Ice Giant Exploration: Results of the NASA-ESA Science Definition Team Study

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The most recent Planetary Science Decadal Survey, "Vision and Voyages for Planetary Science in the Decade 2013-2022", recognized the scientific importance of the Uranus and Neptune planetary systems and prioritized their exploration. In 2016, NASA and ESA established a Science Definition Team (SDT) to assess science priorities and affordable mission concepts for exploration of the Ice Giant planets in preparation for the next Decadal Survey. This study has now been completed and the resulting mission concepts, which demonstrate the feasibility of compelling missions, will be presented.

Since the Voyager 2 flybys of Uranus (1986) and Neptune (1989), the ice giant systems have intrigued and tantalized. Studies of the these systems encompass all disciplines of planetary science, with much cross-disciplinary overlap, particularly when looking at system-wide interactions. Although the SDT initially considered each discipline individually (interiors, atmospheres, magnetospheres, classical satellites, small satellites and rings), broad themes quickly emerged. The SDT compiled 12 main science objectives, which answered more than 50 science questions. That this list is by no means all-encompassing underscores the great breadth of science that could be achieved at either of these planets.

The most important science investigations are ones that address the fundamental questions "What is an ice giant?" and "How do they form?" We therefore consider the objectives of determining interior structure and bulk composition (including noble gases and key isotopic ratios) as the highest priorities. The SDT did not prioritize among the other objectives, and they are listed here in no particular order.

Science Objectives:
1. Constrain the structure and characteristics of the planet's interior, including layering, locations of convective and stable regions, internal dynamics
2. Determine the planet's bulk composition, including abundances and isotopes of heavy elements, He and heavier noble gases
3. Improve knowledge of the planetary dynamo
4. Determine the planet's atmospheric heat balance
5. Measure planet's tropospheric 3-D flow (zonal, meridional, vertical) including winds, waves, storms and their lifecycles, and deep convective activity
6. Characterize the structures and temporal changes in the rings
7. Obtain a complete inventory of small moons, including embedded source bodies in dusty rings and moons that could sculpt and shepherd dense rings
8. Determine surface composition of rings and moons, including organics; search for variations among moons, past and current modification, and evidence of long-term mass exchange / volatile transport
9. Map the shape and surface geology of major and minor satellites
10. Determine the density, mass distribution, internal structure of major satellites and, where possible, small inner satellites and irregular satellites
11. Determine the composition, density, structure, source, spatial and temporal variability, and dynamics

of Triton's atmosphere
12. Investigate solar wind-magnetosphere-ionosphere interactions and constrain plasma transport in the magnetosphere

Multiple mission architectures and instrument complements were considered. A Uranus orbiter with atmospheric probe, launching near 2030, is our recommended baseline mission. The orbiter payload will ideally be in the 90 to 150 kg range, though significant science can be achieved with smaller payloads. Our understanding of ice giants and solar system evolution will be maximized, however, by launching two spacecraft, one to Uranus and one to Neptune. We encourage consideration of these dual-spacecraft, dual-planet missions. We also encourage international collaboration as a way to minimize the cost to individual nations while maximizing the science return from what will likely be the only *in situ* exploration of an ice giant system for the next generation.

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