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THE CASE FOR A URANUS ORBITER

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I. Overview

In the 1990s it was realized that Uranus and Neptune represent a distinct class of planet, fundamentally different from the more familiar gas giants, Jupiter and Saturn. The gas giants are composed mostly of hydrogen (more than 90% by mass). Their hydrogen envelopes are thought to extend all the way to their relatively small rock/ice cores, with molecular H_2 beginning a transition to ionized, metallic hydrogen at mega-bar pressures (Guillot 2005; Lissauer and Stevenson 2007). While Uranus and Neptune also possess hydrogen envelopes, the envelopes are much smaller, accounting for less than 20% of the planet's masses and never making the transition to metallic hydrogen (Guillot 2005). 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. Since these species are thought to have been incorporated into proto-planets primarily as ices—either as solids themselves or as gas trapped in a water-ice clathrate (Hersant et al. 2004)—the term "ice giants" has been adopted. Today, however, there is probably very little ice in Uranus and Neptune, a supercritical fluid being the preferred phase of H_2O at depth. In 2004, the first of many ice giant candidates was reported around another star (Butler et al. 2004), indicating that they are common in our galaxy.

The composition of Uranus and Neptune expresses a formation environment and process different from that of the gas giants, and results in a vastly different interior structure. That interior structure in turn generates a magnetic field and magnetosphere whose external appearance is unlike those found in the gas giant or even terrestrial planets. While these intriguing aspects of Uranus and Neptune are presumably common to all ice giants, there are several properties of Uranus which make it a particularly exciting target for an orbiter mission. Uranus is best able to constrain our understanding of ice-giant interiors because it is most challenging to our current models. It is the only giant planet whose gravity data cannot be fit by a simple 3-component model, with separate layers of rock, ice, and gas. Instead, it requires more realistic mixed-density regions (Podolak et al. 1995). Uranus' anomalously low rate of internal heat emission indicates that much of the interior may not be convective, and has correspondingly higher temperatures (Guillot 2005). While Neptune is thought to have a similar interior, Uranus displays these properties most clearly. It is also worth noting that all giant planets are thought to start from a similar rock-ice core which then gravitationally captures H_2 and He (the core accretion model is reviewed in Lissauer and Stevenson 2007). Since the ice giants have much less gas between us and that core, Uranus might be the best place to learn about the earliest phases of giant planet formation.

Uranus' low rate of internal heat emission deserves mention again because this differentiates it from all the other giant planets (Pearl et al. 1990). It is generally thought to be the result of internal density gradients that inhibit convection and trap the residual heat of formation, though it is possible that some mechanism allowed the heat to be rapidly released early in its history. Uranus is also unique because its large obliquity (98˚) applies an unusual seasonal forcing to the atmosphere; the insolation differences between summer and winter are very large, but the annual averaged insolation as a function of latitude is more uniform than on any other giant planet. On average the poles do, however, receive more sunlight than the equator. Whether the low emission of internal heat and the unusual insolation pattern are related is a matter of current research. Near solstice, Uranus' large obliquity combined with its strongly tilted (~60˚) dipole magnetic field also creates a unique geometry. While both magnetic poles are somewhat orthogonal to the solar wind, one hemisphere is in sunlight for decades and the other is in darkness. UV photo-ionization might create large-scale differences in ionospheric conductivity, maximizing the energy transfer between the solar wind and upper atmosphere in one hemisphere and minimizing it in the other, offering a test of whether or not auroral-type processes are responsible for the super-heated upper atmospheres of all giant planets (Miller et al. 2006). All these special aspects of Uranus' energy balance (low internal heat, unusual insolation, magnetospheric orientation) make it the ideal laboratory to study how the parent star affects giant planets. Insights gained would be particularly useful for studies of extra-solar planets orbiting relatively close to their star (the "hot Jupiters"), where stellar effects would be expected to be correspondingly larger. An improved understanding of Uranus is also needed to allow us to determine whether exo-planets, whose mass and radius are known from transit observations, are gas-giant, ice-giant, or even large terrestrial planets (Sotin et al. 2007). Finally, the relative proximity of Uranus to the Earth makes it a more attractive science target than Neptune because ground-based and near-Earth telescopes can provide higher spatial resolution observations in support of missions to Uranus.

In addition to the above scientific arguments for a mission to Uranus, there are several programmatic factors to consider. Shorter flight-times to Uranus vs. Neptune mean lower costs and greater reliability. Another factor is that a recent JPL study suggests it may be possible to fly a solar-powered mission to Uranus focused on the planet's interior. This could be an enabling architecture given the limited amounts of plutonium on hand for new power supplies and our Nation's current lack of production facilities. A final programmatic factor to consider is one of balance. While all other major categories of Solar System objects have a mission currently flying[1], the ice giants have never had a dedicated mission.

The remainder of this White Paper outlines the most important science questions to be addressed by a mission to Uranus and presents some results from a mission study recently completed at JPL. We suggest that a New Frontiers orbiter to Uranus (or "Small Flagship" if that mission-class is approved) should be a priority for the next decade.

II. Top-Level Uranus Science Questions

This section lists, in roughly priority order, science questions at Uranus and measurement strategies for addressing them.

[1] For the terrestrial planets, Messenger (to Mercury), Venus Express, and several orbiters and landers at Mars. The gas giants have Cassini, and Juno is under construction. Dwarf planets/Kuiper-belt objects will be visited by New Horizons (Pluto) and Dawn (Ceres). The asteroids are being visited by Dawn (Vesta) and Hayabusa. Finally, the study of comets is being advanced by the European's Rosetta mission, as well as NASA's extended missions Stardust/NExT and Deep Impact/EPOXI.

Question 1: **What is the bulk composition and internal structure of Uranus?**
Why this is important: Composition and structure are the properties that define ice giants as distinct from terrestrial and gas giant planets. Knowledge of the ice-to-rock and ice-to-gas ratios as well as the absolute abundance of certain key species, such as noble gases and water, tells us about conditions in the planetary nebula and the planet formation process (Hersant et al. 2004). Whether the gas and heavier components are segregated or well mixed today offers additional clues as to how and when each component was incorporated into the planet, and how much mixing occurred. That mixing strongly influences the chemical and thermal evolution of the planet. Knowledge of the bulk composition and interior structure also allows us to relate current observed properties of the atmosphere (abundances of trace or disequilibrium species such as NH_3 or CO, and the temperature profile) to details of the heat flow, convection, and chemistry occurring today at depth. Finally, understanding the composition and structure of our Solar System's ice giants is a necessary prerequisite to identifying them around other stars from the minimal information available (such as mass and radius), and recognizing if those exoplanetary systems contain a type of planet not seen in our Solar System.
Measurement approaches: High-order measurements of the gravity field (best achieved by tracking one or more spacecraft flying close to the planet over a range of latitudes and longitudes) and deep-atmospheric composition (from microwave sounding, supported by IR spectroscopy for temperature and composition retrievals) are the current ways we can make progress. The gravity field is used to determine the mass distribution within the planet while atmospheric composition is used to constrain abundances, dynamics, and chemical processes occurring deeper down. When combined with models for the equations of state and chemical evolution of the planet, a bulk composition and structure can be inferred. Additional laboratory measurements of the high-pressure equations of state of candidate species will improve this modeling. Atmospheric probes can further advance our understanding of the bulk composition. Shallow probes will determine noble gas and CH_4 abundances representative of the atmosphere, while pressures approaching 40 bars are needed to unravel NH_3, H_2S, and NH_4SH chemistry. A pressure of 100 bars must be reached to begin to constrain atmospheric H_2O and various species that might be in solution with its liquid cloud. High-order measurements of the magnetic field are also useful, in that the location and nature of the field generation region has implications for the internal structure.

Question 2: **Where and how is the magnetic field generated?**
Why this is important: As mentioned above, field generation has implications for the planet's internal structure, marking regions that are both conductive and convective. Uranus may also offer us our best chance to study details of a giant-planet dynamo in action. Its complex field (the dipole term is tilted a remarkable ~60˚ from the axis of rotation) appears to be generated well outside the planet's core, as much as 70% of the way out from the planet's center, making it relatively accessible. Finally, the magnetic field is important because it controls how Uranus interacts with the solar wind and cosmic rays which are thought to drive upper atmospheric chemistry and temperature, as well as atmospheric loss processes. Uranus' extreme obliquity creates unique opportunities to study the coupling between the solar wind and planetary atmospheres.

Measurement approaches: High-order measurements of the magnetic field constrain the location and mechanism of the dynamo. This requires in situ measurements as close to the planet as possible and over a wide range of latitudes and longitudes. UV and IR imaging of the auroral regions, as well as measurements of the charged particle environment, tell us about energy transfer between the solar wind and the atmosphere, but are also ways to help study the magnetic field remotely.

Question 3: **How is internal heat transported to the surface?**
Why this is important: The heat left over from the planetary formation process is important for the evolution of the planet's interior, and its transport to the surface is an important factor controlling convection, circulation, and the temperature structure in the fluid interior and atmosphere. For unknown reasons, Uranus is unique among both the gas and ice giants in emitting a very small amount of internal energy (Pearl et al. 1990). In terms of power emitted per unit mass, Uranus emits about 10 times less energy than Neptune.
Measurement approaches: To determine the amount of internal energy being released, precise measurements of visible-wavelength albedo and thermal IR emission need to be made at a wide range of solar phase angles and incidence angles. Such measurements must be made from a spacecraft. Measurements of any spatial variations in the amount of internal energy being emitted will help constrain the transport mechanisms involved. Observations and models of atmospheric dynamics are also useful, in that they can constrain the amount of energy entering the atmosphere from below. High spatial resolution gravity and magnetic field data could be used to search for mass and temperature anomalies in the interior, potentially tied to convection and heat transport.

Question 4: **What is the nature of Uranus' atmosphere?**
Why this is important: For details, please see the White Paper "The Atmospheres of the Ice Giants". That paper points out unique aspects of the composition, temperature, circulation, aerosols, and variability that can be seen in the ice giant atmospheres. Studying these properties not only teaches us about meteorological, dynamical, and chemical processes in Uranus, but by being able to explore regions of parameter space not previously investigated, we gain insights applicable to all giant planets.
Measurement approaches: Moderate- to high-resolution spectral and spatial imaging at UV, visible, IR, sub-millimeter, and radio wavelengths. A combination of spacecraft (for high spatial resolution) and ground-based (for sampling the decadal time-scale of the seasons) observations is needed.

Question 5: **What is the nature of Uranus' satellite system?**
Why this is important: While all the giant planets have satellite systems, there are unique aspects to those of the ice giants. For example, they lack the large satellites found around Jupiter and Saturn (we ignore Triton because it is believed to be a captured Kuiper Belt object rather than a native of the Neptune system), and the much lower temperatures allow for different surface ices. Given the different formation and evolutionary paths of ice-giant as opposed to gas-giant systems, the uranian satellites shed light on the formation and conditions of the early Solar System. The uranian system is likely to be more representative of an ice-giant satellite system because the capture of Triton is

thought to have ejected Neptune's major satellites, and potentially to have caused extensive thermal processing of the remaining ones (McKinnon and Leith, 1995). Some of the smaller uranian satellites are also dynamically interacting and perhaps unstable, with orbital changes seen between the 1980s and today (Showalter and Lissauer 2006).
Measurement approaches: High spatial and spectral resolution imaging at visible and IR wavelengths to determine composition, age, and the geologic history of the surface. These measurements must be made while the satellite's Northern Hemispheres are in sunlight (the years 2007-2049) to allow imaging of regions not seen by Voyager. High resolution mapping of satellite gravity fields is desired to determine interior structure, particularly at Miranda because its remarkable surface features may be indicative of unusual internal structures. Measurements of any induced magnetic fields of the satellites would indicate the presence of liquid water, which has been predicted for Titania and Oberon (Hussmann et al. 2006). Uranus is particularly suited to this type of investigation because its large, inclined dipole (~60˚) induces large field variations in the satellites as the planet rotates.

Question 6: **What is the nature of Uranus' ring system?**
Why this is important: The uranian ring system is composed of 13 distinct rings: 9 narrow dense rings and two dusty rings in the inner ring system, as well as two tenuous dusty outer rings. Faint dust bands are interspersed between the rings in the inner ring system. We wish to know the composition and detailed structure of the rings, the stability of the ring/moon system, and temporal variability of the rings in order to understand not only uranian ring dynamics, but also the evolution of circumstellar and protoplanetary disks. Many of Uranus' rings are narrow and dense, which may highlight dynamical processes not seen in Saturn's wider rings, or Jupiter and Neptune's under-dense ones. The rings also serve as a probe of Uranus' gravitational field, providing information about equatorial higher-order terms superior to that obtained from flyby spacecraft such as Voyager. Unexplained features of the Uranus rings, such as a lack of centimeter-sized particles (French et al. 1991), the apparent dynamical instability of some rings and moons (Showalter and Lissauer 2006), the blue color of the newly-discovered μ ring (de Pater et al. 2006), and changes since the Voyager encounter of 1986 (de Pater et al. 2007), may also shed light on ring physics and evolution.
Measurement approaches: High resolution, visible-wavelength imaging of the rings at low and high phase angles from spacecraft. Visible and UV observations of stellar occultations. Spacecraft radio occultations. Visible and near-IR spectroscopy.

III. Flight Mission Priorities

A New Frontiers-class mission to Uranus should be a priority for the latter part of the decade. It is the only way to dramatically advance our understanding of ice giants in the professional lifetime of any currently working scientist. This mission would also come at a crucial time for the study of extra-solar planets, where classifying planets based on no more than their mass and radius (and perhaps the atmospheric abundance of a few species) requires us to understand the full region of parameter space occupied by planets in our solar system. Studies have indicated that Discovery-class missions are not feasible for Uranus or Neptune. A Flagship mission to an ice giant, such as the Neptune orbiter recommended by the first Decadal Survey, will likely come only after the Jupiter and

Saturn Flagships recently chosen jointly by NASA and ESA, as well as a possible Flagship to a terrestrial planet. This would put the first data return from an ice giant Flagship more than 40 years into the future. Thus, New Frontiers (or the proposed "Small Flagship" class) appears to be the only practical way to address fundamental ice giant science within the next few decades.

Given the scientific priorities discussed in Section II, an orbiter around Uranus to make high-resolution maps of the gravity and magnetic fields is called for. While these measurements could be made by a fleet of small fly-by spacecraft, a preliminary study done at JPL suggests a single orbiter would be more cost effective. Electric propulsion allows for launches any year, but 2018 is a particularly efficient launch window if only chemical propulsion is used. Flight times to Uranus orbit insertion are typically 8 to 12 years. The study also found (to the surprise of the mission designers) that significant science payloads could be inserted into orbit around Uranus using relatively modest launch vehicles. Cost is therefore the primary limiting factor in adding instruments, making foreign contributions (such as a probe) very attractive. The JPL study also suggests that current and emerging technology could allow a mission focused on the interior of Uranus to be flown using solar power, with primary instruments being scalar and vector magnetometers and dual-frequency radio transmitters. A follow-on study is needed to determine how well additional instruments can be accommodated, and to investigate the cost and science trade-offs between solar and nuclear powered spacecraft.

IV. Ground-Based Research and Research Facilities

A flight mission is required to address the key questions presented in Section II, but there are three main areas of useful ground-based work. First, ground-based astronomy has an important role to play. Large optical, IR, and radio telescopes can be used for long-term studies of large- to medium-scale atmospheric features. A second area of useful research is laboratory and computer studies. Interpretation of remote sensing and gravity measurements is often limited by a lack of knowledge of the properties of species, particularly at the extreme limits of temperature and pressure, while studies of fluid dynamics can lead to a better understanding of what processes are important in rapidly rotating planets. A third area of supporting research is to carry out mission architecture studies. These are needed to determine what orbits and spacecraft resources are available for science, and what trade-offs among cost, reliability, and science return can be made.

V. Technology Needs

These technology developments would benefit or enable important Uranus science.

- Low-power electronics. For some mission architectures, power and not mass is the limiting factor in the science capabilities of the spacecraft.
- Low-insolation, low-temperature solar arrays. As technology improves, it becomes more feasible to fly spacecraft at Uranus without nuclear power.
- Advanced nuclear power sources and new plutonium generation facilities. Nuclear power allows for the most capable outer-solar system missions. We must use our dwindling plutonium supply efficiently, and regenerate that supply.
- Low-cost solar electric propulsion (SEP). For some mission architectures, this could greatly increase the payload or reduce the flight time to Uranus.

VI. Summary

There are many important science questions that can only be addressed by an orbiter at Uranus or Neptune. These planets represent a distinct class of object, with unknown composition and interior structure. Understanding them is necessary for improving our understanding of the formation and evolution of the Solar System, as well as extra-solar planetary systems. Either Uranus or Neptune can serve as the archetype for ice-giant science, and each has unique aspects worthy of study. High-level considerations, however, drive the choice towards Uranus. Its interior structure and heat flow are most difficult to explain with current models, suggesting it can best constrain our knowledge of the interior of ice giants. Uranus' internal heat flow and inclination also allow us to study unsampled regions of giant-planet parameter space, and are particularly important for understanding seasons on all giant planets, planetary evolution, and extra-solar planetary systems. Uranus' satellites may be our best example of an ice-giant system, Neptune's having been dramatically altered by the capture of Triton. The brighter sunlight at Uranus improves visible imaging and reflection spectroscopy of the atmosphere, satellites, and rings. Uranus' uniquely eccentric, dense, and narrow rings offer insights into disk dynamics. If plutonium availability remains a critical issue, Uranus is favored because of the potential of solar-powered missions there. Finally, we note that Uranus missions have shorter flight times than ones to Neptune, meaning lower cost and greater reliability. We suggest that a New Frontiers Uranus orbiter should be a priority for the next decade, supported by ground-based observations and laboratory work.

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