Interdisciplinary Program for Ice Giant Systems

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Less than 5 months ago, Neptune- and Uranus-sized objects were identified around other stars[1]. *Yet fundamental gaps exist in our knowledge of such bodies within our own solar system. We propose that NASA address this gap with an* ***Ice Giant Systems (IGS) Program****, a broad interdisciplinary program that incorporates telescopic observations, theoretical work, and laboratory data geared to outer solar system conditions.* The goal is to understand the diverse components of the ice-giant systems—atmospheres and interiors; magnetic fields and magnetospheres; satellite surfaces, atmospheres, interiors, and environments; ring systems—and how these components interact with one another and with the incident radiation from the Sun. Both the Uranus and Neptune Systems are appropriate study topics, since they are similar in many respects. At the same time, their striking differences provide excellent opportunities for comparative planetology, much as Saturn and Jupiter do for their class of planets, the larger Gas Giants. An IGS program can and should begin now, given the unique—for our current level of technology—seasonal timing for both Uranus (equinox) and Neptune (solstice). The knowledge gleaned from an IGS program in the next decade will help NASA define and drive the necessary technologies for future *in situ* ice giant missions such as a Neptune System Explorer mission[2]. The results will also aid studies of extra-solar planets in this size range by providing "ground truth" for our local representatives of the ice-giant class of planets.

SCIENCE In 1986 and 1989, the Voyager 2 encounters with Uranus and Neptune revolutionized our understanding of those systems. However, since then HST, Keck, NASA's IRTF, and other ground-based observatories have continued to probe these planets and their environs. Our theoretical understanding, grounded primarily in Voyager-era data, is stretched thin and, in some cases, not adequate to explain modern observations[3]. Bringing our understanding of the ice-giant systems up to a level comparable to that of the gas-giant systems of Jupiter (Galileo) and Saturn (Cassini) would enable the extrasolar planet community to make meaningful comparisons with intermediate-sized bodies detected around other stars. Many questions about the ice giant systems are unanswered. What powers their winds? How deep does zonal structure go? What is their atmospheric composition as a function of altitude? Why are the magnetic fields much more asymmetric in ice giants than in gas giants? Are the magnetic fields stable, and what drives them? How did Triton's evolution differ from that of Pluto and other KBOs? What is Triton's atmospheric composition and structure, and how has it changed since Voyager? How does composition vary between/within surface features? What causes Triton's geologic surface structures? Has the geyser distribution changed since Voyager? Have atmospheric changes modified its surface? Ring studies have advanced, too, yet questions remain. Is a resonant model for Neptune's ring arc stability correct? If not, how do arcs remain stable? Are the rings of Uranus mono-layers[4], which would be unique in our Solar System?

NASA GOALS Ice giants systems are relevant to many of the goals articulated in the Vision for Space Exploration[5] and further refined in NASA's Strategic Roadmap Focus Areas[6]: RFA.3: *Sustained program of Solar System exploration;* RFA.4: *Advanced telescopic searches for Earth-like planets and habitable environments;* RFA.8: *Explore the origin, evolution, structure, and destiny of the Universe;* RFA.10: *…understand the effects of the Sun on … the* *solar system…* The IGS Program would support fundamental research for a broad range of planetary phenomena [RFA.3]. Recent or ongoing NASA programs exist for terrestrial-sized planets (Earth, Mars) and for gas-giant planets (Jupiter, Saturn), but not yet for intermediate-sized planets. An IGS Program addresses this significant gap [RFA.3]. Observations of debris disks around other stars provide a global view of the distribution of material and the effect of planets on its distribution. Ice giants, along with gas giants, were key players in the evolution of our circumstellar disk. The formation of Uranus and Neptune, in particular, and their subsequent migration to their present locations, dynamically sculpted the distribution of the nascent Kuiper Belt. The processes of disk evolution in our Solar System led to Earth's habitability today [RFA.4]. Clues to ice giant formation and evolution, hidden in their chemistry and in the chemistry and evolutionary history of Triton and other ice-giant satellites, may provide inputs for studies of circumstellar disk evolution [RFA.8]. The >90° tilt of Uranus' rotation axis creates extreme variation in sunlight compared to that seen by other large planets, which may (or may not) be related to Uranus' apparent lack of an internal heat source. Comparative study of Uranus and Neptune will elucidate the balance of incoming solar radiation and internal heat [RFA.10].

PRIORITIES A top priority is *a robust observational program of ice-giant systems* on existing telescopes (*e.g.*, IRTF, Keck, HST, Spitzer, VLA) and future space-based telescopes (*e.g.*, James Webb Space Telescope), including multi-wavelength, multi-technique observing campaigns for the atmospheres of Uranus and Neptune, and for the reflectivity of Triton. Another key priority is *improvements in theoretical models and simulations pertinent to ice-giant systems*. These will be critical for interpreting existing data, along with data gathered in the proposed IGS program, and for extending ice-giant theory to such bodies around other stars. *Laboratory experiments at temperatures and pressures relevant to ice-giant systems* are essential for interpreting observations of these cold, low-pressure systems. Other priorities are studies of the ring systems of Uranus and Neptune, and periodic astrometric observations of the inner satellites of the ice giants. In the longer term, the "Planetary Decadal Survey" listed a Neptune mission as one of its top priorities[7]. An ice-giant program will build the scientific foundation for this mission. Recent studies[8] indicate a Neptune System mission is feasible given achievable advances in a few key technologies. Outer planet aerocapture is most vital to reducing mission cost. Improved high-efficiency RTGs, autonomy, communications, miniaturization, and temperature-tolerant electronics would enhance the mission, but are required only for specific mission options. These technologies also enhance other proposed missions in both the inner and outer solar system.

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