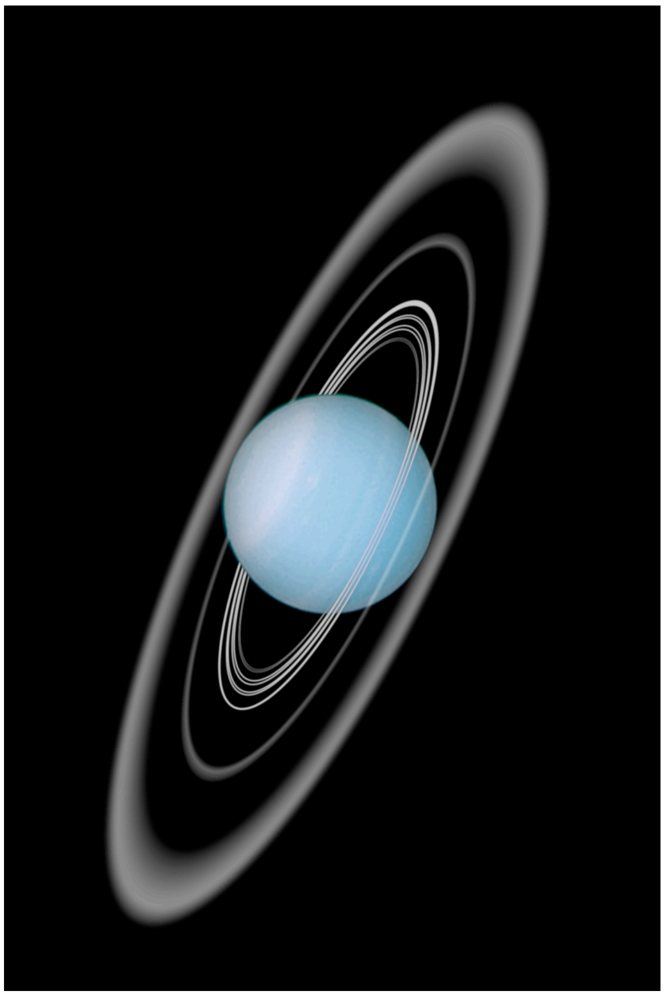
Uranus nears Equinox

A report from the 2006 Pasadena Workshop



Photoillustration by Mark Showalter based on HST data

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5 September 2006

Statement adopted by the attendees of the workshop

Once every 42 years, we have an opportunity
to see the planet Uranus and its moons from pole to pole,
and to view its ring system edge on.
That opportunity comes in 2007.

By observing the Uranus system at equinox in 2007,
we will explore an atmosphere that is changing rapidly.
We will probe newly discovered faint rings.
We will use the rare opportunity of mutual satellite eclipses
to map the brightness variations on large moons.

Observations at the equinoxes of Jupiter, Saturn,
and Pluto provided fundamental insights.
The year 2007 is our chance to do the same
for the Uranus system.

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Introduction

Uranus is most well known for its extreme obliquity: its rotational axis is inclined 98° relative to its orbital plane[1]. This configuration, unique in our Solar System, gives rise to extreme seasonal insolation changes (Fig. 1). In 2007, Uranus will reach equinox, or ring-plane crossing (position 2 in Fig. 1). This is the first equinox of Uranus in the era of modern astronomy. The last equinox, in 1965, occurred during the infancy of most astronomical tools used today (large-format imaging systems, telescope arrays, instruments capable of resolving Uranus and its rings, and ubiquitous computational capability). The next equinox will be in 2049. Thus, these next few years will provide the only opportunity in decades to record equinoctial phenomena such as ring-plane crossings, mutual uranian satellite events, diurnally-driven auroral activity, and atmospheric radiative balance changes driven by seasonal variations in insolation.

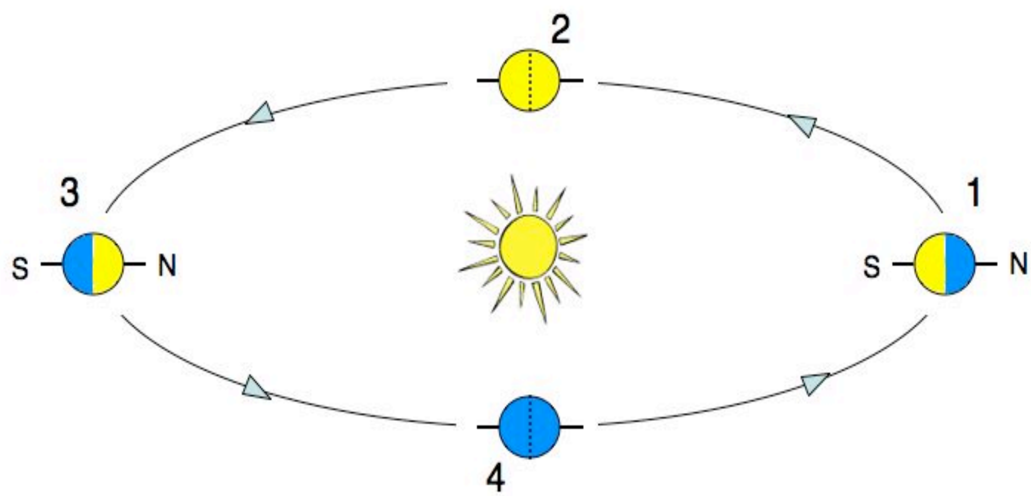

Fig. 1. Seasons of Uranus. Uranus takes 84 years to complete one trip around the sun. (1) Southern-hemisphere solstice occurred in 1985; Voyager flew by Uranus in 1986, near peak solstice. (2) The equinox and ring-plane crossings are in 2007. (3) At the next solstice in 2028, the northern hemisphere of the planet will be fully illuminated. (4) Uranus will not return to an equinoctial position until 2049.

1 Workshop Goals and Format

The "Uranus at Equinox" workshop was held in Pasadena, CA, on 3-4 May 2006. The workshop's primary goal was coordination and facilitation of observations and analyses of the Uranian system[2] during the three-year period surrounding the 2007 equinox and ring-plane crossings (RPX). Other workshop action items included: review the Uranus equinoctial

[1] We adopt the IAU convention for "north" and "south" on Uranus, which means we have been viewing Uranus' *southern* hemisphere in sunlight for the past few decades.

[2] Observations of the Neptune system are also recommended when feasible and when they do not conflict with the primary goal of Uranus system observations. Two reasons for this are: (1) coordinated observations and analyses will facilitate comparative studies of the two ice giants in our Solar System, and (2) Neptune's location in the sky is fortuitously close to that of Uranus, thus such observations are relatively easy to plan and schedule with Uranus programs.

calendar; understand discipline-specific science goals; formulate cross-discipline strategies to optimize facility use; identify "missing" science through group discussion; and initiate actions and assignments. The workshop format was primarily break-out sessions followed by plenary synthesis.

Section 2 briefly reviews the elements of the Uranus system on the eve of equinox. The equinoctial calendar is presented in Section 3. Section 4 identifies key science questions identified by workshop attendees, and outlines the equinox observations needed to address them. Section 5 lists supporting research that will facilitate interpretation of equinox observations. Workshop action items are listed in the concluding section. Appendix A shows the formal workshop agenda; Appendix B shows workshop attendance.

2 Pre-Equinoctial State of the Uranian System

We briefly review the current state of the Uranian atmosphere, satellites, and rings. This is not meant to be a comprehensive historical review, but rather an update with particular focus on those aspects that either seem to show evidence for change, or have potential for exploration during the equinox or ring-plane crossings.

Atmosphere

Hubble Space Telescope (HST) images of Uranus provided unambiguous evidence for seasonal atmospheric change in the troposphere: the south polar region darkened as it began to receive less direct sunlight (Rages et al. 2004). Pre-equinox images from HST and from the Keck 10-meter telescope in Hawaii (Hammel et al. 2005a, 2005b; Sromovsky and Fry 2005) showed tremendous tropospheric cloud activity across the planet (Fig. 2), including changes on time-scales as short as days (Hammel et al. 2005a).

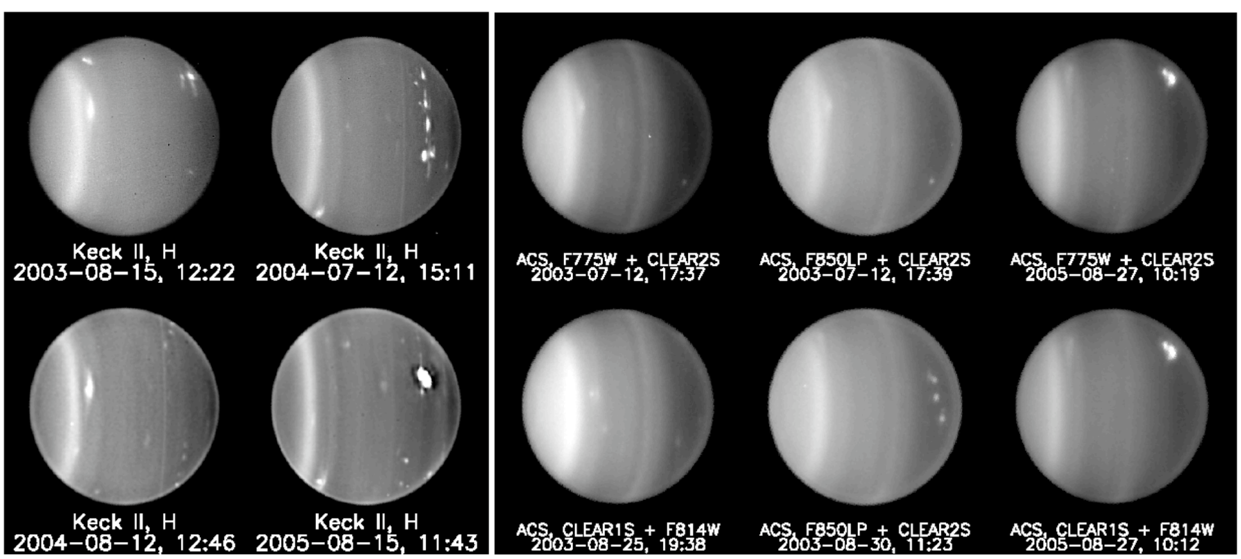

Fig. 2. Keck and HST images of Uranus. The left four H-band (1.6-μm) images are from Keck in 2003, 2004, and 2005. The six images on the right are from HST in 2003 and 2005 at wavelengths ranging from 0.775 μm to longward of 0.850 μm. Both sets of data exhibit dynamic activity in the atmosphere as equinox approaches, with marked latitudinal and longitudinal variability seen at these wavelengths. Images courtesy of L. Sromovsky.

As of 2006, the atmosphere of Uranus was still strikingly asymmetric in the visible and near infrared: a bright ring surrounds its southern pole, but HST and Keck images show no counterpart around the northern pole. A comparison of a simulated Uranus with data obtained at earlier Uranus seasons suggests Uranus must have had a bright ring encircling its north pole in the past (Lockwood and Jerzykewicz 2006; Hammel and Lockwood 2006).

At centimeter and millimeter wavelengths, Uranus is also seen to have strong latitudinal brightness variations (Briggs and Andrew 1980, Jaffe et al. 1984) and to be changing over time (Klein and Turegano 1978, Hofstadter and Butler 2003). These wavelengths probe the deep troposphere, pressures from a few to tens of bars. Spatial and temporal variability is surprising this deep. However, the northern and southern hemispheres are much more symmetric at radio wavelengths than at visible and near-IR wavelengths (Fig. 3), suggesting the radio is seeing deeper than most of the seasonally varying atmospheric patterns.

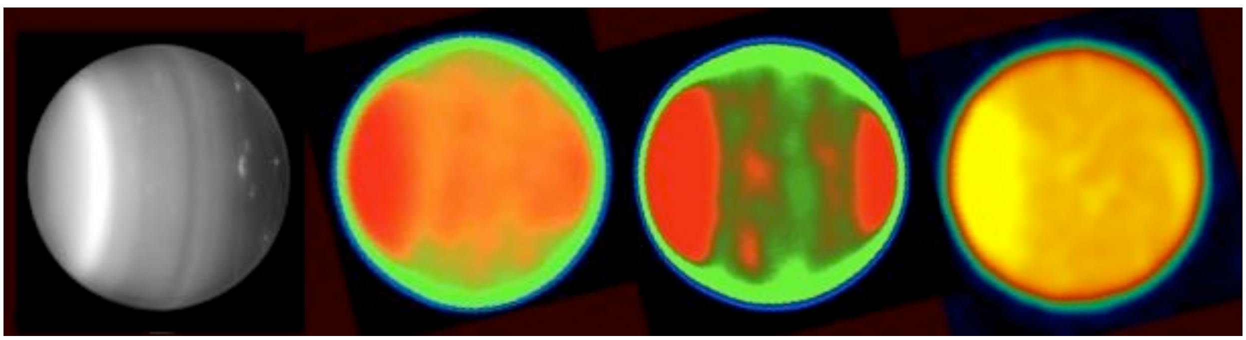

Fig. 3. Uranus with Keck and the VLA. On the far left is an H-band (1.6-μm) image from Keck in 2004. The other three maps were taken at 0.7 cm (2005), 1.3 cm (2005), and 2.0 cm (2003), from left to right respectively. The northern hemisphere is radio bright (it appears fainter at 2 cm because it was less visible in 2003); no bright northern counterpart has been seen at visible or near-infrared wavelengths as of mid 2006. Keck image from Hammel et al. (2005a); radio maps courtesy M. Hofstadter and B. Butler.

New observations are needed at equinox: to compare with data from previous epochs; to track changes; and to bring new instruments to bear on studies of the atmosphere (such as the submillimeter SMA). The seasonal modeling to date (e.g., Wallace 1984; Friedson and Ingersoll 1987) does not adequately predict the observed magnitude, rate, and location of variations already observed. New data are needed on moderately frequent timescales (at least yearly, if not more frequently) in order to understand the actual seasonal changes. More clues for solving the puzzle of seasonal variability on Uranus will emerge as the planet moves through equinox and beyond, assuming that the necessary observations are obtained.

Ionosphere

Uranus has a strong magnetic field (0.228 gauss) inclined 58.6° to its rotational axis and significantly displaced from the center of Uranus (Neptune's magnetic field is similarly tilted and offset). The combined effects of inclination and displacement cause the strength of the magnetic field to vary by a factor of more than ten over the planet's surface (Fig. 4).

The magnetic field of Uranus is not detectable from Earth, nevertheless it can be studied indirectly by its effect on the planet's ionosphere, specifically the detection of H_3^+ ions. Trafton et al. (1993) reported the first detection of H_3^+ emission in the ionosphere of Uranus. The H_3^+

emission on Uranus (Fig. 4) is a few percent of that seen on Jupiter, but curiously appears to be stronger than that seen on Saturn. Saturn is closer to the Sun, thus its UV auroral activity and expected H_3^+ emission, should be stronger than those of Uranus.

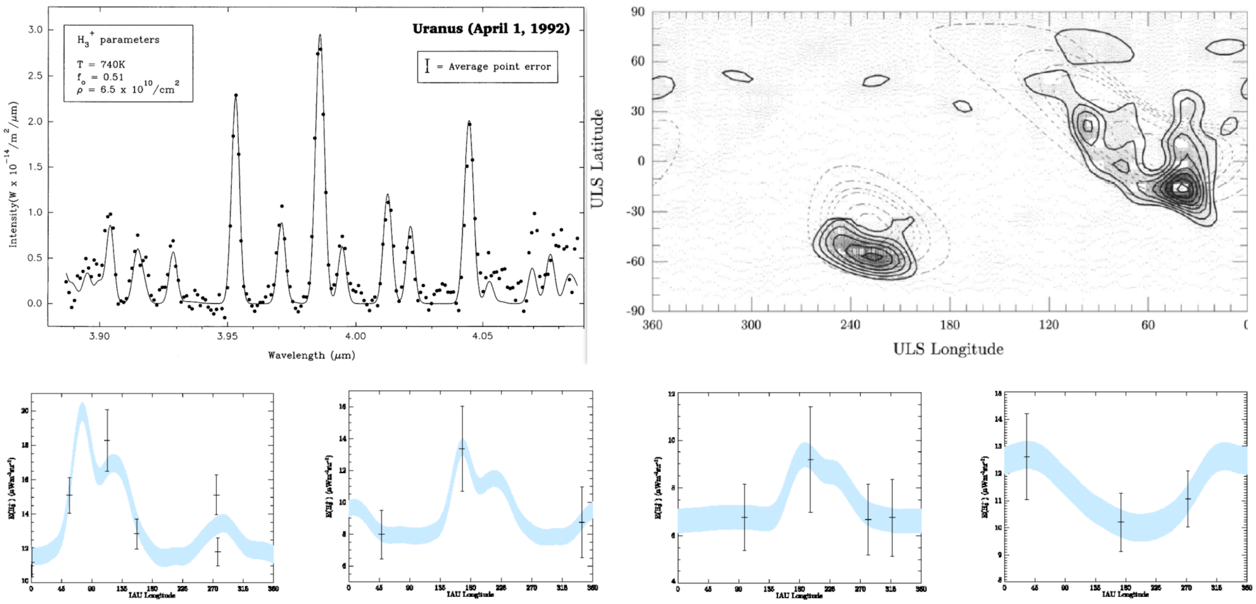

Fig. 4. Uranus ionospheric measurements. Upper left: H_3^+ emission from Uranus dominates the near infrared spectrum near 4 μm (Trafton et al. 1993). Upper right: auroral emission on Uranus is a strong function of latitude in this map from the Voyager era (Herbert and Sandel 1994). Bottom row: a study by Melin (2005) shows good correlation between modern era H_3^+ emission (discrete points) and a prediction based on the Voyager aurora map (broad blue band).

Similarly unexplained is the fact that the thermospheric temperature of Uranus is ~600K (Trafton et al., 1999). As might be expected, this is lower than that of Jupiter (~1000K; Miller et al., 2000), but higher than that of Saturn (~400K; Melin et al., 2006).

The exospheric temperature of Uranus is several hundreds of degrees hotter than can be explained by the absorption of solar UV (Yelle and Miller, 2004), as is also the case for the other giant planets. Particle precipitation and Joule/ion drag heating in the auroral regions have been proposed to explain this for Jupiter (Waite et al., 1983) and Saturn (Smith et al., 2005). However, on Uranus the auroral activity is relatively weak, compared with planet-wide day- and/or electro-glow (Trafton et al., 1999). Explanations for these anomalies await further observations and modeling.

Rings

The main uranian ring system consists of rings first detected in 1977 during a stellar occultation by the planet (Elliot et al. 1977); the main ring system is comprised of 10 narrow rings. An eleventh diffuse ring was seen interior to the narrow ring system in a single Voyager 2 image; Voyager also found dust scattered throughout the main ring system (Smith et al. 1986). de Pater et al. (2006a) confirmed both findings with Keck images (Fig. 5); the data suggested change in the spatial distribution of the dust since Voyager.

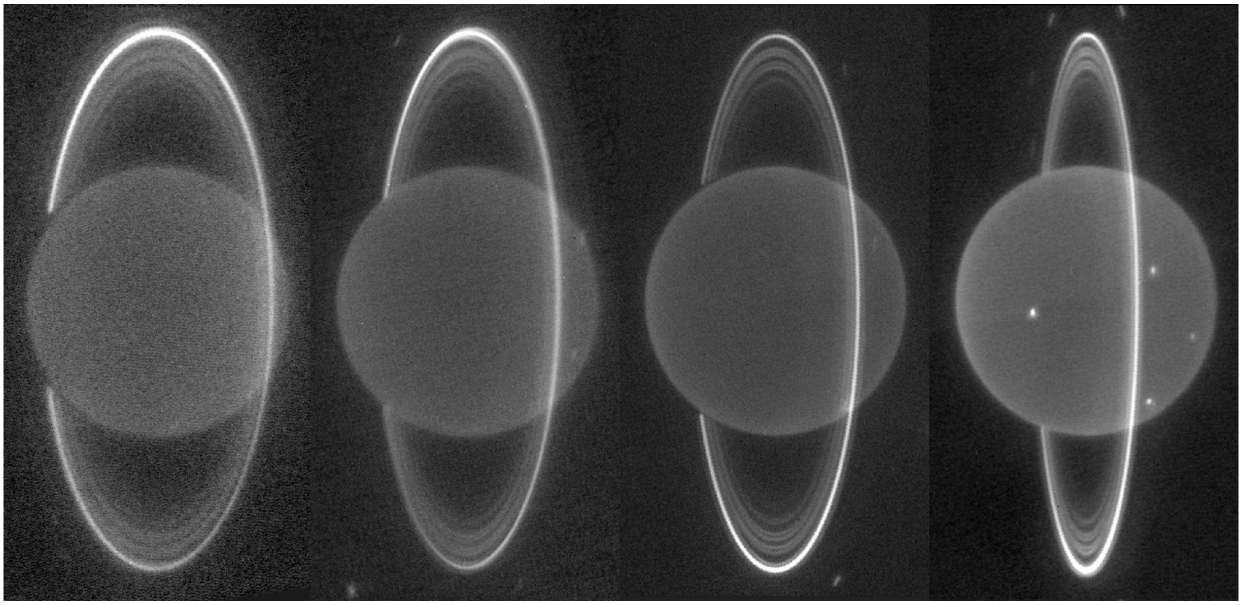

Fig. 5. Rings of Uranus from 2002 through 2004. Uranus and its rings were observed with Adaptive Optics on the Keck II telescope each year from 2001 to 2004. The images were taken at a wavelength of 2.2 μm, where methane absorption darkens the planet. Only high altitude clouds are visible (e.g., in the 2004 image). The south pole of Uranus is to the left. Adapted from de Pater et al. (2006a).

Showalter and Lissauer (2006) discovered two new rings in HST images in 2005 and 2003, with confirming detections in the Voyager images. These newly-detected rings lie outside the main ring system (see cover illustration). Keck images by de Pater et al. (2006b) showed these two new rings to be strikingly colored (Fig. 6), with the outermost quite blue, making it only the second known blue ring in the solar system after Saturn's E ring. The blue rings of Uranus and Saturn probably owe their color to subtle forces acting on dust in the rings that allow smaller particles to survive while larger ones are recaptured by the embedded moons within the rings (Mab and Enceladus for Uranus and Saturn's blue rings, respectively). The other new ring is red, typical of a dusty ring with a "normal" size distribution, such as expected for a collisionally-evolved ring (such as Saturn's G ring; see Fig. 6).

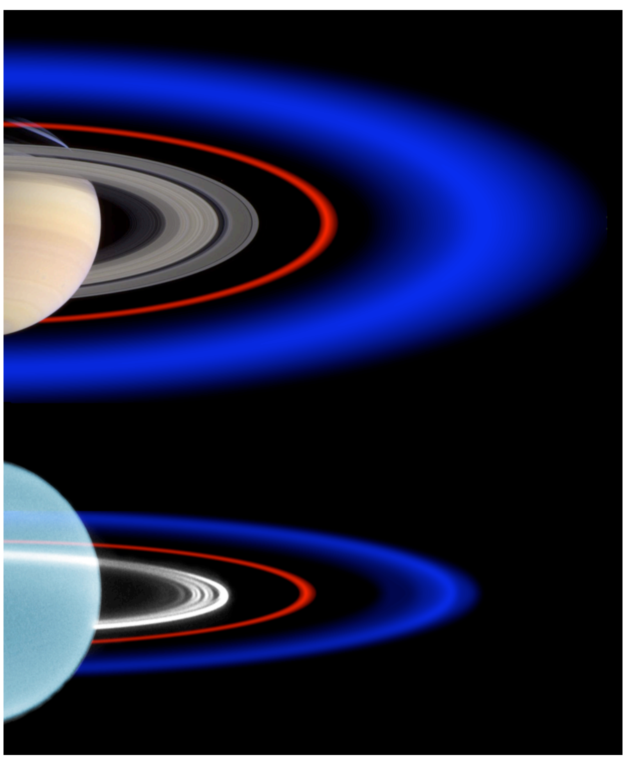

Fig. 6 (left). Schematic of the rings of Uranus compared with those of Saturn. Each system has been scaled to a common planetary radius. Colors were determined by combining data from near-infrared Keck and visible-wavelength HST images. From de Pater et al. (2006b).

Satellites

The five largest satellites of Uranus—Miranda, Ariel, Umbriel, Titania, and Oberon (Fig. 7)—are comparable in size to the icy satellites of Saturn and are composed of nearly equal mixtures of rock and ice. Oberon and Umbriel have the oldest surfaces, dominated by ancient impact craters. On Oberon, however, a dark material of unknown composition seems to have flooded some of the crater floors. Umbriel, the darkest of the large satellites, may contain large amounts of the carbonaceous material that is associated with the rings and the smaller satellites.

Miranda has perhaps the strangest surface in the solar system. Two oval configurations of bright and dark parallel bands, resembling racetracks, and an equally bizarre trapezoidal region are embedded within a much older, heavily cratered, rolling terrain. Indications of hydrated ammonium have been seen in Miranda’s spectrum (Bauer et al. 2002). Ariel and, to a lesser extent, Titania show evidence of widespread surface modification by geological processes that occurred long after the satellites were formed. Ariel also shows evidence of glacier-like ice flows over large areas. Near-infrared spectra of Ariel by Grundy et al. (2003) revealed the signature of CO_2 ice. Grundy et al. (2006) report that Umbriel and Titania have CO_2 ice as well, though less than Ariel.

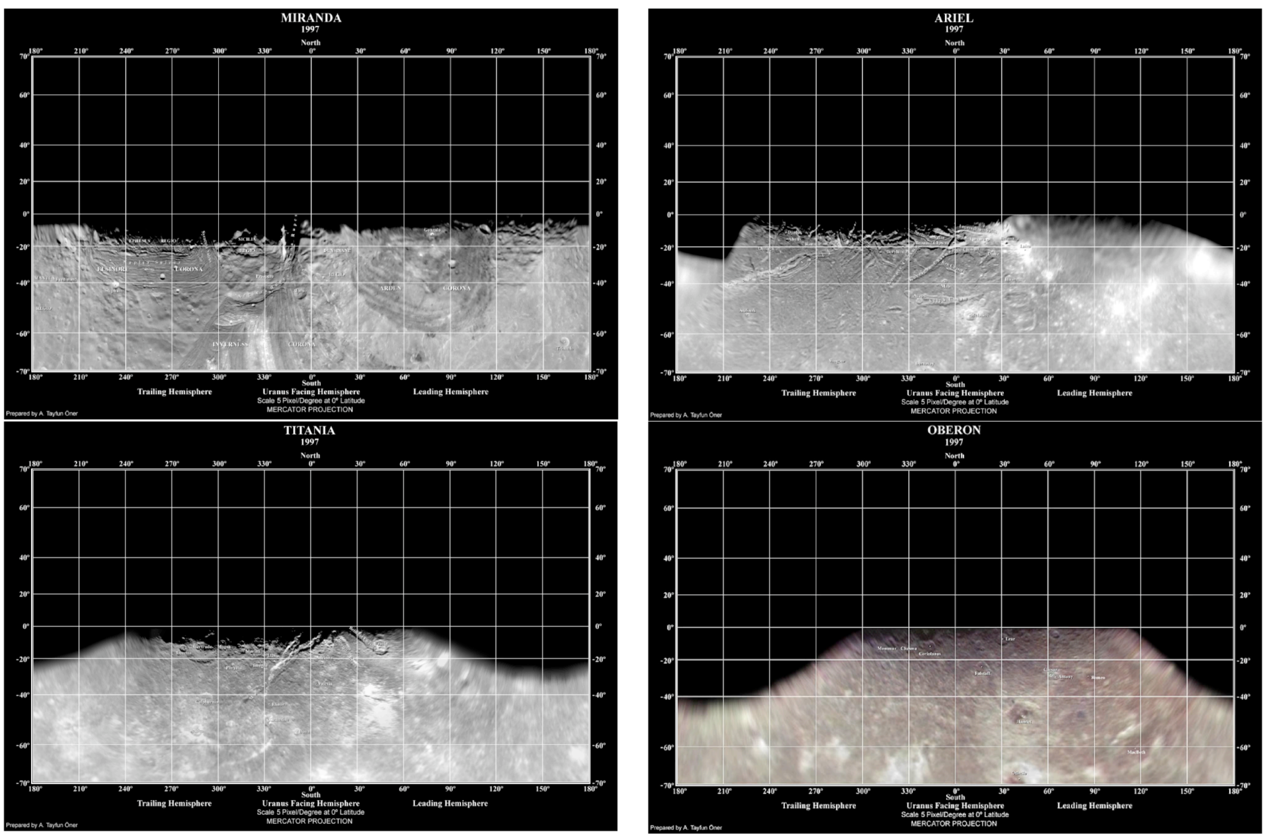

Fig. 7. Maps of four satellites of Uranus. Voyager 2 obtained these mercator maps of Miranda, Ariel, Titania, and Oberon during the 1986 encounter (a similar map was obtained for Umbriel). The encounter occurred near the solstice of Uranus (south pole pointing at the Sun), thus only the southern hemispheres of the moons were illuminated. Northern regions are now receiving insolation, permitting the satellites' reflective properties to be characterized. Maps prepared by A. Tayfun Öner.

However, only half the territory of each satellite was imaged by Voyager 2 because of the solstice illumination of the 1986 encounter (Fig. 7). The northern realms of these moons are now experiencing insolation. Karkoschka (2001) may have already observed some disk-integrated photometric changes on these moons as the more northern latitudes, not seen by Voyager 2, come into view. Limited spatial information may be obtained for these moons during the next few years, both from photometric monitoring over their rotational periods and by observations of mutual events of the larger satellites with smaller moons (Arlot et al. 2006). For Uranus, mutual events and eclipses are only observable near equinox (Fig. 8).

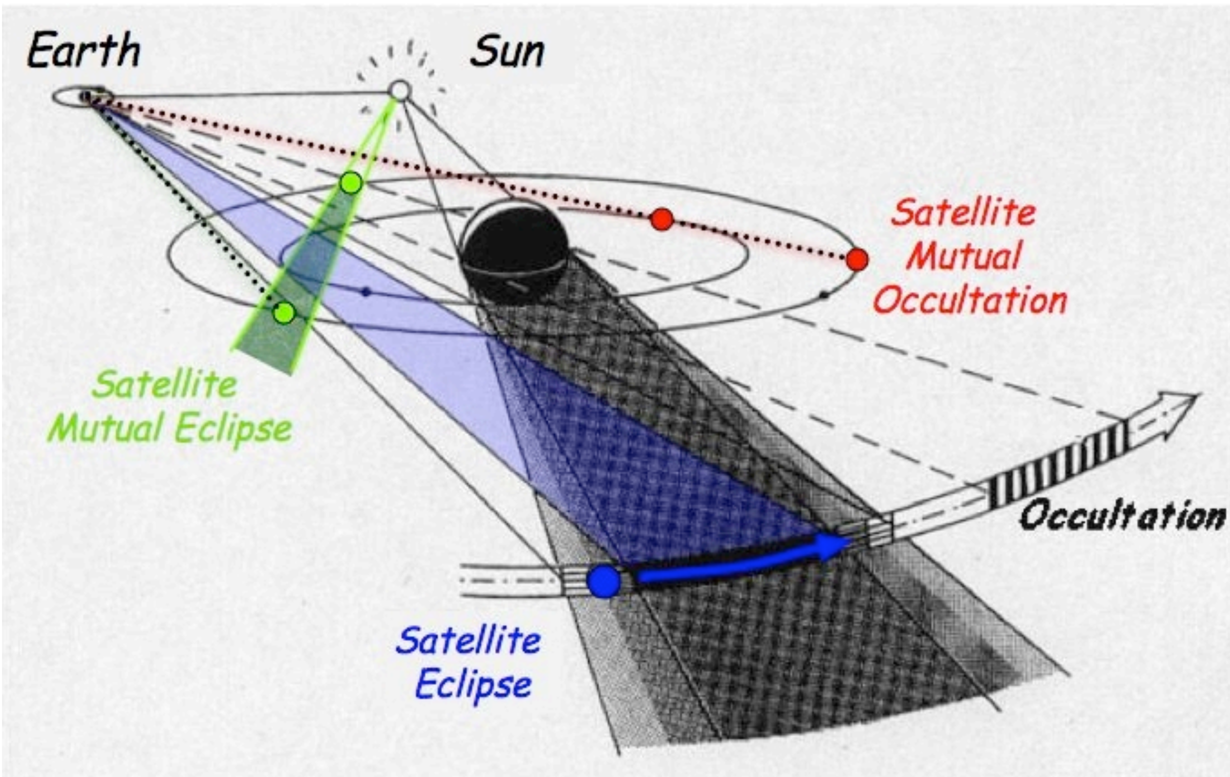

Fig. 8. Geometry of Uranus satellite events. Mutual occultations occur when one moon crosses in front of another moon as seen by the observer, and mutual eclipses occur when a moon enters the shadow of another moon (together, these are referred to as "mutual events"). Satellite eclipses occur when a moon enters the shadow of Uranus. All of these phenomena are only observable when the satellite plane is edge on as seen by the observer. For Uranus, this configuration only occurs near equinox. Illustration credit: Institut de Mécanique Céleste et de Calcul des Éphémérides and H. Hammel.

Little is known about the smaller satellites of Uranus beyond their orbits, color, and approximate reflectivity. Rotational light curves, which remain to be observed for many of these bodies, can constrain the shape and the axis ratios of these satellites, and may thus also provide constraints on their cohesive strength. Some internal physics can be elucidated by much more accurate position determinations of the smaller moons via timing of mutual eclipses and occultations. Some examples include tidal effects, planetary precession, secular precession of satellite orbits, other perturbations, and satellite masses. Mutual events may also reveal sizes for the largest of these moons.

3 Calendar

Tables 1 and 2 summarize key events in 2007 and 2008. Four equinoctial events at Uranus are indicated: RPX1, RPX2, and RPX3 are the three ring-plane crossings as seen from the Earth (Fig. 9), and EQ is the day of equinox (when the sub-solar point is at the uranian equator). For each of these events, the Sun-Earth-Uranus (S-E-U) angle is given to indicate solar interference with the view from the Earth. The sub-Earth latitude is also indicated for each quarter (see also Fig. 9). Table 3 presents candidate stars for occultation and appulses (near misses) of the Uranus system in 2007 and 2008 (J. Bauer, private communication).

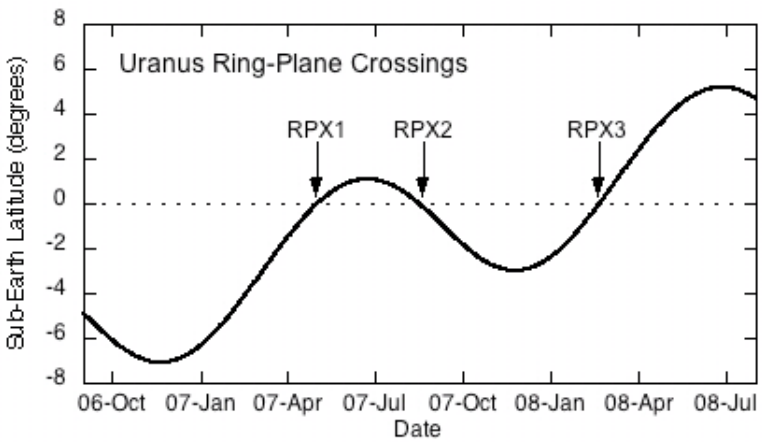

Fig. 9. Sub-Earth latitude of Uranus as a function of time. The reflex motion of Earth causes the sub-Earth latitude to oscillate on a yearly timescale. Thus there are three Uranus ring-place crossing events associated with the equinox.

Table 1. Equinoctial Calendar for 2007

		1st Quarter Jan-Feb-Mar	2nd Quarter Apr-May-Jun	3rd Quarter Jul-Aug-Sep	4th Quarter Oct-Nov-Dec
Event	**Date**				
EQ	7 Dec				EQ
RPX1	2 May		RPX1		
RPX2	16 Aug			RPX2	
S-E-U Angle (deg)			54	155	90
Sub-Earth Lat (deg)		-4.1	0.5	0.0	-3.0
Planetary Science Conferences		AAS, LPSC	AAS		DPS, AGU

Table 2. Equinoctial Calendar for 2008

		1st Quarter Jan-Feb-Mar	2nd Quarter Apr-May-Jun	3rd Quarter Jul-Aug-Sep	4th Quarter Oct-Nov-Dec
Event	**Date**				
RPX3	20 Feb	RPX3			
S-E-U Angle (deg)		16			
Sub-Earth Lat (deg)		-0.3	4.4	4.2	1.2
Planetary Science Conferences		AAS, LPSC	AAS		DPS, AGU

Table 3. Candidate Occultations and Appulses of the Uranus System in 2007 and 2008

	GSC2.2 STARID	RA	DEC	Mag	Sep. (")	JD	UT
+	S3203210851	23 15 40.86	-5 38 25.4	15.2	0.12	2454326.8	2007-Aug-14 04:30
	S3203210161	23 15 18.05	-5 40 44.9	14.2	7.63	2454329.5	2007-Aug-17 02:50
	S32011132689	23 10 08.50	-6 13 40.0	15.3	6.96	2454365.5	2007-Sep-22 00:20
	S32011111802	23 08 15.60	-6 25 16.0	15.2	7.92	2454379.2	2007-Oct-05 18:00
	S3201111171	23 08 00.10	-6 26 51.0	14.3	8.49	2454381.2	2007-Oct-07 19:00
	S32011303410	23 05 21.61	-6 42 14.0	15.2	6.65	2454408.8	2007-Nov-04 03:20
	S32001132012	23 33 05.60	-3 44 13.0	15.4	7.69	2454622.8	2008-Jun-05 07:00
+	S32032225812	23 26 37.00	-4 28 43.0	15.1	1.60	2454722.0	2008-Sep-12 10:30
*	S320322210	23 26 17.99	-4 30 43.0	11.9	2.83	2454724.1	2008-Sep-14 14:00
*	S3203230101	23 24 04.10	-4 44 57.0	13.6	3.25	2454739.5	2008-Sep-30 00:30
*	S3203213159	23 19 58.40	-5 09 56.3	11.9	2.82	2454778.0	2008-Nov-07 13:00
+	S32032113350	23 20 11.60	-5 06 37.0	15.2	1.39	2454821.8	2008-Dec-21 08:30
	S32032113721	23 20 53.40	-5 01 54.0	15.3	4.61	2454830.0	2008-Dec-29 12:00
	S32032113775	23 20 59.20	-5 01 02.0	15.1	6.97	2454831.0	2008-Dec-30 12:40

+ Predicted to pass within the radius of Uranus * Predicted to pass within 2 Uranian radii

Predictions of satellite mutual events can be found in Arlot et al. (2006), and Arlot et al., in preparation. See http://www.imcce.fr/pheura07 for more information and predictive tools.

4 Equinoctial Observations of the Uranian System

Over-Arching Scientific Question from the Planetary Decadal Survey: How do the processes operate that shape the contemporary nature and physical characteristics of Solar System bodies?

Observations of the planet, satellites, and rings of Uranus during its equinox provide a rare opportunity to probe details of this system that are obtainable at no other time during its year. In this section, we discuss the particular opportunities available during equinox, highlighting the key science questions, and the observations that may address them, and some of the facilities[3] that can play unique observational roles in obtaining those observations.

Atmosphere

Atmospheric observations near the time around equinox are important: this atmosphere experiences the most extreme geometry for studying solar forcing. Near-equinox timing permits study of both hemispheres simultaneously and at the same viewing geometry. In addition, long-

[3] The observatories mentioned herein are by no means the only facilities that can be brought to bear on these science issues. They are simply the ones discussed by participants at the workshop. We hope this report encourages astronomers from across the world to participate in observations of this rare event.

term photometry suggests that atmospheric brightness patterns might change significantly during this epoch (Hammel and Lockwood, 2006). Measurements of horizontal variations require spatially-resolved observations of the 3.4-arcsecond disk (limited to facilities such as Keck, HST, VLA, Gemini, VLT, Palomar, SMA).

We need to acquire new data on moderately frequent timescales in order to reveal the actual timescales of change, rather than presumed timescales of change. However, data at the exact moment of equinox is not needed for atmospheric observations. There is value in single observations (i.e., those that do not have a long time base), since new instruments and new wavelengths may provide important clues for understanding the unexpected atmospheric variability. New data at previously observed wavelengths are also needed, to compare with existing data sets. The simultaneous study of Uranus and Neptune is important for comparative planetology; these planets have similar size and bulk composition, yet have very different dynamical and radiative properties, as well as markedly different abundances of some trace species (such as CO).

Key Science Questions for Atmosphere

What are the relative roles of dynamics and radiation in controlling atmospheric properties, and what are the timescales and phase lags?

What is the effect of solar forcing on this giant planet atmosphere (an obliquity extremum in our suite of giant planets which now includes hundreds of extra-solar planets)?

What is the temperature as a function of altitude (few bars to microbars) and latitude?

Key Measurement Objectives for Atmosphere

Composition

- Disk-resolved abundance variations (CH_4, C_2H_2, C_2H_6, oxygen compounds, complex hydrocarbons, ammonia, water?) as a function of latitude, longitude, altitude, and/or time (Keck/NIRC2, Gemini/Michelle, VLA, SMA, UKIRT/UIST)

- Whole-disk abundance variations (same as above) as a function of altitude and/or time (Keck/NIRC2, Gemini/Michelle, IRTF/Spex)

* Variability in vertical mixing, *i.e.*, eddy diffusion (particularly important for atmospheric modelling)

Temperatures

- Troposphere (100-400 mbar, 1 bar)

- Stratosphere to thermosphere via stellar occultations (Table 3)

- Thermal IR

Clouds and hazes

- Altitude, optical properties, particle size; north polar cap formation, south polar cap dissipation; confined convective events (Keck/NIRC2, HST, VLT)

• Shape of satellite eclipse profiles as moons enter and exit the shadow of Uranus (Fig. 8); this probes the planet's atmosphere (1-m or larger class telescopes)

Winds

• Values at high northern latitudes (Keck/NIRC2, HST, VLT)

• Possible changes when compared with pre-equinoctial measurements (Keck/NIRC2, HST, VLT)

Ionosphere

The time around equinox is important because we can see both hemispheres simultaneously and at the same geometry; precise timing is not critical. Spatial variations are important, which requires spatially resolved observations of the 3.4-arcsecond disk (Keck, HST). There is value in single observations (i.e., those that do not have a long time base), because they can be compared with older existing data.

Key Science Questions for Ionosphere

How does Uranus' tilt and offset magnetic axis affect magnetosphere/atmosphere/solar interactions?

Why is the upper atmosphere temperature much hotter than can be explained by solar UV heating?

Can we determine the position of the auroral zones, and use them to measure the rotation rate more accurately than it is currently known?

Key Measurement Objectives for Ionosphere

Aurora and magnetosphere interactions

• Emission in the near infrared (1-5 μm); IRTF/Spex, Subaru/IRCS, and UKIRT/IFU, IRTF/NSFCam2, Keck NIRSPEC, Keck NIRC-2

• Full-disk coverage possible at equinox, which permits detection short-term temporal variation indicative of spatial variability (*i.e.*, via rotational modulation)

Temporal evolution

• Long-term temporal variation of H_3^+, particularly any trend that might (or might not) be correlated with solar cycle dependence (particularly important for atmospheric energetics studies)

Rings

Most ring observations are time-critical. There are three ring-plane crossing events (RPX).

Key Science Questions for Rings

What processes drive the formation and evolution of rings and ring material? Are the rings stable and long-lived?

What are the physical and optical properties of the ring material (particle size distributions: colors of optically-thin rings)? Can the thicknesses of the rings be constrained?

How well can we characterize the outer rings and dust sheets?

Can structure of, and within, the rings be characterized (warps, waves, inclination, orientation)?

Key Measurement Objectives for Rings

Structure of—and within—the known rings

• Warps, waves, inclination, orientation (Keck near-IR imaging; stellar occultations)

• Ring thickness during RPX (multiwavelength visible imaging with HST; Keck near-infrared imaging)

Physical and optical properties of ring material

• Reflectivity as a function of viewing geometry (Keck near-IR)

• Reflectivity as a function of wavelength (Spex IRTF near-IR; Keck near-IR; Palomar visible and near-IR)

• Particle size distribution as inferred from colors (Spex IRTF near-IR; Keck near-IR; Palomar visible and near-IR)

• Polarization (IRTF/NSFCam2)

Presence of as-yet undetected faint outer rings and dust sheets

• Reflectivity as a function of viewing geometry (multiwavelength visible imaging with HST; Keck near-infrared imaging)

Satellites

There are a variety of different types of satellite observations. Some are extremely time critical: e.g., mutual events and satellite eclipses. Others do not require stringent timing: e.g., direct satellite observations.

Key Science Questions for Satellites

Are there spatial (hemispheric) variations in surface properties (e.g., compaction, albedo) or composition that would be detectable as viewing geometry changes, or by mapping via mutual satellite events?

Do seasonal insolation variations trigger large-scale migration of volatile species on the five major satellites, a la Triton's Koyaanismuuyaw (Moore and Spencer 1990) but much more extreme?

What internal physics can be elucidated by much more accurate position determinations of the smaller moons?

What are accurate sizes and possibly shapes for smaller moons?

Key Measurement Objectives for Satellites

Physical and optical properties of satellite surfaces

- Reflectivity as a function of viewing geometry: phase curve and albedo variations (multiwavelength visible imaging with HST; Keck near-infrared imaging). Moderate time criticality (specific phase angles needed).
- Reflectivity as a function of wavelength (IRTF/Spex near-IR; Keck/NIRC2 near-IR; Palomar visible and near-IR; HST)
- Thermal inertias (requires time-resolved thermal-infrared, and possibly near-infrared, observations around the time of eclipses; could be interesting in comparison with Cassini and Galileo results for other icy bodies)
- Polarimetry (IRTF/NSFCam2)

Satellite surface composition

- Molecular absorption strengths (IRTF/Spex near-IR)
- Spatial and temporal variations of composition (IRTF/Spex near-IR)
- Molecular phase transitions; crystallinity (IRTF/Spex near-IR)

Satellite sizes and shapes

- Precise timing of mutual eclipses and occultations (1-m aperture or larger). Extreme time criticality.
- Precise timing and spectrophotometry, post-eclipse brightening (1-m aperture or larger). Extreme time criticality.

5 Supporting Research for Uranus at Equinox

Additional laboratory and theoretical work will enhance the interpretation of the Uranus equinoctial observations. In the short-term (during the equinoctial season), observations are more critical than lab and theory work. Nevertheless, the work described here will improve future studies of the data obtained during the equinox campaign.

Laboratory Work

During discussion sessions at the workshop, the following needs were identified that will aid in interpretation and understanding of Uranus system observations.

- Measure microwave and near-infrared absorption lines at temperatures near 50 K to confirm models extrapolated from measurements at 100 K
- Confirm, in the laboratory, Hydrogen ortho-para conversion rates

- Conduct further work on the detailed line measurements of ethane in the mid-IR (12-μm) region
- Explore further the solid-state chemistry of hydrocarbon particulates as a result of UV irradiation; spectral results particularly needed
- Obtain low-temperature measurements of H_2-H_2, H_2-He absorption in the mid infrared between 7 and 14 μm

Theory and Modeling

During discussion sessions at the workshop, the following needs were identified that will aid in interpretation and understanding of Uranus system observations.

- Comprehensive radiative-dynamical model of Uranus atmosphere
- Cloud microphysical model for the Uranus atmosphere
- Model of the auroral/ionospheric activity on Uranus

6 Workshop Action Items

Organize Pre-Equinox Science Workshops

- Atmospheres: Pasadena DPS, 8 October 2006 (Nancy Chanover)
- Satellites: Obs. de Paris, 16-18 Nov 2006, http://www.imcce.fr/paris2006/ (Jean-Eudes Arlot)
- Rings: TBD (Mark Showalter)

Continue Predictive and Theoretical Work

- Mutual events for small satellites (Valery Lainey)
- Occultations (Julie Moses to contact the usual suspects)
- Contact Paul Steffes (IOPW) re laboratory data (David Huestis)

Create Website for IOPW Uranus at Equinox

- Host website (Tom Stallard)
- Assemble list of existing data (Jim Norwood)
- Assemble list of scheduled observations (Mark Hofstadter)
- Bibliography (Kathy Rages)
- Links to JPL Horizons, Ring Node tools, IMCCE satellites ephemerides (Tom Stallard)

Increase Education and Public Outreach Efforts

- Publications

  Complete and distribute Workshop Summary (Heidi Hammel)

  Other publications: newsletters, magazines, websites (all)

  GAVRT (Mark Hofstadter)

- Plan future "Uranus at Equinox" activities

  Workshop: Chapman Conference or NASA-sponsored event (Heidi Hammel)

  Book: U. Arizona Press or Cambridge University press (Heidi Hammel)

  Special journal issue: Icarus or JGR-Planets (Heidi Hammel)

- Outreach activities

  Talk with various people in relevant positions regarding equinoctial opportunities (all)

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Appendix A - Workshop Agenda

Uranus System at Equinox - Planning Workshop

2-3 May 2006

Conveners: H. B. Hammel (SSI) and Mark Hofstadter (JPL)
supported by NASA

AGENDA

TUESDAY, 2 May 2006

1:00 Welcome — C. Niebur

1:10 Statement of Workshop Goals — H. Hammel

Understand Calendar

Understand Discipline-Specific Science Goals

Formulate Cross-Discipline Strategies to Optimize Facility Use

Identify Oversights or Missing Science

Identify Actions and Assignments

1:30 Overview of Equinox Calendar — M. Hofstadter

2:00 Discipline-specific Goals for breakout sessions — H. Hammel

Possible goals: *science needs;*
timing needs for observations;
future discipline-specific meetings

2:30 *Break*

2:45 Discipline-specific Breakout Sessions

Atmospheres (Facilitator: Amy Simon-Miller)
Satellites and Rings (Facilitator: Heidi Hammel)

4:30 Reports from Discipline-specific Breakout Sessions — Facilitators

5:30 *Adjourn*

6:30 Group Dinner (Hotel Restaurant) provided by NASA

WEDNESDAY, 3 May 2006

9:00 Group Discussion of Discipline-specific Breakout reports — all

9:45 Wavelength-specific Goals for breakout sessions — H. Hammel

Possible goals: *collaborations for joint observing proposals;*
new science that facilities can accomplish;
strategies to get facilities to commit Uranus time in advance;
strategies to make proposals appeal to TAC

10:00 Wavelength-Specific (facility-specific) Breakout Sessions

Radio, submm, mid-infrared (Facilitator: Glenn Orton)
Near-infrared (Facilitator: Padma Yanamandra Fisher)
Visible (Facilitator: Nancy Chanover)

10:45 *Break*

11:15 Continue Breakout Sessions

12:00 *Lunch, provided by NASA*

1:00 Reports from Wavelength-specific Breakout Sessions — Facilitators

2:00 Group Discussion of Wavelength-specific Breakout reports — all

2:30 *Break*

2:45 Group Discussion: solutions for missing science or wavelengths — all

3:15 Group Discussion: solutions for conflicts of timing or facilities — all

4:00 Actions and Assignments — all

Possible actions:

1. *Letter or report to observatories, encouraging "Uranus equinox" time allocations by pointing toward NASA support;*
2. *Letter or report to NSF, OPAG, others (?) encouraging support of Uranus equinox science (NASA ROSES has already done this);*
3. *Discuss venues, times, and organizers for follow-on meetings (e.g., discipline-specific meetings at DPS);*
4. *Publications of Uranus Equinox work (book, special journal issues, etc).*

4:30 Summary — H. Hammel, M. Hofstadter

5:00 *Adjourn*

Appendix B - Workshop Attendance

Name		Affiliation	Interest	Day 1	Day 2
Kevin	Baines	Jet Propulsion Laboratory	Atmosphere	✓	✓
James	Bauer	Jet Propulsion Laboratory	Satellites	✓	✓
Shawn	Brooks	Jet Propulsion Laboratory	Rings, Satellites		✓
Nancy	Chanover	New Mexico State University	Atmosphere	✓	✓
Heidi	Hammel	Space Science Institute	Atmosphere	✓	✓
Mark	Hofstadter	Jet Propulsion Laboratory	Atmosphere	✓	✓
David	Huestis	SRI International	Atmosphere	✓	✓
Erich	Karkoschka	University of Arizona	Atmosphere	✓	✓
Valery	Lainey	IMCCE Observatoire de Paris	Satellites	✓	✓
Sanjay	Limaye	University of Wisconsin	Atmosphere	✓	✓
Jack	Lissauer	Ames Research Center	Rings, Satellites	✓	✓
Julie	Moses	Lunar and Planetary Institute	Atmosphere Modeling	✓	✓
Curt	Niebur	NASA Headquartes	Planet, Rings, Satellites	✓	✓
James	Norwood	New Mexico State University	Atmosphere	✓	✓
Adriana	Ocampo	Jet Propulsion Laboratory	Satellites	✓	
Glenn	Orton	Jet Propulsion Laboratory	Atmosphere	✓	✓
Rosalyn	Pertzborn	University of Wisconsin	Atmosphere	✓	
Kathy	Rages	SETI / Ames Research Center	Atmosphere Modeling	✓	✓
Amy	Simon-Miller	Goddard Space Flight Center	Atmosphere	✓	✓
Tom	Spilker	Jet Propulsion Laboratory	Atmosphere		✓
Linda	Spilker	Jet Propulsion Laboratory	Rings		✓
Tom	Stallard	University College London	Ionosphere	✓	✓
Tanya	Tavenner	New Mexico State University	Atmosphere	✓	
Padma	Yanamandra-Fisher	Jet Propulsion Laboratory	Rings, Satellites, Planet	✓	✓