# FUTURE OBSERVATIONS OF URANUS

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# URANUS SCIENCE WITH SPACE TELESCOPE

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*ABSTRACT*

The Space Telescope Observatory, scheduled for launch in 1985, is described. The advantages of the space environment and the consequent features of ST performance are given, with Uranus observations as examples. The first generation instruments, including two cameras, two spectrographs and a high speed photometer, are discussed. The Space Telescope Science Institute, which will manage the Observatory, is discussed briefly. The potential scientific interaction with the Voyager 2 encounter of Uranus is also considered.

## *INTRODUCTION*

If the circum-Galactic orbit of our Sun had been slightly different in the astronomical past than it actually was, and if stellar perturbations had shorn our Solar System of all its members beyond ten A.U. from the center, then the Copernican model of the System would have been essentially complete as well as correct. If William Herschel had lived in a Solar System such as this, he would still have been a great astronomer. His quality is measured not merely by his discovery of Uranus, which was a singular and unplanned event in his career, but more significantly by his perception that previous improvement in telescope technology had produced major astronomical advances, and that continued efforts to build a better telescope offered the best prospect for further progress. Given the reality of the Solar System, his discovery

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of Uranus was an inevitable result of his approach to his science.

The subject of this paper is also an effort to build a better telescope. It is highly appropriate that a symposium honouring the work of William Herschel should include a contribution of this type. The Space Telescope Observatory (hereafter, ST), which includes a 2.4-meter primary mirror, will be launched into low Earth-orbit by the United States National Aeronautics and Space Administration Space Transportation System (Shuttle). The current schedule has the launch in the first quarter of 1985. The ST will include five scientific instruments, which are replaceable while in orbit. To be consistent with the astronomical potential of its space environment, the primary mirror will be by far the most precisely figured optical element of this size ever built. It is conservatively expected that the ST will produce revolutionary advances in understanding the Universe that are comparable to those due to any other single telescope ever constructed in the entire history of astronomy.

Space Telescope has been the subject of several recent papers. Spitzer (1979) has given a historical summary of the embryonic phase of the project and O'Dell (1981) has given a current overview. An entire volume (Longair and Warner, 1979) has been written concerning the scientific potential of the ST in all branches of astronomy. In that volume, O'Dell and Bahcall summarized the capabilities of the first generation scientific instruments. Among the review papers were ones by Belton on major planet astronomy and by Morrison on observations of smaller bodies. Leckrone (1980) has separately given a detailed account of the characteristics of the first generation instruments and Longair (1979) has described some of the scientific opportunities with ST. Finally, Caldwell (1981) has also summarized the observatory capabilities, using specific objectives for Uranus and Neptune as illustrative examples.

Because of the general availability of such papers, there has been no rigourous attempt here to give complete details of the ST, such as would be required, for example, to prepare an observing proposal. Rather, it is hoped that this paper will ignite the

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interest of those who may not previously have been aware of the unique capabilities of Space Telescope nor of its imminent arrival at operational readiness.

*ADVANTAGES OF THE SPACE ENVIRONMENT*

*Spatial Resolution*

It has long been realized that local refractive inhomogeneities in the Earth's atmosphere distort images of celestial objects far more severely than diffraction effects for all mirrors or lenses larger than about 10 centimeters. However, above the Earth's atmosphere, the only sources of image distortion are diffraction and optical imperfections in the mirrors and telescope structure.

The performance specifications of ST are that the Ritchey-Chretien optics produce an image of a point source at 6328 Å such that 70% of the energy will be included within a radius of 0.1 arc sec. Toward longer wavelengths the performance will rapidly approach the diffraction limit. Toward shorter wavelengths, the actual characteristics may not be determined precisely until the telescope is in orbit. The absolute performance should improve somewhat at shorter wavelengths as the effects of diffraction become smaller. However, it is also possible that small scale telescope imperfections may become significantly more important in the ultraviolet than they are at red wavelengths.

As of this writing, polishing work on two different candidate primary mirrors is nearing completion at the facilities respectively of the Perkin-Elmer and Eastman-Kodak companies. In each case pioneering techniques are being employed. The most recent indications are that the ultraviolet performance will be more toward the optimistic rather than the pessimistic side of the range of possibilities.

One characteristic of the space environment that is very different from the Earth's surface is that the instrumental point spread function (PSF) is not only very narrow but also very stable in time. It will be possible to calibrate the PSF accurately and to employ sophisticated image restoration techniques to produce

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spatial resolution that is somewhat better than the raw data. A conservative estimate is that the improvement will be at least a factor of ten better than ground-based observations with respect to linear spatial resolution (>100 in areal information). Such an improvement will produce Uranus images of a quality comparable to superior images of Jupiter before the advent of flyby missions.

Resolving power alone does not determine the total information content of an image, of course. Contrast is also an important factor. Uranus is well known to exhibit characteristic absorptions due to methane ($CH_4$) which are almost 100% in the strong bands longward of 10000 Å and which decrease to invisibility near 5000 Å. Ground-based imaging is adequate to show that image pairs in and adjacent to the strong $CH_4$ bands show very prominent differential contrast whereas broadband or short wavelength images do not (J. Westphal, private communication, 1981). One of the first generation cameras aboard ST will be equipped with appropriate filters designed to obtain the maximum possible contrast in atmospheric features on Uranus.

The actual performance of the Space Telescope at any time will depend on the camera being used then. It will be related to such parameters as the image size, the detector pixel size and the ST data handling capacity. Examples will be discussed later in this paper. The ultimate resolution will be set by the rms jitter in the pointing control system, which is expected to be 0.007 arc sec.

*Range of Accessible Wavelengths*

The ST optical system will permit high efficiency throughput down to 1200 Å, below which the $MgF_2$ coatings will rapidly suppress further penetration. The region between this instrumental boundary and the ground-based cutoff at 3000 Å contains atomic, ionic and molecular electronic transitions that are important for all objects of astrophysical interest. Uranus is not an exception.

Below 1500 Å, $CH_4$ is strongly absorbing. The degree to which this absorption and the Rayleigh scattering from $H_2$ combine to give the reflectivity in this wavelength range will be determined by the

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vertical distribution of $CH_4$ in the Uranian stratosphere. There is almost certainly some saturation of $CH_4$ on Uranus (eg. Danielson, 1977). The far ultraviolet spectrum offers an excellent prospect for modelling this situation quantitatively. No other astronomical satellite has had the capability of detecting Uranus at such short wavelengths. It will be a routine observation for ST.

The other three giant planets beside Uranus all have distinct stratospheric thermal emission features due to ethane ($C_2H_6$) at 12 μm and acetylene ($C_2H_2$) at 13 μm. Uranus does not (Gillett and Rieke, 1977). The difference could be due either to Uranus' having a cooler stratosphere than the other giants or to lower hydrocarbon abundances, or both.

These molecules also have electronic absorption features. In particular, $C_2H_2$ has a distinctive series of absorption bands between 1700 and 1800 Å that have been detected on Jupiter and Saturn (eg. Owen _et al_., 1980). However, Uranus is at the limit of detectability at these wavelengths (Caldwell _et al_., 1981) and Neptune is too faint to have been observed there with previous satellites. Spectra of Uranus and Neptune below 1800 Å would be exceptionally useful in clarifying the statospheric compositions of the outer two giant planets; both would be easy targets for ST.

The upper limit to the useful wavelength range for the ST Observatory is longward of 1 mm. There is little incentive to investigate this region with ST, because many ground-based radio telescopes will perform better there. However, it is expected that ST will generally do better than ground-based instruments throughout the three decades of infrared radiation from $10^{-4}$ to $10^{-1}$ cm wavelength.

The telescope optics will be at the ambient temperature of near - Earth orbit. There will be provision for cryogenically cooled detectors, although no such detectors are included in the first generation of instruments. The absence of the background radiation from the Earth's atmosphere and the long-term stability of the PSF will permit ST to perform background subtraction for infrared photometry by moving the entire telescope to a nearby sky

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pointing after minutes or hours of integration on the target, rather than chopping between sky and target at a frequency of tens of hertz, as ground-based telescopes typically do.

Uranus has many unusual infrared properties that could profitably be investigated with the ST. For example, its geometric albedo at 5 μm is $2 \times 10^{-3}$ (Brown et al., 1981), by far the lowest of the giant planets there. This must be due both to a general absence of particulate scatterers in the stratosphere of Uranus, and to very strong molecular absorbers in this spectral region.

From the ground, the signal from Uranus is so weak and the sky is so bright that it will probably be impossible to perform high resolution spectroscopy to identify the absorbers. From ST, a suitable spectrometer would have a much better chance of success.

To cite another example, photometry of Uranus longward of 10 μm is valuable for determining the thermal structure of the atmosphere of Uranus, but it is extremely difficult to achieve from the ground the photometric accuracy necessary to constrain models usefully. ST could also make improvements here.

In summary, the ST will have an unobstructed spectral range over four decades in wavelength, from the far ultraviolet to the submillimeter range, much of which is totally or partially blocked for ground-based observers.

*Limiting Sensitivity*

Implicit in the discussion of the preceding section is the realization that the terrestrial sky brightness limits the faintness to which ground-based telescopes can observe. For many aspects of planetary astronomy, this limitation is unimportant because planets are typically bright objects. However, the improvement in limiting sensitivity from space is one of the most important advantages that ST has for many other branches of astronomy, notably cosmology.

The observational limit is, of course, a function of the time which is invested in a project. With the practical assumption that ST integration times will be limited to ten hours, the ST capabi-

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lities may be summarized as follows: it is expected to be able to reach at least two stellar magnitudes fainter than the best ground-based telescopes have done in the "transparent" windows of the Earth's atmosphere, and to do very much better than that between the windows. It will reach about eight magnitudes fainter than previous orbiting ultraviolet observatories.

*Absence of Scintillation*

The rapid variations of the optical paths through the Earth's atmosphere limit astronomical observations of variable events with time scales comparable to that of the atmospheric variations. This scintillation also limits the ability to do accurate photometry of faint targets that are close to bright ones, as the Earth's atmosphere randomly confuses the two signals.

These general limitations restrict a type of planetary observation that has come to be exploited successfully in the past decade - the occultation of stars by Solar System objects. For airless bodies, such events provide information on diameters and shapes that is more accurate that even ST imaging can achieve (eg. Millis et al., 1981)! For planetary atmospheres, differential refraction during the occultation leads to a measurement of the atmospheric refractivity with height, which, together with the assumption of hydrostatic equilibrium, leads to models of the atmospheric thermal structure at very low density levels. However, terrestrial scintillation introduces noise features that can grossly distort the derived models, and which can render intrinsic planetary atmospheric features confusing.

In the space environment of ST, the only variability will be that of the event itself. ST can take advantage of the absence of scintillation to include in an observing aperture only a small portion of the planet being occulted. This would be hopeless from the ground. This advantage could be translated into higher signal-to-noise ratios for specific events, or the ability to observe occultations of fainter stars, which are much more numerous.

Because ST will occupy only a single point in space and time,

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it will generally be able to observe only occultations by objects with large shadows - that is, the giant planets and their ring systems. Asteroids and small satellites will probably remain for ground-based observers with small, mobile telescopes, who can alter their location to maximize the observability of a particular event.

Occultations by Uranus should therefore form a significant portion of this kind of planetary activity from ST.

## *THE FIRST GENERATION SCIENTIFIC INSTRUMENTS*

### *Overview*

Scientific instruments (SI) are located near the Cassegrain focus of the telescope, behind the primary mirror. There are two general types: "axial" instruments are about the size of a coffin, and have their long axes parallel to the telescope optical axis; "radial" instruments resemble a truncated wedge, are of the same order of size and are located between the axial instruments and the back of the primary mirror. There are four "bays" for each kind of instrument. Three of the radial bays contain Fine Guidance Sensors, which sample the outer parts of the focal surface, nine arc minutes from the optical axis, and provide the information for fine guiding and astrometry. The fourth radial bay samples the middle three arc minutes of the focal surface by means of a pick-off mirror. All four axial instruments have a corner touching the optical axis, behind the radial pick-off mirror. Light therefore enters these instruments only in an off-axis direction, requiring internal corrections to restore image quality.

The Observatory selects the current observing instrument, and particular apertures in that instrument, by means of small pointing manoeuvres of the entire spacecraft.

### *Wide Field/Planetary Camera*

This is the first generation radial instrument. Its development team is led by Professor James A. Westphal of the California Institute of Technology. Its primary purpose is imaging, with some low dispersion spectroscopic capability. It has the widest field

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of view of any SI, and the broadest spectral range.

The camera has two modes of operation, selectable by a rotation of an internal reflecting pyramid. These modes are named "wide field" (f/12.9; 2.7 x 2.7 [arc min]$^2$) and "planetary" (f/30; 1.2 x 1.2 [arc min]$^2$). In each mode, the detector consists of 4 silicon charge-coupled devices. There are 8 such CCDs in the camera, each including 800 x 800 pixels. For each mode, the image is reassembled in the data processing stage into an equivalent 1600 x 1600 image, with no loss of information at the internal boundaries.

Its wide spectral range is made possible by an organic phosphor coating, which converts ultraviolet photons to visual ones, where the intrinsic CCD efficiency is high. The net quantum efficiency exceeds 1% from 1150 Å to 11000 Å, peaking at 55% near 5500 Å. It has the only near infrared imaging capability of the first generation SIs.

Its photometric accuracy is ~1%. Its dynamic range is $10^5$, permitting the simultaneous recording of widely different brightness levels in the same field. In normal imaging, spectral definition comes from 48 filters, including methane ($CH_4$) band filters for imaging the giant planets. There will also be prisms and transmission grating for low dispersion objective spectra, and polarizers at several wavelengths.

*Faint Object Camera*

This axial instrument, designed and built by the European Space Agency, also has two modes: f/96 (11 x 11 [arc sec]$^2$) and f/48 (22 x 22 [arc sec]$^2$). Its field of view is actually limited by the observatory data handling capacity. It will achieve the highest possible spatial resolution and will reach the faintest objects for the first generation SIs. It has much greater speed than the WF/PC in the ultraviolet. The peak quantum efficiency is ~26% at 3000 Å.

It will contain approximately 48 selectable filters, including neutral density and special purpose ones, objective prisms and

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polarizers. It will also have a coronographic capability, featuring a 0.6 arc sec occulting disk that will permit recording objects 1 arc sec apart which differ in brightness by ~ 10 stellar magnitudes.

There will also be a fixed grating spectroscopic mode, permitting observations in three orders: 3600 - 5400 Å; 1800 - 2700 Å and 1200 - 1800 Å at a resolution of $\lambda/\Delta\lambda \sim 2 \times 10^3$. This performance is less than those of the spectrographs discussed below, but this instrument has the unique feature among first generation SIs of providing spatial information perpendicular to the dispersion direction. Its entrance slit is 10 x 0.1 (arc sec)$^2$.

*Faint Object Spectrograph*

This axial instrument is being developed by a team led by Dr. Richard Harms of the University of California at San Diego. It will obtain low and moderate resolution spectra of objects fainter than those accessible from the ground. It has two operational modes, with resolutions respectively of $\lambda/\Delta\lambda \sim 10^3$ and $10^2$.

It will have a usable spectral range from 1150 Å to 9000 Å, although its quantum efficiency drops to 1% near 7000 Å and decreases rapidly toward longer wavelengths. It will also exploit the ST spatial resolution capability on extended sources, with 10 entrance apertures ranging in size from 0.1 to 4.3 arc sec.

Other features of the FOS include polarization capability below 3000 Å, and a time resolution for sufficiently bright objects of 50 μ sec. The observatory data handling capacity will permit up to 100 exposures/sec for the 512 diode spectra.

*High Resolution Spectrograph*

This instrument is being developed by a team directed by Dr. John C. Brandt of the Goddard Space Flight Center. It will provide the highest spectral resolution of any of the first generation SIs. There will be three modes, with $\lambda/\Delta\lambda \sim 10^5$, $2 \times 10^4$, and $2 \times 10^3$.

Its high resolution capability is achieved at some cost in other parameters. For example, it will operate only below 3200 Å, and it will have only two selectable spatial resolutions, 0.25 and

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2.0 arc sec. However, it will have high time resolution capability (~ 25 m sec), and it will also have a finite response below 1150 Å, both useful for very bright sources.

Its highest resolution observations will be totally without precedent in space astronomy. Therefore, astronomical objects themselves will not be totally adequate as calibrators, and the HRS will rely on its own internal light sources for spectral and photometric calibration.

*High-Speed Photometer*

Dr. Robert C. Bless of the University of Wisconsin is the leader of the development team for this, the mechanically most simple SI of the first generation. It has two basic purposes: high time resolution (up to 16 μ sec) and high photometric precision (0.2%). In both these respects, it will be the best performer among first generation SIs. It can be related to a ground-based clock with an accuracy of 10 m sec.

Its detectors include four image dissectors which together cover the range from 1150 Å to 6500 Å. Apertures of 0.4, 1.0 and 10 arc sec will be available.

A fifth detector, a side-looking gallium arsenide photomultiplier tube with peak sensitivity from 6000 to 9000 Å, was added specifically to enhance the observability of stellar occultations by planets. The red-sensitive tube is desirable because most stars in the sky are red, and the light from giant planets can be greatly suppressed in the red by choosing a filter in a strong methane band. Since it is the starlight which is the useful signal in such an observation, the best signal-to-noise therefore typically occurs in the near-infrared $CH_4$ bands.

The HSP will also be able to measure linear polarization below 4000 Å. Its dynamic range will be ~ $10^8$.

*Fine Guidance System*

There are three fine guidance sensors, which sample the focal plane outside the SI fields of view. The light detector in each

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sensor is an image dissector/interferometer combination. The system is used for guiding the observatory, with 2 FGSs required at any time for this purpose. The third is free to perform astrometric observations.

Each sensor will measure relative positions within its own field of view (69 [arc min]$^2$) to within 0.002 arc sec. The magnitude range for astrometric targets (including those observed through netural density filters) is 4 $m_V$ to 20 $m_V$. It will be able to track moving targets.

The ST astrometry science team leader is Dr. W. H. Jefferys of the University of Texas at Austin.

*Future Instruments*

The descriptions above refer to instruments selected in a competition in 1978. It has always been the intention of NASA to provide for the replacement of these instruments as they become obsolete or defective. There will probably be an announcement of opportunity for at least one new instrument before this paper is in press. Among the obvious areas where the first generation instruments are deficient are the lack of high spectral resolution above 3000 Å, the lack of imaging above 1 μm and the general lack of infrared capability. These areas will be prime ones on which second generation instruments will focus.

It should be emphasized that NASA's record in this entire project is consistent with choosing the best possible science for ST. The competition for second generation instruments will be completely open to all who wish to participate, and all will be given an unbiased evaluation.

## *SCIENCE MANAGEMENT*

In an unprecedented approach to the task of operating the ST, NASA is in the process of contracting management responsibilities to the Association of Universities for Research in Astronomy, Inc. (AURA). AURA has chosen the Johns Hopkins University in Baltimore, Maryland, to be the location of its Space Telescope Science Insti-

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tute, an independent establishment that will run the Observatory.

It will solicit observing proposals from the astronomical community, evaluate those proposals in a peer review system, provide such support as guide star selection for fine pointing, collect and archive the data, and provide facilities for data analysis. It will be the astronomer's prime (and probably only) point of contact with the system.

A related development is that there will be a European coordinating center for ST activities, primarily data analysis support. This will be managed by the European Space Agency. Its site is currently the subject of a competition among several prominent European astronomical centers.

*THE LAUNCH DATE*

As mentioned in the introduction, the current plan is to launch ST in the first quarter of 1985. This should permit observations to begin in time to participate in two unique astronomical events: the 1985 - 1986 apparition of Halley's comet and the January 24, 1986 encounter of Uranus by Voyager 2 (Stone, this volume).

The current launch schedule is the result of a slippage due mainly to financial problems. Although the schedule has been determined by dollars and not by science considerations, it has, by chance, now been set at virtually the last possible moment that will permit full exploitation of the ST's capabilities for these events. This statement includes recognition of the finite time required to commission the ST after launch, the finite time necessary to assimilate new science, the finite lead time for inclusion of new data into Voyager planning, and pre-perihelion cometary phenomena.

If there is any further slippage, unique science in two areas will probably be lost irretrievably.

Since the primary interest of this volume is Uranus, not Halley, a few considerations of the interaction between ST and Voyager 2 will be given here. It is first noted that at the time

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of encounter, Voyager 2 will be travelling nearly parallel to the rotational axis of Uranus. Therefore, its closest approaches to the planet, the satellites and the rings will be simultaneous, not sequential as in previous encounters. Therefore, improved scientific understanding of all the phenomena of the Uranus system before the encounter will be invaluable in planning for the precious few hours of greatest opportunity.

It is expected that Voyager's imaging capability will exceed typical ground-based performance for about thirteen months before encounter (Stone, this volume). However, ST will exceed ground-based achievements by an order of magnitude in linear resolution, and may also have advantage over Voyager 2 with respect to the location of filters and the intrinsic contrast of atmospheric features on Uranus. It is therefore possible that the best available information on Uranus will come from ST until such a late time that further information would not be in time to impact the encounter plans.

Concerning the detectability of faint rings and satellites, it is not clear which mission will have the advantage. Starting about a year from encounter, Voyager will be the best imaging system. Several months later, after the ST launch, ST will be the best. Subsequently, as Voyager gets closer, it will regain primacy for a brief time. If there are currently undetected rings or satellites of Uranus, their discovery could come from either spacecraft, depending on how bright they are. It is conceivable that each spacecraft could take turns discovering progressively fainter bodies!

## *CONCLUSION*

In the introduction, it was noted that the scientific career of William Herschel was not limited merely to his observations of Uranus. Similarly, it is certainly true that observations of Uranus will form a very small part of the total science program of ST. However, Uranus will be an important part of that program, and perhaps one of the most important planetary targets.

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Current knowledge of the Solar System is distressingly inhomogeneous. The more distant memebers of the system are virtual strangers compared to our near neighbours, which are being examined at the microscopic level. Surely it will be impossible to claim a definitive understanding of the whole planetary system until all of its important members become less mysterious. For this reason, it is the opinion of the author that Uranus, together with Neptune and Pluto, should be ranked first among the major planets in terms of ST observing priority.

If the first two hundred years of the study of Uranus are frustrating because it still seems little more than a point source of light, there is some relief in the real prospect that various endeavours, of which the Space Telescope is a leading example, will provide unparalelled progress in the next five.

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