolve the energy transfer processes that potentially contributes to the very high temperatures in Ice Giant stratospheres and thermospheres [55, 56].

Clouds In the visible and near-infrared, Uranus and Neptune display a variety of cloud morphologies. Multi-wavelength observations can constrain vertical cloud structure, particle size and single-scattering albedo using radiative-transfer analysis. Cloud models for Uranus [57, 58, 59, 60] and Neptune [61, 62, 63] consistently evoke an extended haze layer at 50–100 mbar, located above a thin CH_4 ice cloud whose base is near 1.3 bar, and an optically thick H_2S cloud whose base is likely to be ~2–4 bars. Radiative-transfer-based models produce degenerate solutions where multiple possibilities for cloud particle properties and vertical structure can fit the observations equally well. *In situ* measurements provide a ground-truth to remote-sensing observations, yielding information about clouds much deeper than can be observed remotely. Tests of the Equilibrium Cloud Condensation (ECC) models predicting the location of clouds based on the relative abundances of condensables can be tested to determine the expected presence of CH_4 and H_2S [64,65], and the possible presence of a cloud of NH_3 near 10 bars depending on the sequestration of NH_3 in a deeper NH_4SH cloud and the amount of NH_3 dissolved in a deep and massive liquid-water cloud. Direct probe measurements would verify or refute the conclusion that NH_3 gas is unlikely due to the detection of tropospheric H_2S [66, 67], suggesting that H_2S is more abundant than NH_3. Although a deep probe would be needed to reach an NH_4SH cloud, a probe readily capable of reaching 10 bars could detect both CH_4 and H_2S cloud particles.

Convection and Meteorological Features Neptune is known for dark vortices surrounded by bright companion clouds [68, 10], and Uranus has rare dark vortices [69] and brighter cloud systems [70]. Many of these features are long-lived, but their depth into the lower troposphere is unknown. Large-scale waves can also affect the atmosphere well below the upper-cloud layer [71].

Optimal locations for the probe entry [72] are not free of zonal inhomogeneities. It will be important to contextualize the interpretation of vertical profiles of all *in situ* atmospheric properties using remote observations of the descent region or regions and their properties at and above the cloud level. Because the Galileo probe descended into a very anomalous region of the atmosphere, this was a key element to understand its otherwise puzzling results on clouds and condensates [73].

Chemistry Precise measurements of the abundance of tropospheric CH_4 coupled with knowledge of vertical mixing, which can be determined precisely only by *in situ* measurements, are a key to the accurate modeling of stratospheric hydrocarbon generation. For Uranus and Neptune, this includes CO and CO_2 with the oxygen component derived externally from interplanetary dust or comets. These constituents are important because they are optically active and therefore affect the aerosol structure and energy balance of the atmosphere.

Summary of Key Measurements The following *in situ* measurements will constrain models of Ice Giant formation and evolution, as well as models of key processes in the atmosphere.

- *Tropospheric abundances of noble gases He, Ne, Xe, Kr, Ar and their isotopes* should be measured to trace materials in the subreservoirs of the PSN. The accuracy of He should be as good as the Galileo measurement at Jupiter (±2%) and to ±1% for Ne, Xe, Kr, and Ar in order to enable a direct comparison with other known Solar System values.
- *Tropospheric abundances of C, N, S and P down to 10 bars or greater* should be obtained to accuracies of 10% or better, similar to the protosolar abundance uncertainties.
- *Isotopic ratios* should be measured with accuracies of ±5% for D/H and $^{15}N/^{14}N$, ±3% for $^{3}He/^{4}He$, and ±1% for $^{17}O/^{16}O$, $^{18}O/^{16}O$, $^{13}C/^{12}C$. This will enable the determination of the main reservoir of these species in the PSN.
- *Tropospheric abundances of CO and PH_3* should be measured. Having both brackets the deep H_2O abundance [74]. CO alone may not be enough due to deep thermal profile uncertainties [75].
- *Temperature profile from the stratosphere down to 10 bars* would establish the stability of the atmospheres toward vertical motions and constrain the opacity properties of clouds at or above these levels (CH_4, NH_3 or H_2S clouds). Testing lapse rates for consistency with sub- or superadiabatic values is a key to mechanisms for internal heat transport. It would also determine whether convection is inhibited by the mean molecular weight gradient [52]. This measurement is essential to verify results derived from global remote-sensing observations of thermal emission.
- *Cloud and haze particle number density, size, shape and opacity* should be derived from measurements of aerosol scattering properties over a range of phase angles. *In situ* measurements would constrain the vertical variability of cloud and haze properties and help determine the effect of cloud condensation or photochemical haze formation as well as the contribution of energy relinquished by the phase change of by the phase change of CH_4, NH_3, and H_2S on the lapse rate.
- *Doppler-wind* measurements provide the wind profiles in the lower troposphere, below the depths of cloud tops where most cloud-tracking measurements are made. Comparing these winds with vertical profiles of condensable abundances and temperature data enables the relative importance of thermal and humidity winds to be quantified.
- *Conductivity* measurements as a function of altitude would indicate the types of clouds that support charge separation to generate lightning. Combined with meteorological and chemical data, conductivity measurements would also permit extraction of the charge distribution of aerosol particles, improving our understanding of the role of electrical processes in cloud formation, aerosol microphysics and lightning generation.
- *Ortho-to-para H_2 ratio* measurements would constrain the degree of vertical convection and the convective capability at different cloud-condensing layers and are essential to understand the vertical profile of atmospheric stability in the cold atmospheres of Uranus and Neptune [76].

3. Summary

Measurements from descent probes into the atmospheres of Uranus and Neptune are extremely important. They provide unique observations of composition, structure and dynamics that are not available from remote-sensing observations and are directly relevant to the origin and evolution of the Solar System and to comparisons of processes active in the atmospheres of Uranus and Neptune. Moreover, they are also relevant to the many exoplanets falling into the same mass range.

References

1. Gomes, R., Levison, H. F., Tsiganis, K., et al. 2005, Nature, 435, 466.
2. Chambers, J. E., & Wetherill, G. W. 2001, Meteoritics and Planetary Science, 36, 38.
3. Owen, T., Mahaffy, P., Niemann, H. B., et al. 1999, Nature, 402, 269.
4. Rymer, A. et al. 2018. Solar System Exoplanets White Paper. 2018arXiv180403573R.s
5. Hofstadter, M., Simon, A., Atreya, S., et al. 2019, Planetary & Space Sci., in press.
6. Pollack, J. B., Hubickyj, O., Bodenheimer, P., et al. 1996, Icarus, 124, 62.
7. Alibert, Y., Mousis, O., & Benz, W. 2005, Astrophys. J. Lett., 622, L145.
8. Alibert, Y., Mousis, O., Mordasini, C., et al. 2005, Astrophys. J. Lett., 626, L57.
9. Dodson-Robinson, S. E., & Bodenheimer, P. 2010, Icarus, 207, 491.
10. Helled, R., Bodenheimer, P., Podolak, M., et al. 2014, Protostars & Planets VI, 643.
11. Lin, D. N. C., & Papaloizou, J. 1986, Astrophys. J., 307, 395.
12. Ward, W. R. 1997, Icarus, 126, 261.
13. Gautier, D., Hersant, F., Mousis, O., et al. 2001, Astrophys. J. Lett., 550, L227.
14. Hersant, F., Gautier, D., & Hure´, J.-M. 2001, Astrophys. J., 554, 391.
15. Young, R. E. 1998, Journal of Geophysical Research, 103, 22775.
16. Folkner, W. M., Woo, R., & Nandi, S. 1998, J. Geophys. Res., 103, 22847.
17. Ragent, B., Colburn, D. S., Rages, K. A., et al. 1998, J. Geophys. Res., 103, 22891.
18. Atkinson, D. H., Pollack, J. B., & Seiff, A. 1998, J. Geophys. Res, 103, 22911.
19. Sromovsky, L. A., Collard, A. D., Fry, P. M., et al. 1998, J. Geophys. Res., 103, 2929.
20. Niemann, H. B., Atreya, S. K., Carignan, G. R., et al. 1998, J. Geophys. Res., 103, 22831.
21. Von Zahn, U. Hunten, D. M. & Lehmacher, G. 1998 J. Geophys. Res. 103, 22815.
22. Wong, M. H., Mahaffy, P. R., Atreya, S. K., et al. 2004, Icarus, 171, 153.
23. Atreya, S. K., Wong, M. H., Owen, T. C., et al. 1999, Planetary & Space Sci., 47, 1243.
24. Wilson, H. F., & Militzer, B. 2010, Phys. Rev. Lett., 104, 121101.
25. Guillot, T. 2005, Ann. Rev. Earth & Planetary Sci., 33, 493.
26. Kaspi, Y., Showman, A. P., Hubbard, W. B. et al. 2013, Nature, 497, 344.
27. Feuchtgruber, H., Lellouch, E., Orton, G., et al. 2013, Astron. & Astrophys., 551, A126.
28. Ali-Dib, M., Mousis, O., Petit, J.-M., et al. 2014, Astrophys. J., 793, 9.
29. Geiss, J., & Gloeckler, G. 1998, Space Science Reviews, 84, 239.
30. Marty, B., Chaussidon, M., Wiens, R. C., et al. 2011, Science, 332, 1533.
31. Fouchet, T., Lellouch, E., Be´zard, B., et al. 2000, Icarus, 143, 223.
32. Mousis, O., Fletcher, L. N., Lebreton, J.-P., et al. 2014, Planetary & Space Sci., 104, 29.
33, Mousis, O., Lunine, J. I., Fletcher, L. N., et al. 2014, Astrophys. J., 796, L28
34. Rubin, M., Altwegg, K., Balsiger, H., et al. 2015, Science, 348, 232.
35. Le Roy, L., Altwegg, K., Balsiger, H., et al. 2015, Astron, & Astrophys,, 583, A1.
36. Bockele´e-Morvan, D., Crovisier, J., Mumma, M. J., et al. 2004, Comets II, 391.
37. Boss, A. P., Wetherill, G. W., & Haghighipour, N. 2002, Icarus, 156, 291.
38. Bar-Nun, A., Notesco, G., & Owen, T. 2007, Icarus, 190, 655.

39. Mousis, O., Lunine, J. I., Picaud, S., et al. 2010, Faraday Discussions, 147, 509.
40. Mousis, O., Lunine, J. I., Madhusudhan, N., et al. 2012, Astrophys. J. Lett., 751, L7.
41. Stevenson, D. J., & Lunine, J. I. 1988, Icarus, 75, 146.
42. Sa´nchez-Lavega, A. et al. 2019, in Zonal Jets. Cambridge Univ. Press, eds: Galperin & Read.
43. Kaspi, Y., Galanti, E., Hubbard, W. B. et al. 2018, Nature, 555, 223.
44. Guillot, T., Miguel, Y., Millitzer, B. et al. 2018, Nature, 555, 227.
45. Galanti, E., Kaspi, Y., Miguel, Y. et al. 2019, Geophys. Res. Lett., 46, 616.
46. Sun, Z. P., Schubert, G., Stoker, C. R. 1991, Icarus, 91, 154.
47. Lian Y. & Showman, A. P. 2010, Icarus, 207, 373.
48. Orton, G. S. Fletcher, L. N., Moses, J. I. et al. 2014, Icarus, 243, 494.
49. Fletcher, L. N., de Pater, I., Orton, G. S. et al. 2014, Icarus, 231, 146.
50. Lindal, G. F., Lyons, J.R., Sweetnam, D. N. et al. 1987, J. Geophys. Res. 92, 14987.
51. Lindal, G. F. 1992, Astron. J., 103, 967.
52. Guillot, T. 1995, Science, 269, 1697.
53. Leconte, K., Selsis, F., Hersant, F. et al. 2017, Astronomy & Astrophysics, 598, A98.
54. Friedson, A. J., & Gonzales, E. J. 2017, Icarus, 297, 160.
55. Herbert, F., Sandel, B. R., Yelle, R. V. et al. 1987, J. Geophys. Res., 92, 15093.
56. Li, C., Le, T., Zhang X., et al. 2018, J. Quant. Spectrosc. & Radiat. Transf., 217, 353.
57. West, R. A., Baines, K. H., Pollack, J. B., 1991, in Uranus, University of Arizona Press, eds: Bergstralh, J.T., Miner, E. D., Matthews, M.S.
58. Irwin, P. G. J., Teanby, N. A., Davis, G. R. 2009, Icarus, 203, 287.
59. de Kleer, K., Luszcz-Cook, S., de Pater, I. et al. 2015, Icarus, 256, 120.
60. Irwin, P. G. J., Wong, M. H. Simon, A. A. et al. 2017, Icarus, 288, 99.
61. Hammel, H. B., Baines, K. H., Bergstralh, J. T., 1989, Icarus, 80, 416.
62. Baines, K. H., Hammel, H. B., 1994, Icarus, 109, 20.
63. Irwin, P. G. J., Fletcher, L. N., Tice, D. et al. 2016, Icarus, 271, 418.
64. Weidenschilling, S. J., Lewis, J. S. 1973, Icarus, 20, 465.
65. Atreya, S. K., Wong, A. S. 2005, Space Sci. Rev., 116, 12.
66. Irwin, P. G. J., Toledo, D., Garland, R. 2018, Nature Astronomy, 2, 420.
67. Sromovsky, L. A., de Pater, I., Fry, P. M. et al. 2015, Icarus, 258, 192.
68. Smith, B. A., Soderblom, L. A., Banfield, D. et al. 1989, Science, 246, 1422.
69. Hammel, H. B., Sromovsky, L. A., Fry, P. M. et al. 2009, Icarus, 201, 257.
70. Sromovsky, L. A., de Pater, I., Fry, P. M. et al. 2015, Icarus, 258, 192.
71. Showman, A. P., Ingersoll, A. P., 1999, Icarus, 132, 205.
72. Fletcher, L. N. et al. 2020. Space Sci. Rev. 216, 2.
73. Orton, G. S., Fisher, B. M., Baines, K. H. et al. 1998, J. Geophys. Res, 103, 22791.
74. Visscher, C., & Fegley, B. 2005, Astrophys. J, 623, 1221.
75. Cavalie´, T., Venot, O., Selsis, F., et al. 2017, Icarus, 291, 1.
76. Banfield, D., et al. 2005. IEEE Aerospace Conference paper #1294, p691-694.

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