PLANETARY ASTRONOMY WITH THE SPACE TELESCOPE

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1. INTRODUCTION

The increases in resolution and sensitivity promised by ST over IUE, Copernicus, and OAO-2 will make it a facility of great significance to planetary astronomy, for each of these latter satellites have convincingly demonstrated the ability of earth-orbiting telescopes to contribute to the subject.

My goals in this paper are: to highlight a few problem areas in planetary astronomy that demonstrate the utility and power of the ST; to emphasize the potential for 'discovery' in solar system observations with ST; to emphasize the need for coherent and long-term scheduling commitments and the value of cooperative observations with orbiter or flyby missions; and finally to emphasize to planetary astronomers *that the time to plan and articulate their observational programs and strategies for use of the telescope is now.*

1.1. Experimental Methods in Planetary Astronomy

Observing with earth-orbiting telescopes is now one of many techniques used in planetary astronomy, and the relative importance of these various methods is often, I think, misunderstood. One often encounters the view, for instance, that, as a result of our ability to directly probe, or orbit, solar system objects, remote sensing by ground-based and earth orbital means is of minor importance.

The primary reason why this is not true is that planetary science is still very much in the 'discovery' stage. Unexpected 'discoveries' that are being made today are as likely to be the result of exploratory observations on the ground (new detectors, better instrumentation, new facilities) or in earth-orbit (OAO-2, Copernicus, IUE) as by flyby and orbiting space probes. There are, of course, many substantial areas

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of the subject (e.g. geology of planetary surfaces) where, I think orbiting or landed spacecraft are absolutely essential for further advances. However, there are yet other problems where cooperative observations made from the ground, earth-orbit, and deep space are essential for their advance.

Table 1 attempts to illustrate some of the interplay between the major experimental techniques currently used in planetary astronomy. It can be seen that telescopic observations from earth-orbit not only compensate for many of the disadvantages of ground-based work, but they also compensate for many of the less often recognized disadvantages of the otherwise essential deep space missions.

All three approaches should be used in a complementary way for the most scientific advantage. The potential of earth-orbital observations from ST, SIRTF, and several other probable shuttle based instruments, particularly when used in conjunction with deep space missions, is, I believe, the most significant, as well as the most poorly understood, opportunity in planetary astronomy today.

1.2. Current Problems in Planetary Astronomy

Planetary astronomy today divides into three major areas:

(i) Reconnaissance and exploration of the outer planets and their satellites.

(ii) A detailed exploration of the terrestrial planets (Mars, Venus).

(iii) Reconnaissance of primitive bodies in the solar system (comets, asteroids).

Table 1. Comparison of Experimental Methods in Planetary Astronomy (assumes the existence of ST)

Method	Primary Advantages	Primary Disadvantages
Ground Based	Instrumental sophistication, Lowest cost, Programmatic flexibility, Rapid time response to 'discovery' Large optical throughput	Inadequate spacial resolution, Inadequate spectral coverage, Weather; poor time sampling, Limited observing geometry, High sky background in IR
Earth-Orbit	Excellent time sampling (no weather), Excellent spectral coverage, Reasonable time response to 'discovery', Low sky background, Adequate spacial resolution for some objectives	High cost, Limited observing geometry
Deep-Space Missions	Excellent spacial resolution, *in situ* measurements Excellent spectral coverage, Dedicated objectives. Extended observing geometry, Sample return	High cost, Limited spacial and temporal sampling, Programmatic inflexibility, Simple instrumentation, Non-refurbishable, Long planning cycle, Poor time response to 'discovery'.

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I expect that the ST will lead to major advances in terms of (i) and (iii). However, all three areas demand deep space missions for their advancement and the program currently consists of Pioneer Venus, Voyager, and Galileo with VOIR, Comet Rendezvous and SOP[2] as potential candidates. The word 'reconnaissance' is carefully chosen for many objects are, as I discussed above, still characterized by the unknown and by the excitement of totally unexpected 'discovery.' A broad, quick, first look is the essence of much of the work being done.

Table 2 gives a few examples of recent important discoveries in this field which serve to emphasize that all three basic experimental methods contribute major advances.

The plain fact is that there is still much to learn about the system of planets among which we live. In Table 3 I have attempted to list what I view as the major problems facing the planetary astronomer today. It underscores the fundamental nature of the questions that are being addressed and the fact that adequate knowledge of some of the most obvious phenomena does not yet exist. It also illustrates areas in which I think ST will help to resolve problems.

In the following sections I shall try to illustrate the possible payoff in utilizing the ST for the following selected problems:

1. Atmospheric dynamics.
2. Stratospheric and upper atmospheric processes.
3. Circumplanetary nebulae.

The work done with the ST would not be expected to resolve these problems alone. We can be assured that data generated by sophisticated instruments on the ground as well as data from *in situ* probes, sample returns, and orbiting spacecraft will also be essential. I expect that the very best scientific use of space telescope in planetary astronomy will require a very careful coordination of these different experimental methods.

Table 2. A Few Examples of Recent Discoveries of Major Importance to Planetary Astronomy

	Discovery	Date	Method
1.	Uranus Rings	1977	Photometry: Airborne Observatory
2.	Pluto's Moon	1978	Photography: G. B. Telescope
3.	Neptune's Internal Heat Source	1978	Radiometry: Balloon Telescope
4.	Io's Sodium Cloud	1973	High Resolution Spectroscopy: G. B. Telescope
5.	Lyman Band (H_2) Emission on Jupiter	1973	Rocket Spectrometer
6.	C_2H_2 on Saturn	1979	IUE
7.	Io Induced H_2 Aurora	1978	Copernicus
8.	Jupiter's Rings	1979	Imagery: Voyager
9.	Io Volcanism	1979	Imagery: Voyager
10.	Jupiter's Plasma Torus	1979	EUV Spectroscopy: Voyager

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Table 3. Some Major Problems* in Present Day
Planetary Astronomy

*I address only problems concerning the planets. D. Morrison in a companion paper addresses other solar system objects. The notation (ST) means that I expect ST to provide information important to the resolution of the problem.

OBJECT	PROBLEM
Jupiter and Saturn	1) What is the origin of their banded appearance? (ST) 2) What is the cause of their atmospheric coloring? (ST) 3) What is the origin of their equatorial jets? (ST) 4) What physical processes govern the Jovian Sulphur Torus and inner magnetosphere? (ST)
Uranus and Neptune	1) What is the chemical composition of their atmospheres? (ST) 2) Why does Neptune show a strong internal heat source and Uranus does not? 3) Why do these two planets have such different stratospheres? (ST) 4) How fast do Uranus and Neptune rotate? (ST)
Venus and Mars	1) Why does Mars have global dust storms? (ST) 2) What is the explanation of the peculiar circulation of the Venus stratosphere? (ST)
Mercury	1) What does the 'other' side of Mercury look like? (ST)
Pluto and its Moon	1) What are their sizes, masses, bulk composition? (ST)

2. SPACE TELESCOPE CAPABILITIES

The capability of ST for solar system observations should become immediately clear by looking at Table 4 which is a list of the solar system science objectives proposed by the principle investigators and their teams. I draw the following conclusions from this table:

(i) All ST instruments have viable solar system objectives,

(ii) Many of the objectives are associated with time dependent phenomena, and, in fact, need extended and carefully sampled time series of observations for their fulfillment,

(iii) Many objectives would be enhanced if done in coordination with a deep-space mission (e.g. circulation studies of Jupiter coordinated with Galileo, or studies of chemistry and structures in Halley's comet coordinated with the Halley/Tempel 2 rendezvous),

(iv) Some objectives would be enhanced if coordinated with ground-based observations (e.g. comet tail studies, coordinated with wide field photography of tail; UV marking studies of Venus coordinated with Doppler and CO_2 measurements from the ground),

(v) To pursue all of these studies in depth could easily consume most of the available time, especially in the early years after launch.

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Table 4. Scientific Objectives in Planetary Astronomy Proposed by ST Principle Investigator Teams

Instrument	Science Objectives
WF/PC	1) Studies of atmospheric circulation on Jupiter and Saturn. 2) Determination of gross vertical structure of visible and upper atmospheres of Jupiter, Saturn, and Uranus. 3) Optical oblatness of Uranus and Neptune. 4) Aeolian transport on Mars: origin of dust storms, behavior of condensate clouds, support for future lander missions. 5) Evaluation of UV marking on Venus. 6) Exploration of the appearance of planets below 2900 Å. 7) Surface chemistry of airless bodies. 8) Radius of Pluto. 9) Search for extra solar planets. 10) Structure of cometary atmospheres.
FOC	1) Structure and evolution of cometary phenomena. 2) Time dependent features on planetary surfaces.
FOS	1) Structures and velocities in cometary atmospheres and tails
HRS	1) Composition, structure, and evolution of circumplanetary nebulae: Io's plasma torus. 2) Isotopic ratios in cometary atmosphers: D/H in Halley. 3) Raman scattering in planetary atmospheres. 4) Center to limb behavior of upper atmospheric emissions. 5) Line profiles of upper atmospheric emissions. 6) Auroral activity/dayglow/aeronomy
HSP	1) Diameters of solar system objects. 2) Vertical profiles of physical parameters in planetary atmospheres.
FGS	1) Positional information on outer planet satellites.

In light of the latter conclusion it is clearly essential to know what is "do-able" so that returned data will be of essentially guaranteed scientific potential. It is also clear that there are preferred times at which certain objectives should be addressed.

In this section I attempt to evaluate the sensitivity and resolution capabilities of the ST instruments in order to estimate their capability for planetary objectives. I also present a calendar for solar system observations which indicates the preferred timing of some of the proposed studies.

2.1. Sensitivity

The discussion of instrumental sensitivity given in Bahcall and O'Dell (1979) makes use of units (visual magnitudes) which are inconvenient when applied to planetary problems. Units of surface bright-

Table 5a. Representative Values* for the Surface Brightness of the Planets in Reflected Sunlight at Three Wavelengths (photons . cm^{-2} . A^{-1} . $ster^{-1}$. sec^{-1})

Planet	2000 Å	5500 Å	10000 Å
Mercury	1.3×10^{9}	1.8×10^{12}	8.1×10^{11}
Venus	1.0×10^{10}	6.4×10^{12}	3.2×10^{12}
Mars	2.8×10^{9}	2.8×10^{11}	3.8×10^{11}
Jupiter	1.1×10^{8}	1.2×10^{11}	1.4×10^{10}
Saturn	3.5×10^{7}	3.6×10^{10}	4.3×10^{9}
Uranus	1.2×10^{7}	1.1×10^{10}	2.8×10^{8}
Neptune	4.8×10^{6}	4.0×10^{9}	7.7×10^{7}
Pluto	2.1×10^{6}	1.9×10^{9}	9.7×10^{8}

*These values are representative and do not represent any particular area on the planetary disk. These values are not recommended as a basis for precise calculations for specific problems.

Table 5b. Characteristic Brightnesses and Line Widths for Selected Emission Line Phenomena (Rayleigh units)*

Phenomenon	Surface Brightness	Estimated Line Width (FWHM Å)
Geocoronal Lyman α	1-10 kR	∿0.06
Jupiter Lyman α	1-20 kR	∿0.09
Venus Lyman α	∿18 kR	∿0.02
Mars Lyman α	∿ 5 kR	∿0.01
Saturn Lyman α	∿ 1 kR	∿0.09
Uranus Lyman α	∿300 R (?)	∿0.05
Neptune Lyman α	∿150 R (?)	∿0.05
Io Torus Lyman α	0-300 R	∿0.01
Io Flux Tube Lyman α	∿100 kR (?)	∿0.02
Io Sodium (5889 Å)	∿ 10 kR	0.024-0.068
Io SII (1256 Å)	43R**	∿0.09
Saturn Ring Lyman α	∿200 R	∿0.01
Saturn Torus Lyman α	∿500 R (?)	∿0.01
Jupiter Lyman Band Lines (1608 Å)	∿20 ∿100 R (?)	∿0.03

*Values followed by (?) are guesses or, at least, very rough estimates.
**Estimate by D. E. Shemansky (1979).

ness are preferred for most problems, i.e. photons $cm^{-2}Å^{-1}steradian^{-1}$ sec^{-1}, or in some cases, the Rayleigh. This latter unit is equivalent to a surface brightness of $(10^6/4\pi)$ photons $cm^{-2}sec^{-1}ster^{-1}$ and is used to represent the frequency integrated brightness of emission lines from extended objects.

In Table 5a I give representative values of the surface brightness of the planets at three wavelengths: 2000, 5500, 10000 Å. In Table 5b I give estimates (guesses) of the brightness and line width for a few important emission line phenomena. The information in these tables help define the performance required of the telescope.

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Table 6a. Estimated Counting Rates (per pixel per 100 A or per spectral element) for ST Instruments on Planetary Disk (counts . sec^{-1})$^{+}$

INSTRUMENT	λ(A)	M*	V	M	J	S	U	N	P⁺⁺
WF	2000	1.3(2)	9.5(2)	2.8(1)	1.2(1)	3.5(0)	1.2(0)	4.8(-1)	2.1(-1)
	5500	1.8(5)	6.3(5)	2.8(4)	1.2(4)	3.6(3)	1.1(3)	4.0(2)	1.9(2)
	10000	8.1(4)	3.2(5)	3.8(4)	1.4(3)	4.3(2)	2.8(1)	7.6(0)	9.7(1)
PC	2000	2.3(1)	1.8(2)	5.0(0)	2.0(0)	6.2(-1)	2.2(-1)	8.6(-2)	3.7(-2)
	5500	3.2(4)	1.2(5)	5.0(3)	2.1(3)	6.5(2)	2.0(2)	7.2(1)	3.4(1)
	10000	1.4(4)	6.1(4)	6.8(3)	2.5(2)	7.8(1)	5.0(0)	1.4(0)	1.7(1)
FOC (f/96)	2000	6.2(0)	4.5(1)	1.3(0)	5.5(-1)	1.6(-1)	5.8(-2)	2.3(-2)	1 (-2)
	5500	8.6(3)	3.0(4)	1.3(3)	5.7(2)	1.7(2)	5.3(1)	1.9(1)	9 (0)
FOS** (10^3)	2000	2.8(0)	2.2(1)	6.1(-1)	2.4(-1)	7.5(-2)	2.7(-2)	1.0(-2)	3.2(-3)
	5500	1.2(4)	4.1(4)	1.8(3)	7.6(2)	2.3(2)	7.0(1)	2.6(1)	8 (0)
HRS (10^5)	2000	6.6(-2)	5.2(-1)	1.4(-2)	5.7(-3)	1.7(-3)	6.3(-4)	2.4(-4)	2.8(-5)
HSP	2000	2.1(3)	1.5(4)	4.4(2)	1.8(2)	5.6(1)	1.9(1)	8.0(0)	3.4(-1)
	5500	2.9(6)	1 (7)	4.4(5)	1.9(5)	5.6(1)	1.8(4)	6.8(3)	3.0(2)

*M = Mercury; V = Venus; etc.

$^{+}$1.8(5) = 1.8 x 10^5 explains the numerical formalism used in the table. I have assumed an effective quantum efficiency of 10% for the imaging detectors and the HSP.

$^{++}$Angular size relative to FOV taken into account (Pluto radius ∿ 0.″073)

**Assumed apertures were FOS = 0.″15 square; HRS = 0.″25 square; effective quantum efficiency = 5%.

Table 6b. Estimated Counting Rates Per Emission Line for HRS (counts sec^{-1})*

Phenomenon	HRS (1.2 x 10^5) Count Rate	HRS (1.2 x 10^5) FWHM (Diodes)	HRS (2 x 10^4) Count Rate	HRS (2 x 10^4) FWHM (Diodes)
Geocoronal Lyman α	0.3-3	6	19-190	1
Jupiter Lyman α	0.3-6	9	19-380	1.5
Venus Lyman α	5	2	320	< 1
Mars Lyman α	2	1	130	< 1
Saturn Lyman α	0.3	9	19	1.5
Uranus Lyman α	0.1	5	6	1
Neptune Lyman α	.04	5	3	1
Io Torus Lyman α	0.1	1	6	< 1
Io Flux Tube Lyman α	3	2	190	< 1
Io SII (1256 Å)	.01	9	0.6	1.5
Saturn Ring Lyman α	.05	1	3	< 1
Saturn Torus Lyman α	0.1	1	6	< 1
Jupiter Lyman Band Lines	0.005-0.03	2	0.3-2	< 1

*Assumes 5% effective quantum efficiency.

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In Tables 6a and 6b I have estimated, using the information given in Bahcall and O'Dell, the expected 'counting' rates, or alternatively the rate of generation of measurable charge, in each of the instruments.

Evaluation of the information in Table 6a and 6b depends on both the sources of noise and also whether the detector reaches saturation at the minimum exposure time. The noise sources are collected in Table 7. The highest counting rates or brightest scenes that can be handled by the various instruments without the use of neutral density filters appear to be: WF/PC $\gtrsim$ 4 x 10^5cts. sec^{-1}; FOC $\leq$ 4 x 10^7 photons sec^{-1} $cm^{-2}Å^{-1}ster^{-1}$(neutral density filters are provided with this instrument that give attenuation factors that range from 1 to 1.6 x 10^5). Data on maximum rates was not available for the other instruments, but 10^5 cts/sec is probably a reasonable limit. Important missing data which will not be available until after launch is the actual level of scattered light in the spectrometers.

In the imaging mode the WF/PC should have no problems with the brighter planets providing the spectral bandwidths are $\leq$ 100 Å. For the faintest planet, Pluto, it should be possible to obtain spacially resolved images at S/N ∿10 in less than two hours through a 100 Å filter centered near 2000 Å.

By making use of its attenuating filters, the FOC should also be able to operate on all of the planets, except perhaps Venus in the visual; however, this is probably not scientifically important. This instrument should be able to acquire spacially resolved images of Pluto near 2000 Å (the hardest case) with a S/N ∿10 in less than three hours through a 100 Å filter. With suitable filters imaging of emission line phenomena down to the 1 kilorayleigh level seems achievable.

In the spectrographic mode, the FOS will be able to operate on all the planets with 10^3 resolution. Even Pluto can be reached by the FOS at 2000 Å in about 14 hours for a S/N per spectral element of ∿10. The HRS should be able to use its full resolving power out to Jupiter where I estimate a S/N of 10 per spectral element can be achieved in approximately

Table 7. Estimates of Noise Sources in ST Instruments (Count sec^{-1} per pixel as per spectral element)

Instrument	Dark	Readout Noise	Sky[+]	Instrumental Scattering
WF	0.01	±15	2.7(-3)	-
PC	0.01	±15	4.9(-3)	-
FOC	0.0001		1.3(-4)	-
FOS	0.002		1.7(-3)	?
HRS	$\lesssim$0.01		8.4(-6)	?
HSP	?	-	1 (-1)	-

*Readout noise is RMS electrons per read.

[+]Assumes flat spectrum.

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13 hours at 2000 Å. At longer wavelengths, e.g. 3000 Å, the counting rates will be up by a factor of 50-100 which may make it even possible to obtain high resolution spectra at S/N ∿10 of Neptune at this wavelength in about an hour.

For emission line sources the HRS will be able to reach sources ∿1 kR/spectral element with a S/N ∿10 in six minutes in its highest resolution mode. The FOS with its smallest entrance aperture will reach ∿1.0 kR/spectral element in ∿ 15 minutes but with higher spacial resolution than the HRS. At the lower resolution of 2 x 10^4 with a 2.0 arc sec aperture the HRS should be able to reach emission features of ∿2 R/spectral element in one hour at a S/N ∿10.

In summary, a comparison of these performance figures with expected brightness levels shows that the instruments on ST have adequate sensitivity to explore the disks of all of the planets in the UV down to 2000 Å with unprecendented spectral and spacial resolution. Also, most known planetary emission line phenomena are available to the HRS at resolutions of 2 x 10^4 or greater within short observing times again implying a substantial 'discovery' capability.

2.2. Spacial Resolution

I use the following conventions for estimating the resolutions: When the imaging performance is limited at the detector, *experience* shows that the smallest details that can be recognized correspond to about 2.2 pixels; when the performance is limited by the telescope, I have used the Rayleigh criterion. For instruments with single apertures I take the effective linear resolution to be 2.2 times their FOV. The stability of the telescope system should not appreciably affect the effective resolution capability.

While the above conventions may seem arbitrary, their utility is based on the experience that resulting estimates of resolution can be reliably compared with linear scales of physical interest on planetary surfaces or atmospheres.

The planets can be observed from ST over a range of distances; in Table 8 I have collected values of the range of linear resolutions that should be possible for each planet. For the purposes of comparison I also include estimates of what I think can be done under various ground-based seeing conditions.

To assess these capabilities I use the following rules of thumb, which are again based on experience:

(i) For exploration and 'discovery' any resolution up to and better than the best ground-based resolution. This rule also covers all emission line studies as well as imaging.

(ii) For detailed atmospheric circulation studies experience with Venus indicates that a resolution of between 1 to 5 scale heights is desirable.

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Table 8. Range of Possible Linear Resolution Achieved by

ST Instruments on the Planets (kilometers)*

*The two figures in each box represent the resolution at the closest and furthest distance that ST can observe the planet.

Planet	Radius	Atmospheric Scale Height	WF	PC	FOC	FOS	HRS	HSP	Ground Based	
									Best	Average
Mercury	2420	-	152	62	34	227	379	606	342	1368
Venus	6120	5	48 / 256	20 / 104	11 / 58	72 / 382	120 / 638	191 / 1021	108 / 576	132 / 2880
Mars	3380	11	84 / 342	34 / 139	19 / 77	125 / 511	209 / 853	334 / 1365	108 / 770	432 / 3081
Jupiter	71600	20	672 / 970	273 / 393	151 / 218	1004 / 1448	1680 / 2418	2681 / 3866	1513 / 2181	6052 / 8726
Saturn	60000	33	1366 / 1669	555 / 678	307 / 375	2041 / 2493	3407 / 4162	5449 / 6654	3074 / 3755	12297 / 15019
Uranus	25900	25	2909 / 3216	1182 / 1306	654 / 724	4345 / 4804	7254 / 8020	11599 / 12823	6545 / 7236	26179 / 28944
Neptune	24100	15	4651 / 4960	1890 / 2015	1046 / 1116	6948 / 7409	11600 / 12370	18574 / 19778	10465 / 11160	41861 / 44640
Pluto	1600	?	4688 / 4992	1904 / 2028	1054 / 1123	7003 / 7456	11690 / 12448	18693 / 19905	10548 / 11232	42192 / 44928

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(iii) For photogeology resolutions of $\lesssim$ 1 km are required for useful work.

(iv) For examining the chemistry of planetary surfaces, resolution of $\lesssim$ km are desired.

(v) For useful estimates of global properties resolutions of $\sim$ 5% of the radius or better are required.

The linear resolution capabilities of all the instruments (except perhaps the HSP) coupled with the potential for observations over extended times emphasized the considerable discovery and exploration potential on all of the planets. This will be particularly true for imaging of Pluto, Uranus, Neptune, Mercury, and for emission line studies.

For atmospheric circulation studies Venus and Mars are excellent candidates with the PC as the preferred instrument. The FOC has better resolution characteristics but suffers from its small field of view. Jupiter is also a strong candidate for extended atmospheric studies even though the linear resolution at 273 km is some 13 scale heights. Voyager data has shown that the main features of the global circulations associated within the zone-belt structure can be reliably followed at this resolution. Thus, extended PC studies of global scale atmosphere dynamics on Jupiter when coupled with higher resolution studies ($\sim$15 km) of limited regions from an orbiting spacecraft (Galileo) can be expected to have considerable payoff (see Section 3).

The ST does not seem to have a lot to offer to photogeologists for detailed morphological studies. However, in the related area of the surface chemistry, the new spectral range of ST combined with resolutions of a few tens of kilometers seems to have considerable potential (Loffler, 1974).

Finally, ST will provide us with our first clearly resolved views of the Pluto system and provide knowledge on masses, density, and bulk composition. ST observations can also considerably refine our knowledge of the oblateness and rotation of Uranus and Neptune.

2.3. Spectral Resolution and Range

The spectral resolution of 1.2 x 10^5 will allow radial velocities to be determined to about ±150 m/sec which should be valuable in work on the Io torus. From the data in Table 6b we can see that details of the Lyman α profile will be available for giant planets for the first time. This will say much about mixing processes in these atmospheres. Also the high temperatures in the Io plasma torus can be probed. It may turn out that the most important benefit of the combination of high spectral resolution and sensitivity on the ST is its potential for the discovery of faint emission or absorption lines diagnostic of excitation processes, chemistry, and temperature. Relative intensities of individual H_2 Lyman band lines on Jupiter would be an example of this.

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2.4. Time Table for Planetary Observations

I have stressed in the introduction that some planetary observations will have preferred times for their execution. For example, observations of Mercury at aphelion will have greatest interest when the illuminated hemisphere is the one not previously examined by Mariner 10. Similarly Martian dust storms would be best observed when the planet is approaching perihelion. Mission time tables should also be taken into account; extended atmospheric studies of Jupiter might be best done during the 20 months of the Galileo mission, etc.

Figure 1 gives an overview of the timing of planetary phenomena and NASA's program for solar system exploration from which we can assess the impact on ST. A number of obvious things leap to the eye. First, all planets will be available for immediate investigation by the ST, and I would expect the basic parameters of the Pluto system to be worked out within a month. Preliminary exploration of planetary disks in the UV will be done. Within the year we could have our best look at the other side of Mercury. (Note the limited chances to do this.) Halley will also be in the sky at a distance of 8.2 AU from the sun with a nuclear magnitude of ∿21 and a study of its nucleus and evolving atmosphere would be started immediately in conjunction with ground-based work.

Mars will also be approaching opposition, but probably the best apparition for following the development of a global dust storm is likely

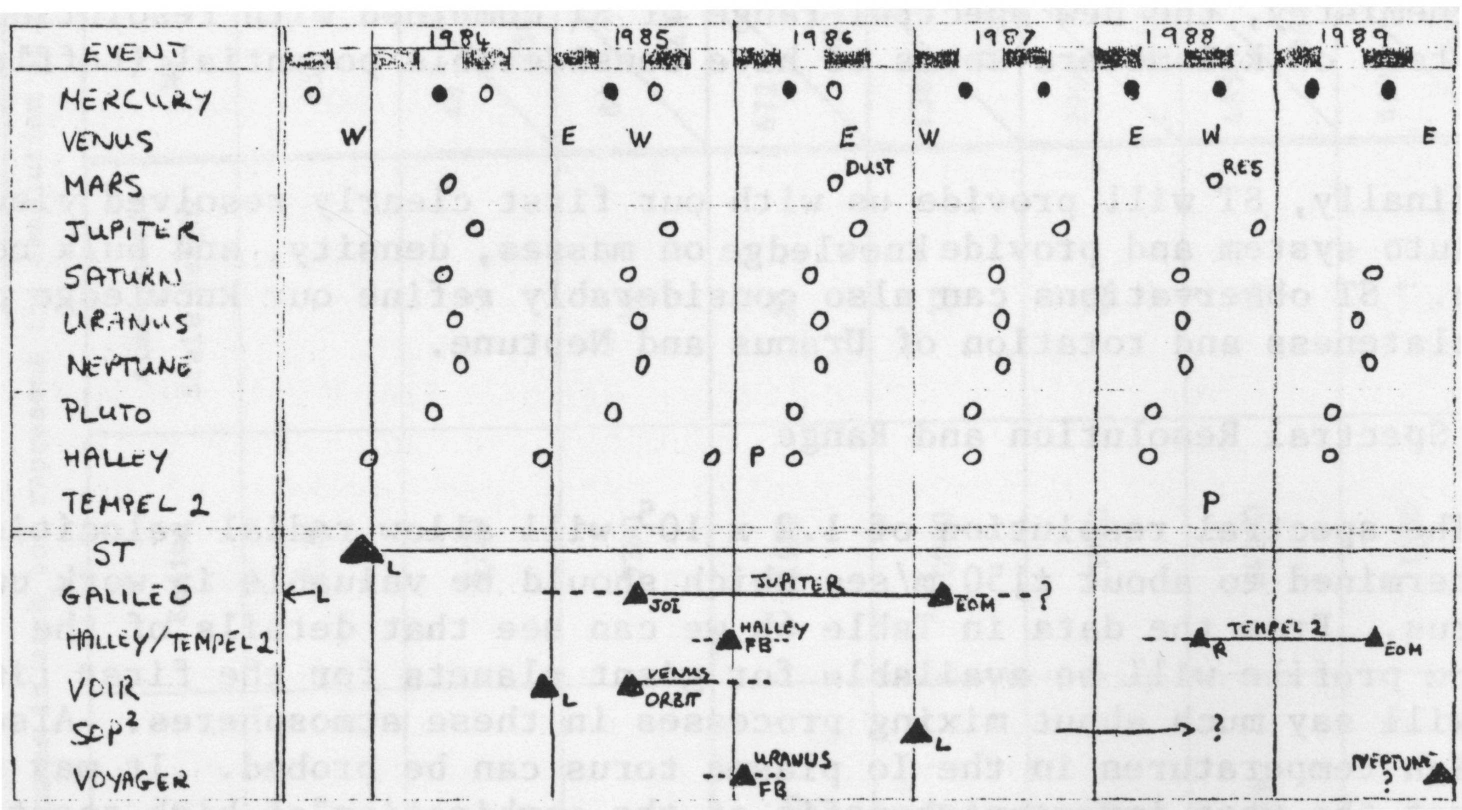

Fig. 1. Mercury: O denotes times when the hemisphere not seen by Mariner 10 is illuminated. Venus: E,W denote maximum elongation East/West. Mars: Dust refers to preperihelion opposition, RES refers to opposition with best surface resolution. Jupiter and Other Planets: O denotes opposition. Halley and Tempel 2: P denotes perihelion passage.

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to be in 1986 when opposition occurs just prior to perihelion. The best spacial resolution on the surface of Mars within this time period will be in 1988.

1985/86 is clearly a very important period for planetary astronomy not only because of the Galileo and comet mission, but also because of a potential flyby of Uranus by Voyager 2.

2.5. Capabilities for Selected Problems

2.5.1. Atmospheric Dynamics. The understanding of motions in planetary atmospheres is of interest for at least two obvious reasons: (i) as Stone (1972) points out, the whole question of understanding the vertical structure and local energy balance in an atmosphere usually requires knowledge of the large scale circulation. He points out that a simple radiative-convective calculation for the earth's atmosphere would predict the lapse near the ground to be adiabatic (9.8°K km^{-1}), i.e. that the troposphere was unstable; in fact, this is not the case and energy transport due to large scale motions reduces the lapse rate to about two-thirds of this value, i.e. a static stability of $\sim$3.3°K km^{-1}. (ii) The second reason is more qualitative: We *observe* many long-lived, large scale phenomena, for which we are unable to give a convincing physical (or chemical) explanation. The great red spot on Jupiter is the obvious example.

To make headway in this field it is believed, on the basis of experience in fluid dynamics and meteorology, to be necessary to have measurements of dynamical phenomena over wide range of time and length scale. Figure 2 (provided by P. Gierasch) illustrates this for various fluid dynamical phenomena that might exist in planetary atmospheres. The subject is new and has had most development for the Martian troposphere and the Venus stratosphere. For Mars information on global scale drives for motions has been derived from thermal IR measurements made from Mariner 9 (Pirraglia and Conrath, 1974), and wind fields from surface markings and local sampling at the Viking lander sites. For Mars, theory and observation generally seem to agree. For Venus the information is from apparent motions of UV markings, sporadic information on the horizontal drift of descent probes, and a growing body of Doppler measurements made spectroscopically from the ground (Traub and Carleton, 1979). In this case there are many theories and a poor factual base.

For the outer planets, and Jupiter in particular, the basis of information so far has been imaging of apparent motions by tracing the motion of atmospheric markings at various latitudes. Unfortunately, as can be seen from examining Figure 2, there seems to be little hope for adequately pursuing the problem with ground-based telescopes - even if the weather allowed adequate time sampling. It is still too early to say what the spectacular Voyager sequences can tell us in physical terms except that our factual base will be enormously expanded by virtue of the extended observing time. What contributions can Space Telescope make to this growing field? From a reconnaissance point of view Uranus

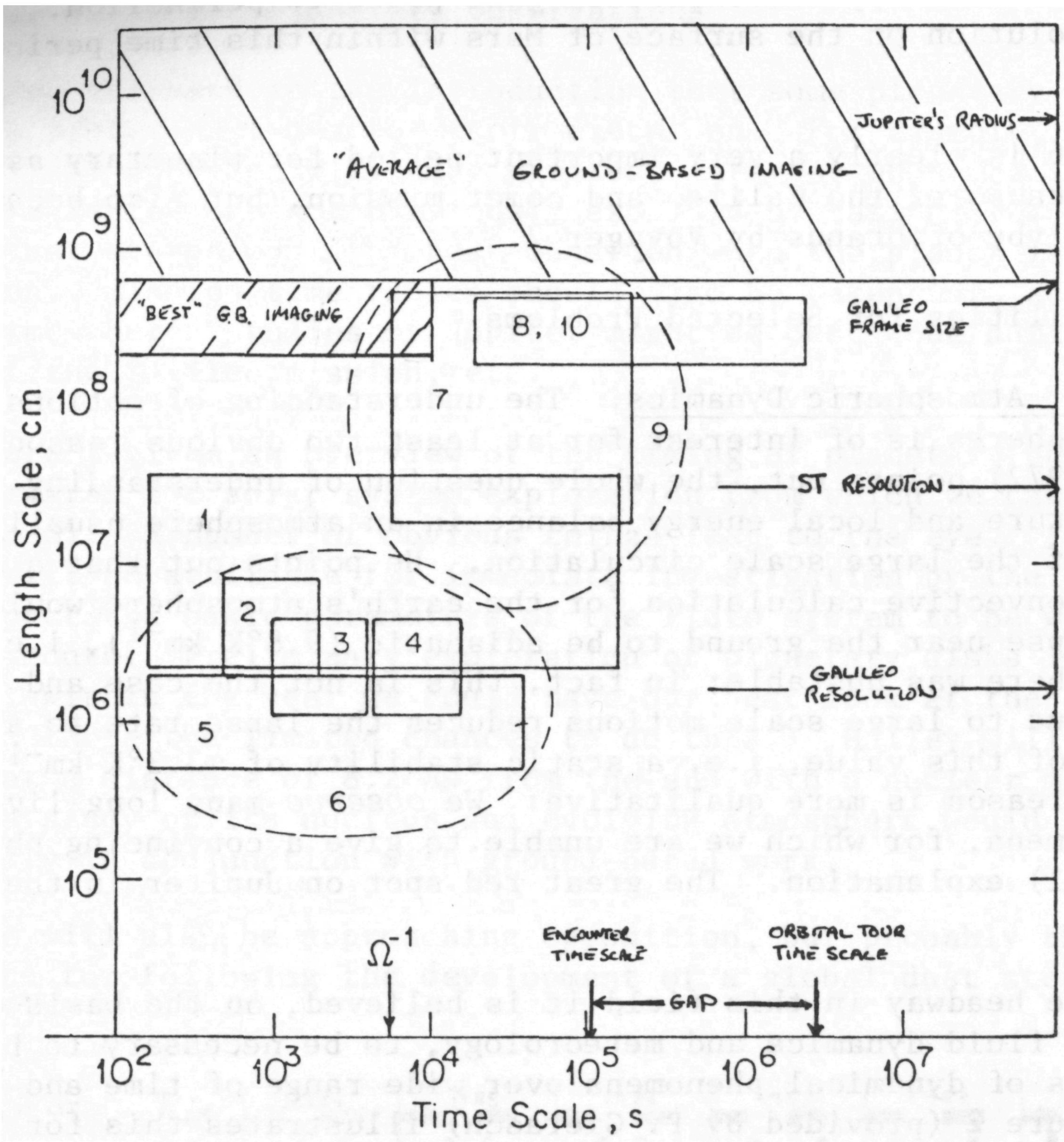

Fig. 2. Time and Spacial Scales Associated with Atmospheric Dynamics at Jupiter; based on a Diagram by P. J. Gierasch (1978). 1) Vertical shear measurement. 2) H_2O moist convection. 3) NH_3 moist convection. 4) Mixing-length convection. 5) Vertical shear instability. 6) Inertia-gravity waves. 7) Inertial-baroclinic instability. 9) Rossby planetary waves. 10) Horizontal shear measurement, spot flows.

and Neptune are natural objectives for the imaging cameras. We would like to know what kind of organization, if any, exists in their atmospheres. The imaging should be done in near IR CH_4 bands and in the far ultraviolet where there is a chance to see markings.

From a more detailed point of view we know from experience that if the available spacial resolution is in the range of 1-5 scale heights *and* the image format is big enough, then much can be said about global motions *provided the time sampling is dense enough or extended over a sufficient length of time.* For the planetary camera on ST, these conditions can be met for Mars, Venus, and almost for Jupiter, providing the time can be made available. My reservation about Jupiter is mar-

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ginal and disappears if the space telescope is utilized to tackle these problems in the same time frame of the Galileo mission (cf. Section 3).

In order to be more specific about particular observing programs that I would expect to be proposed for ST, I offer the following list:

- Origin and evolution of global dust storms on Mars.
- Individual Martian cloud dynamics.
- Nature of the bow-wave and circumequatorial jets in the Venus stratosphere.
- Nature of the Venus UV patterns (global UV imaging done in conjunction with Doppler measurements from the ground).
- Nature and stability of the equatorial jets on other high speed streams in the Jovian and Saturnian atmospheres.
- Interaction of classes of spots on Jupiter (further tests of the soliton hypothesis).
- Jovian equatorial plumes: Are they instabilities or evidence for waves?
- Development of the Jovian global circulation during the Galileo mission.
- etc.

2.5.2. Stratospheric and Upper Atmospheric Processes. The chemical and physical processes that occur in the upper atmospheres of the planets (and some satellites) are exceedingly complex and in many cases poorly understood. Aeronomical theories are very good at explaining what is observed but have a very poor record of predicting what might be observed (e.g. the non-prediction of the hot Jovian thermosphere (Atreya and Donahue, 1976); and the surprise at finding such a weakly developed ionosphere on Mars (McElroy, 1973).

Furthering our understanding is of interest since these phenomena have a bearing, not only on the course of our every day lives (for example, the stability of the O_3 layer in the earth's atmosphere), but on such atmospheric properties as overall chemical stability and evolution, large scale vertical mixing and interactions with the surrounding space environment.

The observations of these phenomena are, in general, exceedingly difficult to make and involve just about every conceivable observing technique including the use of earth-orbiting telescopes. Both OAO-2 and Copernicus have been used successfully (Hayes et al., 1972; Riegler, 1976) to probe the topside of the O_3 layer and Copernicus has been used to probe thermospheric H_2 and O_2 distributions (Atreya et al., 1976). IUE and Copernicus are also providing important results for other planetary atmospheres; e.g. the possible detection of a powerful source of Lyman α emission at the foot of Io's flux tube in the Jovian ionosphere (Atreya et al., 1977); and a convincing spectrum showing C_2H_2 in Saturn's stratosphere (Moos et al., 1979). The primary observational methods that concern us as far as Space Telescope seem to be the following:

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(i) direct detection through remote spectroscopy of upper atmospheric emissions,
(ii) observing the occultation of stars by a planet's (or satellite's) atmosphere.

We can best understand the utility of ST for exploring the details of planetary airglow through considerations of Figures 3a and 3b which show the best published spectra of Jupiter in the far UV (Giles et al., 1976; Anderson et al., 1969). Both of these are rocket spectra. In the region 1100 Å - 1500 Å the low albedo is dominated by strong CH_4 absorption near the $n(H_2) \sim 10^{15}$ cm^{-3} density level; longward of 1500 Å the low albedo is a result of Rayleigh scattering from H_2 over a presently unknown combination of absorption due to at leat C_2H_6, C_2H_2, NH_3, and photochemically produces aerosols. The two most prominent features in the spectrum are Lyman α and the NH_3 dip between 1700 - 2000 Å. The far UV spectrum also shows a measurable albedo between 1250 and 1520 Å for which Giles et al. make a convincing identification with the Lyman band of H_2, although at the resolution of 25 Å these are far from resolved. The only higher resolution spectra in this range are resolved spectra of Lyman α obtained by Atreya et al, 1977; and by Bertaux et al., 1979) with Copernicus. The Voyager UVS spectrometer clearly, but briefly, showed strong Lyman band emissions in the polar regions of the planet and was able to get spacial information across the disc in Lyman α but only at low spectra resolution (∿ 10 Å). The Galileo spectrometer will cover this entire spectral region with good spacial resolution and high sensitivity but again with low spectral resolution. Both Copernicus and IUE have moderate spacial resolution and high spectral resolution capability but generally lack the sensitivity to adequately make use of it on planets.

ST provides what is missing and what is required to complement the work already done and also the investigations to be done by Galileo: high spectral resolution combined with good spacial resolution and adequate sensitivity. Perhaps even more importantly ST allows us to pursue these problems deeper into the solar system - to Saturn, Uranus, and Neptune.

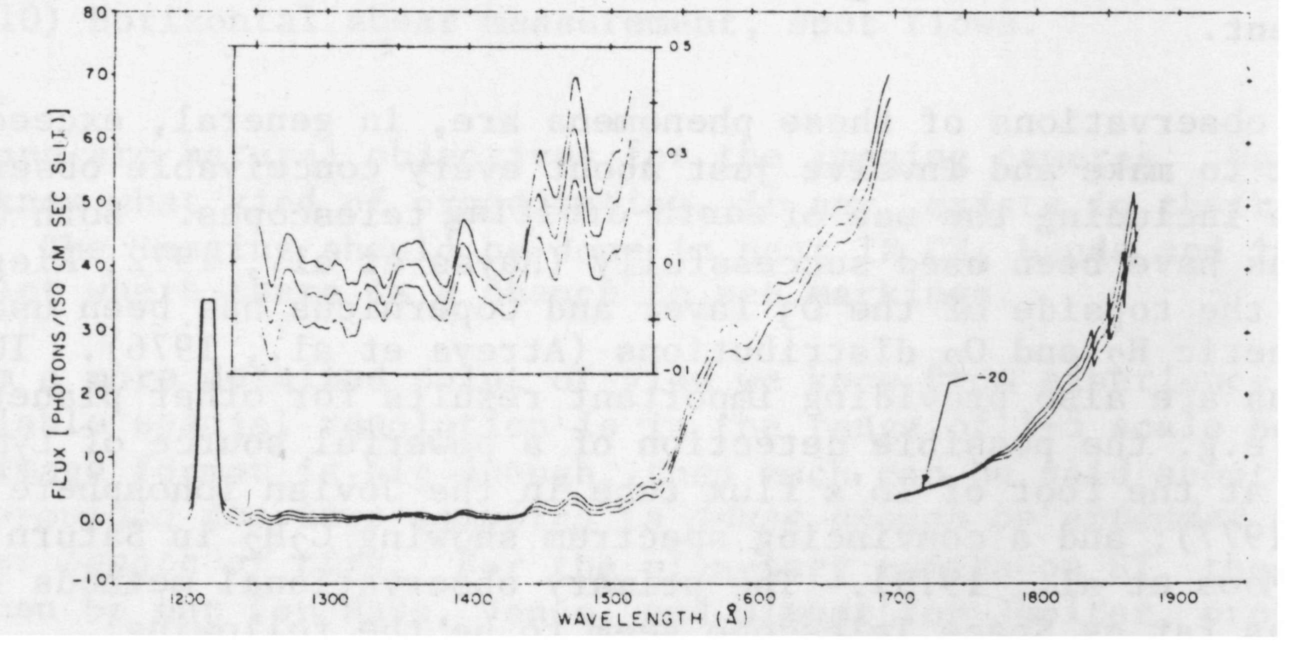

Fig. 3a. Jupiter Ultraviolet Spectrum (Giles et al., 1976)

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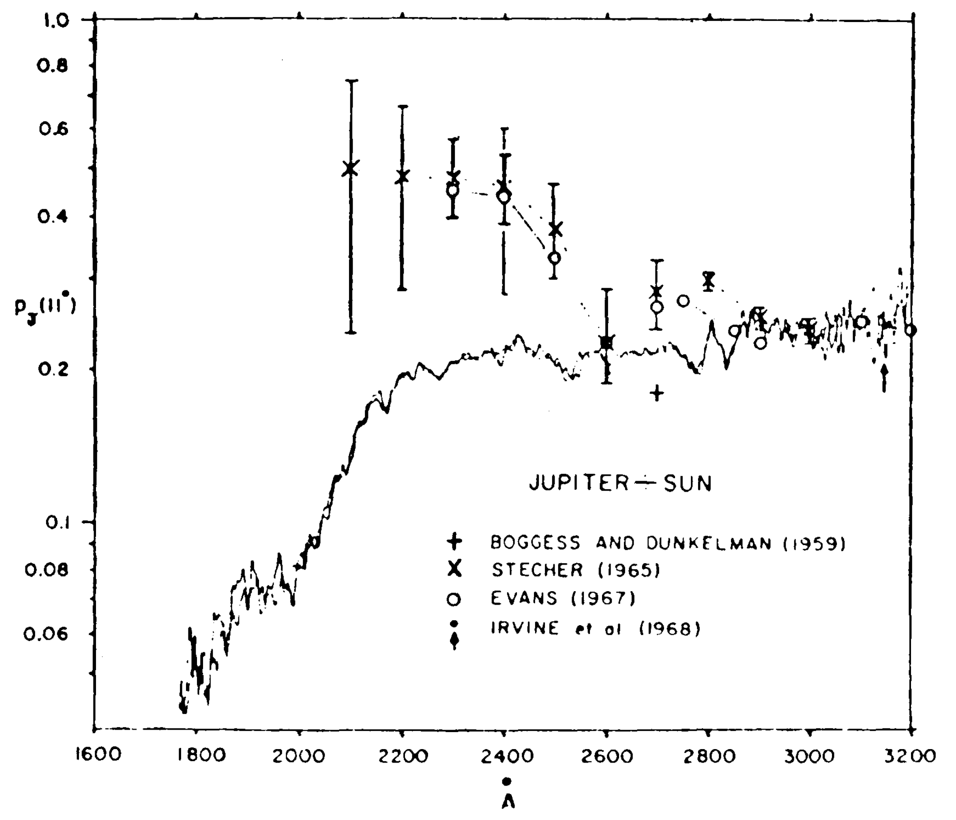

Fig. 3b. Jupiter Ultraviolet Spectrum (Anderson et al., 1969)

Let me outline some of the more obvious problems I expect ST to address in this field:

(a) Examination of the profile of Lyman α and its spacial dependence across Jupiter and Saturn. The current explanation of Jupiter Lyman α intensities (Wallace and Hunten, 1973) limits scattering to the column of H above the homopause. This is because the more massive CH_4 molecules which are the primary sink for solar photons at this wavelength, diffusively separates out at this level in the atmosphere. The theory shows that the Ly α albedo, the shape of the line, and its distribution over the disk is therefore governed by the extent of dynamical mixing processes in the lower atmosphere; i.e. the eddy diffusion coefficient, which in turn governs the chemical equilibrium of the upper stratosphere (Strobel, 1975). To date, the sporadic measurements of the Lyman α albedo have all given very different results ranging from 1-20 kR and provide little confirmation of theory and generate considerable confusion. ST has the capability to attack these problems in detail.

(b) Examination of the albedo and profile of Lyman α and the distribution of lines in the Lyman bands of H_2 in Jupiter's *auroral* regions and the foot of Io's flux should give new knowledge on the location and nature of the excitation processes involved. Auroral Ly α may reach ∿ 100 kR (Shemansky, private communication) and should present little problem to ST. The Lyman bands should have individual lines whose intensities reach ∿ 100 R which are also within reach of ST. Auroral activity associated with H should also be looked for on Saturn, Uranus, and Neptune since the results of Brown (1975) indicate that all of these planets may have magnetospheres.

(c) Unknown emissions. The probable fact that the atmosphere of each of the major planets sits in an active magnetosphere, plus the

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possibility, at least in Jupiter's case, that metallic atoms are entering the atmosphere from the outside, suggest that there may be many unknown features to their airglow spectra. ST should be involved in a reconnaissance for such emissions to the limit of its sensitivity.

Observations of the occultation of stars by planetary atmospheres from ST also have much to commend them. This technique, which has produced many significant results, is limited by (a) the rarity of events with bright enough stars, (b) atmospheric seeing, and (c) the speed of the occultation event. The combination of pointing stability, small effective aperture (to discriminate against background light from the occulting object), and the sensitivity of the HSP over a wide spectral range would make it the best available instrument for future planetary occultation studies. Further gains might accrue from making occultation studies. Further gains might accrue from making occultation measurements in the UV, and also by using the spacecraft motion to slow the occultation event down. Elliott (private communication) estimates that as a result of the potential improvement in data quality, the frequency of useful occultations by the outer planets could increase by a factor of 5 to 20 for ST over ground-based. Currently, for example, Neptune offers a single worthwhile opportunity every 5-10 years while from ST Elliott expects this to rise to 1-2 occultations per year.

One of the primary objectives of these experiments should be to acquire enough independent occultations events (hopefully in cooperation with ground-based observers) to settle the question of the origin of occultation 'flashes.' At present it seems impossible to reasonably decide whether these are the result of incoherent turbulence in the stratosphere (Young, 1976; Jokipii and Hubbard, 1977) or due to large amplitude wave propagation (French and Gierasch, 1974) or to stable layers. A lot is at stake here for the most widely entertained explanation for the 1000° K Jovian thermosphere is the wave phenomenon (Atreya and Donahue, 1976).

Finally, it has been pointed out to me by S. Atreya that the pointing stability of the ST combined with its ability to obtain high spectral resolution in the UV over reasonable spectral bandwidth make it a very important instrument for probing the abundance and distribution of minor constituents in the upper stratosphere, particularly during the night. He finds that it should be possible to sound many constituents important to the chemistry of the O_3 layer; he notes that ClO, NO HNO_3, NO_2, CCl_4, and O_3 itself should all be observable from ST if the programmatic complexities of performing stellar occultations can be overcome.

2.5.3. Circumplanetary Nebulae. The phenomenon which I call circumplanetary nebulae was first recognized when McDonough and Brice (1973) pointed out that hydrogen atoms escaping from Titan's upper atmosphere would not be able to escape the gravitation attraction of Saturn and would probably form a 'hydrogen torus' encircling the planet. They suggested that such hydrogen tori might be commonplace in the outer solar

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system and called for a Lyman α search for them. In the same year Brown (1974) discovered the neutral sodium cloud (a partial torus) emanating from Io, Blamont (1974) calculated that Saturn's rings should retain a measurable OH/H atmosphere, and finally in December of the same year, Pioneer 10 arrived at Jupiter to discover a neutral hydrogen torus associated with Io (Carlson and Judge, 1974).

Since that time Weiser, Vitz and Moos (1977) may have discovered, using a rocket borne spectrometer, the hydrogen atmosphere associated with Saturn's ring (200 R); Wu, Judge and Carlson (1978) may have found clouds of O and H associated with Europa, and finally, a host of neutral and ionized atoms (K, SII, SIII, OII, OIII) have been found by ground-based, earth-orbital, and Voyager observations in the vicinity of Io with the ionized component in a torus locked to Jupiter's magnetic equator. The subject is an excellent example of the primary theme of this article, which is the synergism of observations made from the ground, earth-orbit, and deep space.

The physical mechanisms that govern the Io related plasma and neutral tori are far from clear: Source mechanisms that have been suggested include sporadic eruptive ejection from Io volcanos, sputtering from the surface, and thermal escape from a tenuous atmosphere. Loss and excitation of observable species appears to be due to electron collisions, charge transfer, and to diffusion out of the region of the torus.

The stability of the system is also in question. The sodium cloud appears to be relatively stable; while the neutral hydrogen cloud seen by Pioneer had disappeared at the Voyager encounter. The hot ($\sim 10^5$K) sulphur and oxygen plasma torus found by Voyager on the other hand, was not present when Pioneer flew by. There are now indications of major changes between Voyager 1 and Voyager 2. There is evidence in both the ground-based data and Voyager data that strong compositional and temperature gradients occur in the region. A strong acceleration mechanism is also apparently at work for O, Na, and S nuclei with energies in excess of 7 Mev have been found in the immediate vicinity of Io (Vogt et al., 1979). Neutral sodium (a small fraction of the total) has been seen flowing out from Io at velocities up to 18 km sec^{-1} as the satellite passes through Jupiter's magnetic equator (Trafton, 1975).

The capabilities of ST for pursuing these problems is substantial. In the 'discovery' mode the evolutionary behavior and temperature of the now missing, neutral hydrogen torus at Jupiter is a natural objective. For example, is it possible that the hydrogen and plasma tori are mutually exclusive, the latter being sporadic and dependent on intermittent volcanic activity? The brightness of the H torus during the Pioneer flyby was $\sim$ 300 R and is within easy reach of the HRS in the 2 x 10^4 resolution mode. Similarly a search for emission (H and OH) originating from Europa may be possible to a few tens of Rayleighs given enough observing time. This emission might also be sporadic and related to upwelling of slush through Europa's cracked crust. At Saturn it is unclear what will be important for much will depend on the results from the Pioneer 10 and subsequent spacecraft; however, if Blamont's estimate of 100-500 R for the Titan torus is roughly correct, then it should be within easy reach of ST as should the ring atmosphere. A look at Neptune might also be worthwhile; extrapolating Blamont's Titan estimate to the distance of Triton we might be surprised to find as much as 50 R of Ly α. This would have implications for Triton's atmosphere and for the environment within which it orbits Neptune. Finally Uranus is so peculiar in so many unexpected ways, we had better have a look there also!

In a more detailed mode an examination of the plasma torus is an obvious objective. ST can contribute knowledge regarding its composition, stability, the sources that feed it, and its interaction with Jupiter (if any). The ST may also find signs of D, Ca, C, Si, N, Mg, S, O as well as emissions in the torus due to SIII (1194, 1201), SII (1256). Shemansky (1979) predicts 60 and 43 R for these latter emissions. This work could again be done in conjunction with observations of Na, K, SII, OII, SIII from the ground and should reveal detailed information regarding the source mechanisms at work, temperatures, and compositional homogeneity as the nebula evolves. The high spectral resolution capability should allow secure identification of emitting species to be made.

The special spacial resolution capabilities of the ST spectrometer, when used to probe neutral species very close to the satellite, may also be able to distinguish in a definite way just where on the satellite the source locations are located. The interpretive study of Murcray and Goody's (1978) sodium cloud pictures by Smyth and McElroy (1978) seem to indicate that examining D line intensity contours perhaps as close as $\sim$ 2 arc sec from the satellite would give secure knowledge of the location of source on its surface. Finally, another obvious problem is to characterize the emission at the foot of Io's flux tube and its relation to torus activity and to radio bursts.

3. THE GALILEO IMAGING PROBLEM: AN EXAMPLE OF THE USE OF THE SPACE TELESCOPE IN CONJUNCTION WITH A DEEP SPACE MISSION.

The Galileo spacecraft will drop a probe into the Jovian atmosphere in June 1985 and then will itself be injected into orbit around the planet. The orbiter will operate for 20 months negotiating some 11 encounters with the Galilean satellites. One of the main objectives of the mission is to investigate the chemical composition and physical state of Jupiter's atmosphere. It is in attaining this objective that an extended sequence of observations from ST, particularly with the planetary camera, would be of tremendous value.

3.1 What Galileo Can Do and Some of Its Limitations

The Galileo spacecraft is of the dual-spinner type; it is also an exceedingly massive spacecraft. As a result of the latter factor and also because of the finite booster power of the shuttle/IUS combination, the spacecraft must arrive at Jupiter on a trajectory that approaches the

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planet at a high phase angle (∿ 120°); also the initial orbit is characterized by long looping orbits extending to the night side. The situation is illustrated in Figure 4.

Because of the long nightside orbits only a small fraction of time (20-30%) will be available for viewing the lighted hemisphere; also, on approach to the planet (or receding from it), the imaging, and other remote sensing instruments on the stabilized part of the spacecraft, must look past the spinning section which is characterized by several extremely long booms. The remote sensing instruments are therefore in a 'shoot-through-the-booms' mode for a substantial period - including the entire initial approach trajectory! The three booms rotate at 3.3 rpm and periodically obstruct the view. The problems of approach and recessional imagery are made worse by a recent Voygaer finding that at phase angle of 120 degrees and greater, planetary features loose much of their contrast. The final component of this problem is that because of severe weight limitations the imaging system on this spacecraft is limited to a single camera, and for reasons that are not germane to this discussion, the camera has a very high resolution capability and, consequently, a small FOV (∿ 8 mr square). The result is that when the camera *can* see Jupiter adequately, the images are usually limited to very small areas of the planet.

The Galileo imaging system is superlative in its capability to deal with surfaces of the satellites, and detailed studies of special features in Jupiter's atmosphere. However, as a result of the above problem, it

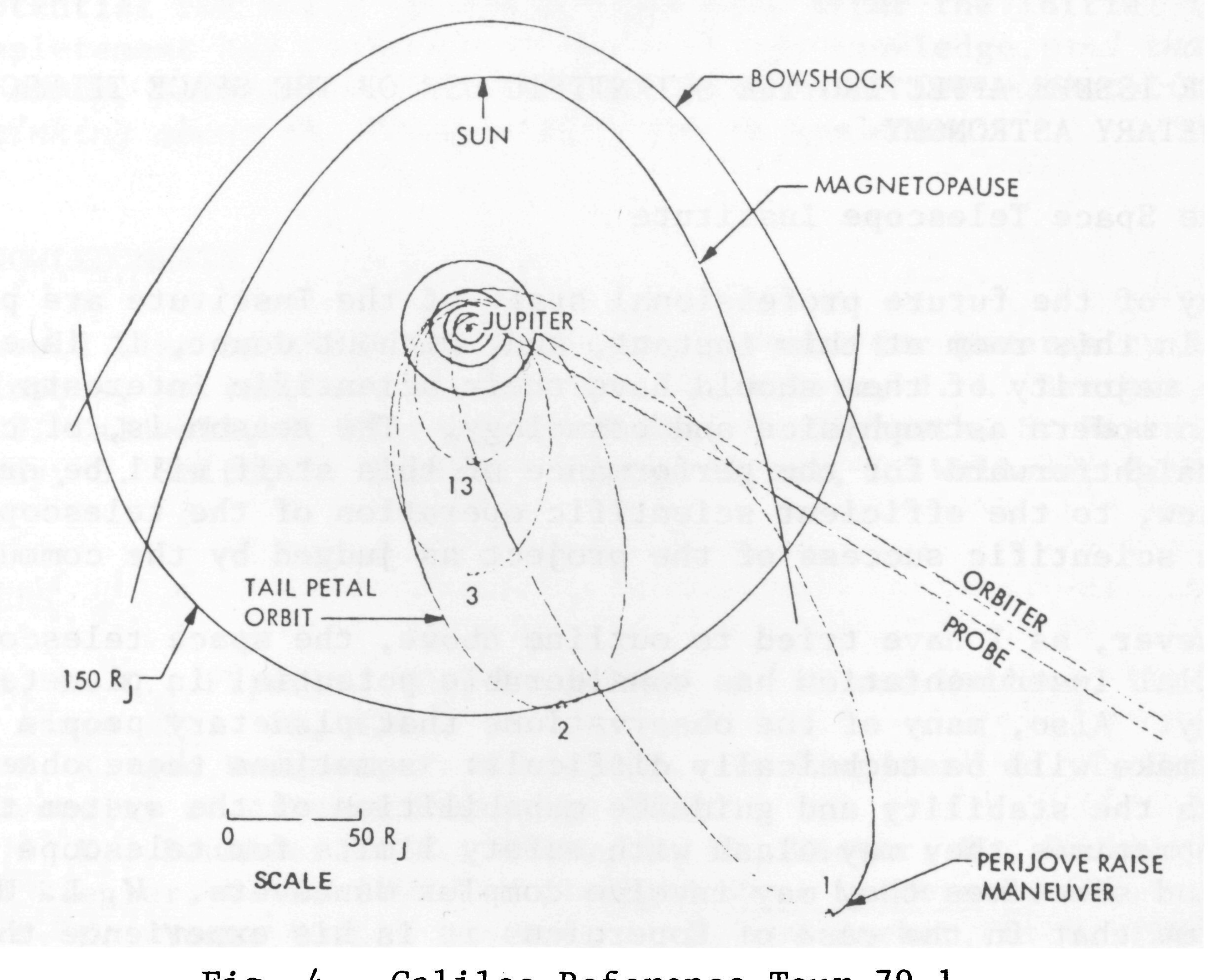

Fig. 4. Galileo Reference Tour 79-1

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lacks the ability to obtain high quality information on the global state of Jupiter's atmosphere *on a continuing basis*. As a result, it will not be possible for Galileo to adequately inform itself on the general state of Jupiter's atmosphere during the initial approach, or during probe entry, or of its subsequent changes. It will not be possible, at least in any simple way, to accurately target on particular atmospheric phenomena that we wish to examine in detail during each perijove pass. Finally, it will be difficult to properly characterize the global context of the probe descent region.

3.2 The Role of the Space Telescope in the Galileo Mission

The role of ST in Galileo as far as the problems I have posed above are concerned is to provide continuing global coverage of the state of Jupiter's atmosphere over the duration of the Galileo mission. The ideal observing program would call for about two image every 1/4 rotation ($\sim$ 2 1/2 hours) throughout the approach to the end of the mission, i.e. $\sim$ 650 days! This is roughly 12,000 images. This can be compared with the roughly 50,000 images that will be taken from Galileo itself. Such an observing effort is what the Galileo imaging team would like to get. Some compromise is presumably inevitable. The scientific value of this coverage would not only be to substantially enhance our understanding of dynamical processes that are occurring in Jupiter's atmosphere, but allow us to extend out detailed knowledge of the probe descent region to a global context. It would increase our confidence in the relevance of much of the probe data to the discussion of Jupiter's atmosphere as a whole.

4. OTHER ISSUES AFFECTING THE SCIENTIFIC USE OF THE SPACE TELESCOPE IN PLANETARY ASTRONOMY

4.1. The Space Telescope Institute

Many of the future professional staff of the Institute are probably sitting in this room at this instant, and, without doubt, it is essential that the majority of them should have their scientific interests firmly rooted in modern astrophysics and cosmology. The reason is, of course, very straightforward for the performance of this staff will be crucial, in my view, to the efficient scientific operation of the telescope and ultimate scientific success of the project as judged by the community.

However, as I have tried to outline above, the space telescope and its initial instrumentation has considerable potential in planetary astronomy. Also, many of the observations that planetary people will want to make will be technically difficult: sometimes these observations will push the stability and guidance capabilities of the system to their limit, sometimes they may clash with safety limits for telescope operations, and sometimes they may involve complex maneuvers. W. L. Upson II informs me that in the case of Copernicus it is his experience that observations of solar system objects are by far the most demanding to plan and execute.

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In addition considerable thought and advice will have to be given on the scheduling problem so that the maximum benefit of cooperative observations with orbital, rendezvous and flyby spacecraft can be obtained.

It seems to me, and I speak both to any potential institute director that might be sitting here as well as the larger community of planetary astronomers, that as a result of these complications, it seems to me to be essential that some of the professional staff of the forthcoming institute should be planetary astronomers if the best scientific use of the ST for solar system problems is to be achieved.

4.2. Refurbishment

The initial instrumental capabilities on ST are extremely powerful and will certainly provide a major leap in our knowledge of solar system objects. However, there are some obvious problem areas that the telescope system will not at first, be able to address; for example, high spacial resolution imaging capability of the telescope could be put to excellent use in the visible and near infrared if it could be coupled with directly high spectral resolution. Center-to-limb observations in the H_2 quadrupole lines on the outer planets for probing the vertical structure and location of cloud layers in their atmospheres is an example which cannot be done with the present complement of instruments and for which instruments are currently being developed on the ground.

I bring this topic up because I believe the ST will continue to have great potential for solar system studies well after the initial instrument completement has yielded its share of new knowledge, *and that it is not too early, particularly in the case of complex instrumentation to start thinking about the first refurbishment cycle now.*

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DISCUSSION

Smith (Discussion leader): ST can provide crucial knowledge of the Uranus and Neptune systems which will assist Voyager Project in making a 1985 decision of whether or not to send Voyager 2 past Uranus at the appropriate point in space to carry it onward to Neptune. Since a trajectory through the aiming point could compromise the scientific yield at Uranus, such a decision should be made with the greatest possible understanding of both planetary systems.

There can be little doubt that complex organic chemistry, similar to that which occurred on Earth prior to the formation of life, is still going on in the atmospheres of the giant planets. Production and destruction rates are not known, but complex organic molecules are likely to be locally concentrated. Many of these prebiotic molecules have diagnostic or quasi-diagnostic absorptions in the spectral range 2300-2700 Å. High dispersion, high resolution spectroscopy of selected regions on Jupiter and perhaps Saturn should be included in the observing program.

Many studies of interest to planetary scientists can be accomplished with a single or a few observations. Others, relating to time-dependent phenomena, may require extensive observing programs which will have to be judged in competition with other scientific objectives.

Time-lapse sequences of global circulation of Jupiter's atmosphere obtained by Voyager have spatial resolutions from 5 to 3 times poorer than those attainable by ST. The Voyager observations cover only two brief epochs in Jupiter's changing "weather" patterns. A much more detailed and temporally complete study could be accomplished by ST.

Caldwell: I have two comments to make on the subject of planetary astronomy with Space Telescope. They concern priorities for planetary study, and practical considerations for making such observations.

First, it is apparent that planetary science by itself could oversubscribe the available time on ST. Furthermore, this saturation would include uniformly good science. Therefore, there seems to be no viable alternative to the painful necessity for the planetary community to discipline itself and make priority judgements about the various programs. I therefore propose a criterion for rating ST Solar System research.

Currently, the quality of knowledge about the planets is excessively heterogeneous, with some planets known in intimate detail (Venus, Mars, Jupiter) and some are only poorly known (Mercury, Neptune, Pluto). Moreover, those planets that are well known are such because of their location, not their intrinsic interest. In fact, no one knows which planets are most interesting.

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The basic aim of our research is to provide an understanding of the origin and evolution of the Solar System. It seems to me that a necessary basis for this work is to establish data of more nearly uniform quality about the extremes of the system. To some extent, any comprehensive theory must be limited by the least precise data in it.

My suggestion, therefore, is to weight planetary proposals somewhat according to the current ignorance of the target. This would not imply any quota or ceiling on the absolute number of successful planetary proposals. It should not absolutely exclude programs of extraordinary merit (Galileo support, for example) for any planet. But it would discourage people from doing just "more of the same". And if the remote objects should unexpectedly prove to be relatively uninteresting, the policy could quickly be changed.

My second point is that planets have their own peculiar observing problems. Venus, for example, never gets more than about 47 degrees from the Sun. To observe this planet, one must slew the ST a large distance to a pointing that is more favorable with respect to thermal and power considerations on every orbit. Thus the brightness of the planet is more than counteracted by the excessive slewing time in the total accounting for time.

Recently, the ST project considered an engineering exercise in which Venus was hypothetically imaged once per day for cloud dynamics studies. However, because of the limited fraction of the disk observable, and the speeds of the features, such a sampling would produce no overlapping of images, and would be useless for their stated purpose. It would be necessary to increase the sampling rate by a factor of two or more to make the scheme viable.

We must therefore address the hard question of whether such a project, meritorious though it may be, is worth the cost in time. If it requires one hundred hours of slewing to achieve one hour of cumulative exposure, it is just as costly as one that requires one hour of slewing for one hundred hours of exposure.

Atreya: I have two comments on Mike Beltons' presentation: first, I would like to emphasize the importance of planetary line shape measurements. A good example is Jovian Lyman-α. So far, there are only three spectral doppler line profile measurements of this emission, all on Copernicus. Mike has already discussed how the significant atmospheric parameter, the eddy diffusion coefficient, may be determined from Jovian Lyman-α. Actually, one needs only the total intensity for doing that. The line profile however can provide the temperature of the upper atmosphere. The only two temperature measurements are: Pioneer epoch at the solar minimum, and Voyager at the solar maximum. The upper atmospheric temperature has increased dramatically by more than

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60% during this period. It is extremely important that the Jovian Lyman-α spectral profiles be monitored continuously to understand the physical processes leading to the heating of the exosphere of Jupiter. It has become apparent that Jupiter sustains a corona. What remains to be known is how this energy is supplied to its upper atmosphere, what causes its temporal variation, and whether or not the variation is sporadic. The ST is perfectly suited for accomplishing this task. The above arguments are equally applicable to the emission lines of the Io plasma torus.

Secondly, ST is the most powerful instrument yet to come along for detecting trace pollutants in the earth's stratosphere. The technique used will be similar to the limb "grazing" stellar occultation demonstrated to be highly successful on Copernicus. Although atmospheric refraction, instrumental scattering and guidance problems limited the Copernicus observations down to about 44 km (about one scale height below the stratopause) it is precisely the region between 50 and 100 km which is in need of most help. This is due to the fact that the influence of trace pollutants on the atmosphere, particularly ozone, is predicted by theoretical models applied to the stratosphere ($z < 50$ km). In order to have confidence in these models, they must be capable of successfully predicting the distribution, diurnal, temporal and latitudinal variations of the "natural or unperturbed" atmosphere between 50 and 100 km. This region is not accessible by conventional techniques such as balloons, rockets or other earth orbiting vehicles. The ST with its excellent stability, guidance capability and sensitivity is ideally suited to carrying out stellar occultation exercises to determine parts per billion (even tenths of ppb) pollutants in the height range greater than 40 km.

Moos: The combination of spatial and spectral resolution can provide significant information about the interaction of the magnetosphere and the atmosphere of a planet, and hence about the nature of the plasma trapped in the magnetic field. On Jupiter, for example, ultraviolet emissions are expected where magnetic field lines from the magnetotail, the Ioian torus and Io itself enter the atmosphere. Since the field lines from each of these sources enter the atmosphere at different latitudes and longitudes, each source will have a different spatial signature. At present, we do not know how these sources change with solar activity and with planetary parameters. Using the IUE instrument with a resolution of ∿ 6 arcsec it is possible to observe the auroral zones on Jupiter. With much improved spatial resolution, it will be possible not only to differentiate between the plasma sources but to discover unsuspected kinds of magnetospheric plasma sources.

Belton: While on the subject of plasma tori and magnetospheres, it should be noted that both Saturn and Uranus have been detected as radio emitters indicating they probably have magnetospheres similar to Jupiter. Magnetospheric studies and related observations should not be restricted to Jupiter.

Pilcher: You have just heard a number of reasons for studying the Jovian magnetosphere. I'd like to point out another, perhaps broader, reason. The Jovian magnetosphere contains a unique example of an astrophysical plasma that we can study both by means of conventional astronomical techniques and by means of *in situ* observations. This capability of sending spacecraft to a plasma that emits several of the lines that have been observed for decades in the study of planetary nebulae and other astrophysical plasmas may afford us an unparalleled opportunity to further our understanding of the relationship between the plasma conditions in these distant astronomical objects and the radiation they emit.

I can best illustrate the capabilities of the Space Telescope for studies of the Jovian magnetospheric plasma by showing you the results of some recent ground-based observations. These data are images of the Jovian sulfur ring in the λ 6731 Å forbidden line of S II. This transition from a meta-stable level, being excited predominantly by electron collisions, is diagnostic of the characteristics of the ambient thermal plasma as well as those of the sulfur plasma itself. The spatial structure and temporal variability in these data, acquired on two successive nights in April 1979, make it clear that the Space Telescope can be used to great advantage in the study of this system. I propose that at least three ST instruments may be used extremely profitably for these observations.

1. Wide Field Camera - Images of the circum-Jovian ring of heavy ion plasma may be obtained in a variety of lines of sulfur, oxygen, sodium, potassium, etc. in a variety of ionization states (e.g., SI-IV, OI-IV). These images may be used to deduce the nature of the source of the heavy ion plasma as well as some aspects of the plasma characteristics.

2. Faint Object Camera Spectrographic Mode - The high degree of spatial structure (see, for instance, the "fan" observed in the sulfur ring) combined with the diagnostic nature of line ratios (these may be used to determine n_e, T_e) makes this a powerful technique for examining the small-scale spatial non-uniformities in the plasma.

3. High Resolution Spectrograph - This instrument will allow us to measure precise emission wavelengths and line shapes, providing unique information on the plasma dynamics.

Elliot: I would like to describe briefly the study of planetary upper atmospheres using the technique of stellar occultations and describe the new results that we would hope to obtain with the Space Telescope. The main reason for using the Space Telescope for occultations is that a much higher signal-to-noise ratio can be achieved for most events, due to the rejection of background light from the occulting planet that is possible with a small focal plane aperture, and the absence of

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scintillation noise from the earth's atmosphere. For example, only about six stellar occultations appropriate for the study of planetary atmospheres, have been observed in the last twenty-five years. With the high speed photometer on the ST, we expect the capability to increase to a few per year per planet.

From a stellar occultation we obtain a variety of information about the occulting planet and its ring system, if it has one. From the occultation by ring material we learn the detailed optical depth structure of the rings and their precise relative positions - the positional accuracy is about 10^{-4} arc-seconds at the distance of Uranus, for example. From the occultation by the planet itself, we obtain the temperature, pressure and number density profiles of its upper atmosphere at the 10^{-2} millibar pressure level. The only other method to obtain the structure of the atmosphere at this level is by spacecraft probes that directly enter the atmosphere. For planets beyond Jupiter, no missions involving entry probes are currently funded.

Several questions come to mind, which we could hope to answer with occultation observations with the ST: Do Triton and Pluto have atmospheres? What are the temperatures and dynamical properties of the upper atmospheres of Saturn and Titan? Why is the upper atmosphere of Uranus about 40 K cooler than that of Neptune, and what are the origins of the "wavelike" temperature variations observed in the occultation profiles obtained for these planets? Further information on this topic can be obtained from my review article in this year's issue of the Annual Reviews of Astronomy and Astrophysics.