EXPLORATION OF URANUS AND NEPTUNE: LOOKING INTO THE PAST AND TOWARDS THE FUTURE OF ICE GIANT PLANETS. K. M. Soderlund[1], M. D. Hofstadter[2], A. Simon[3], S. Atreya[4], D. Banfield[5], J. Fortney[6], A. Hayes[5], M. Hedman[7], G. Hospodarsky[8], K. Mandt[9], A. Masters[10], M. Showalter[11], D. Turrini[12], E. P. Turtle[9], [1]Institute for Geophysics, John A. & Katherine G. Jackson School of Geosciences, The University of Texas at Austin (krista@ig.utexas.edu), [2]Jet Propulsion Laboratory/Caltech, [3]Goddard Space Flight Center, [4]University of Michigan Ann Arbor, [5]Cornell University, [6]University of California Santa Cruz, [7]University of Idaho, [8]University of Iowa, [9]Johns Hopkins Applied Physics Lab, [10]Imperial College London UK, [11]SETI Institute, [12]Institue for Space Astrophysics and Planetology Rome Italy.

Discovered in 1781 by William Herschel, Uranus is one of two ice giant planets in our solar system. Neptune was discovered 65 years later in 1846 by Johann Galle following the orbital predictions of Urbain Le Verrier and John Couch Adams. Our closest glimpse of these planets came from the Voyager 2 flybys, reaching the Uranian system in 1986 and the Neptunian system in 1989. With the advent of space-based telescopes and advanced optics techniques, observations of ice giant planets continue to propel new discoveries of both their physical and chemical properties, as well as their prevalence around other stars [1]. Complementarily, laboratory and numerical experiments facilitate process-based studies that not only advance our understanding of these observations, but also help explain how and why differences exist between Uranus and Neptune in particular and across giant planets more broadly.

Uranus and Neptune are important to study because they challenge our understanding of how planets form and evolve, display unique physical properties in their interiors, atmospheres, magnetospheres, rings, and satellites, and are common around other stars [2]. By deciphering the mysteries of the ice giants in our solar system, we will simultaneously make fundamental insights into the formation, evolution, and workings of planetary systems in general.

What We Know (And Don't Know): Uranus and Neptune represent a distinct class of ice giant planets that are fundamentally different from the better explored gas giants, Jupiter and Saturn. The gas giants are composed mostly of hydrogen and helium, with molecular H_2 transitioning to metallic hydrogen at mega-bar pressures that may form a dilute core with dissolved heavy elements at greater depths [3,4]. While Uranus and Neptune also possess hydrogen and helium envelopes, the envelopes are much smaller, accounting for less than 20% of the planets' masses and never making the transition to metallic hydrogen [3; c.f. 5]. The bulk composition of these planets is dominated by much heavier elements. Based on cosmic abundances, oxygen, carbon, nitrogen, and sulfur are the likely candidates, although few measurements exist of their relative abundances [6]. Since these species are thought to have been incorporated into protoplanets primarily as ices, the term "ice giants" has been adopted. Today, however, a supercritical fluid is the preferred phase of H_2O at depth.

The internal structures of these planets are poorly constrained, and no existing models can fit both gravity field and intrinsic heat flux measurements without ad hoc assumptions [7]. Significant questions remain, such as: Are there distinct compositional boundaries in the interior? What parts of these planets are convective and what are the resulting flow characteristics in the deep interior?

These questions have important consequences for the intrinsic magnetic fields of Uranus and Neptune that are presumably driven by a convective dynamo in the ionic ocean [8]. The multipolar, non-axisymmetric field morphologies of these planets were a surprise upon their discovery, and it is still not well understood why these fields are remarkably different compared to all other planets in our solar system [9]. The lack of alignment between the rotation and magnetic poles creates unique and variable orientations to the solar wind, particularly on Uranus whose rotation axis is almost in the plane of its orbit [10].

The tilt of Uranus is one of several intriguing differences compared to Neptune. Another major distinction is that, unlike all of the other the giant planets, Uranus emits little internal heat [11,12]. Despite these differences, the atmospheric dynamics of both planets are superficially quite similar with retrograde equatorial jets and prograde jets poleward of the mid-latitudes [13]. Storm activity, however, does vary between the two planets, with Neptune showing a very dynamic atmosphere with multiple storms while Uranus was quiescent during the Voyager encounter with subsequent periods of extreme activity [14,15]. Meridional circulations, especially at depth, are poorly characterized, despite being the main driver of all atmospheric motions.

The rings and satellites of the ice giants also differ markedly from those of the gas giants and from each other. Uranus' classical rings are narrow and dense, quite different from the broad expanse of Saturn's or the tenuous ones at Jupiter; the rings are also gravitationally entwined with a densely packed system of smaller moons that interact chaotically on short time scales [16]. Neptune's rings display their own unique features, dominated by large clumps that evolve on decadal timescales [17]. Many questions remain to be answered on what processes control the ring structures, dynamics, and their temporal variability.

Uranus hosts several mid-sized moons whose surface ices are different from those of Jupiter and Saturn's satellites, as would be expected given the colder temperatures in the zone of the ice giants. These mid-sized moons show features indicative of endogenic activity, such as Miranda's patchwork geologic morphology, the flow-like features on the floors of Ariel's graben, and Umbriel's bright polar feature. The smaller satellite Mab is also associated with a mysterious ring [18]. Neptune's satellite system is dominated by the captured Kuiper Belt object, Triton. That capture is believed to have ejected or destroyed any larger, native moons of Neptune [19], leaving only a family of small native moons today. But Triton itself is of great interest, having an atmosphere, active geysers, and unusual geology. Since only the southern hemispheres were illuminated during the Voyager flybys, we have an incomplete picture of these satellites and critical information about the moons' geologies, compositions, and internal structures is lacking.

The ice giants challenge our understanding of planet formation and evolution [20]. Their smaller amounts of hydrogen and helium is often attributed to the slower accretion rates at larger distances from the Sun. However, recent models of solar system formation suggest that Uranus and Neptune may have undergone substantial radial migration during the early parts of the solar system's history, complicating efforts to understand the conditions under which the ice giants formed. Furthermore, Uranus' extreme obliquity and Neptune's capture of Triton suggest that both systems experienced dramatic events in their early history, which perhaps reflect drastic changes in the structure of the early outer solar system.

Future Exploration: We have not yet carried out a detailed exploration of either ice giant, leaving significant holes in our understanding of these systems. The 2011 Decadal Survey [21] recognized the importance of Uranus and Neptune, and called for exploration of an ice giant system with a Flagship mission. In preparation for the next Decadal Survey, NASA, with ESA participation, conducted a broad study of possible ice giant missions in the 2024 – 2037 timeframe.

The highest-priority science objectives identified by this study [2] trace to internal structure and bulk composition (including noble gases and isotopic ratios) of the ice giants. These fundamental properties are necessary to understand the formation, evolution, and workings of an ice giant. Ten additional science objectives, all given equal priority, were also identified to advance our understanding of atmospheric dynamics, intrinsic magnetic fields and magnetospheres, rings, and satellites of the ice giants. These objectives, in condensed form, include:

- exploring the nature and driving forces of atmospheric dynamics;
- understanding the planetary dynamo and the flow of energy and mass from the solar wind into the magnetosphere and upper atmosphere;
- characterizing the thin, dense rings of Uranus, including their chaotic gravitational interplay with small moons, and the clumpy rings of Neptune;
- and determining the geology, composition, and internal structure of Uranus' major satellites and Triton, along with its atmosphere and plumes.

Uranus and Neptune are equally valuable and compelling as scientific targets. While equal, however, they are not equivalent. Each planet teaches us different things, and there is tremendous value in visiting both Uranus and Neptune with orbiter-probe spacecrafts.

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