(NASA-CR-140436) OUTER PLANETS GRAND TOUR ULTRAVIOLET SPECTROSCOPY EXPERIMENT Final Report (Pittsburgh Univ.) 27 p HC $4.50 CSCL 22A

N74-34295

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G3/30 50416

FINAL REPORT

to

National Aeronautics and Space Administration

NASA Grant NGR 39-011-134

Outer Planets Grand Tour
Ultraviolet Spectroscopy Experiment

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30 September 1974

1. Team Organization and Membership

The Ultra-Violet Spectroscopy Team for the mission definition phase of the Outer Planets Mission consisted of the following scientists:

T.M. Donahue, University of Pittsburgh, Team Leader

M.J.S. Belton, Kitt Peak National Observatory

A.L. Broadfoot, Kitt Peak National Observatory

A. Dalgarno, Harvard University

R.M. Goody, Harvard University

J.C. McConnell, Harvard University

M.B. McElroy, Harvard University

H.W. Moos, The Johns Hopkins University

T.M. Donahue served as team leader and also as member of the Science Steering Group for the mission.

M.J.S. Belton was responsible for studies of orbit trade-offs, observing sequence trade-offs and experimental pointing-scan platform characteristics. Because of his duties as leader of the NASA formed imaging team he participated fully only in the early phases of the UVS team's activities.

A.L. Broadfoot and H.W. Moos were responsible for spectrometer design and engineering.

A. Dalgarno, R.M. Goody, M.B. McElroy and J.C. McConnell identified spectral emission and absorption features to be studied, generated profiles of these features for assumed spacecraft trajectories and model atmospheres and studied the implications of the proposed observations for the atmospheric sciences of the planets.

2. Team Activities

The first team meeting was held January 4, 1971 at the Center for Earth and Planetary Physics, Harvard University. Present were all members except Professor Moos who had not yet joined the group. It was decided:

1) The principal objective of the UV observations should be to measure the composition of the atmospheres of the outer planets. Emphasis was to be placed on hydrogen and helium, presumably the most abundant species in the atmospheres. A guiding principal was that every effort was to be made to provide a means of relating density profiles obtained in the upper atmosphere to the mixed region of the atmosphere.

2) Airglow observations of H Lα and HeI 584Å radiation off the bright limb would be useful at Jupiter and Saturn in giving H and He upper atmosphere densities. Beyond Saturn only Lyman α would produce observable airglow emission rates.

3) The upper atmosphere airglow observations might be supplemented by observation of H_2 fluorescence lines excited by solar lines in accidental resonance according to Dalgarno. Some of these solar lines (e.g. Lyman β)

penetrate deeply into the atmosphere and excite H_2 lines at low altitudes. It might be possible to track H_2 by observing these lines down to the neighborhood of the turbopause.

4) Observation of the sun in the UV as it is occulted by the planet would be a useful tool to determine H, He, H_2 and perhaps other species in the atmospheres of all the planets. This would be the only method possible, beyond Saturn because of the weakness of the airglow except for HLα at Uranus and beyond.

5) During the cruise phase scans of the celestial sphere would permit mapping the distribution of interplanetary H and He. In particular the distribution of interstellar hydrogen near the earth could be mapped.

6) The preferred instrument for both airglow and occultation would be an objective grating spectrometer with an array of channel multiplier detectors in the focal plane. During close encounter the instrument would act as a multi-wavelength monochromator. The grating would be fixed and detectors set to observe, say 1216Å, 584Å, 1607Å (the Lyman H_2 fluorescence), at either side of 504Å, 805Å and 918Å, the absorption edges for He, H_2 and H and at other wavelengths set to map minor constituents like methane through the turbopause. The instrument would be similar to that being prepared for Mariner 73.

7) Attention should be given to combining both instruments in one, looking directly at the atmosphere off the bright limb but pointed toward a reflecting sphere during occultation.

8) During approach and far encounter the grating could be rotated through a small angle to provide spectral mapping. This is a desirable exercise in an exploratory "fly by" mission and the proper job for a spectrometer.

9) Channeltron lifetime and radiation damage was identified as a major item of concern.

10) T.M. Donahue was elected Team Leader.

The second team meeting was held at the Huntington-Sheraton Hotel in Pasadena, California on May 10 and 11, 1971.

All members were present with the exception of R.M. Goody and M.J.S. Belton.

1) A.L. Broadfoot was designated deputy team leader.

2) It was agreed that major emphasis must be placed on finding a method of locating the turbopause. Most promising appeared to be use of absorption features of methane during occultation. McElroy agreed to explore the possibilities

and reported that results obtained to date seemed to be very promising.

3) Moos proposed to determine experimentally the emission features excited in CH_4 and NH_3 by X rays and XUV.

4) Dalgarno agreed to examine excitation of airglow features by photoelectrons and to determine the penetration of solar radiation exciting the H_2 fluorescence spectra.

5) McElroy and McConnell were to undertake to produce occultation profiles (with help from Donahue) for the H, H_2 and He band edge features as well as for pressure induced H_2 and HD transitions and for the methane bands. They also agreed to examine airglow emissions related to ionospheric reactions.

6) A.L. Broadfoot proposed that he acquire from Bendix some new closely packed detector arrays to determine whether we can develop arrays of closely spaced and aligned sensitive strips.

The third team meeting was held at the Center for Earth and Planetary Physics, Harvard on January 12, 1972. All members were present except M.J.S. Belton. Mr. R.H. Sparks of J.P.L. the experiment representative with the project also was present.

1) Donahue summarized the history of the project since the last team meeting, covering the reduction in scope from the full TOPS to the minimum science (130 lbs.,650 M) payload, the Woods Hole SSB meeting and the PSC/SPAC briefings. He discussed the questions raised concerning overlapping objectives of the IR, UVS and UV Lα teams.

2) Currently favored trajectories for the JSP77 and JUN79 missions were examined. In order to span no more than 25km with the slit at closest approach the fields of view and counting rates would be:

<u>JUN79</u>

Uranus	120,000 km	2×10^{-4} radius	5×10^{-2} cts/sec R
	200,000 km		
Neptune	as close as we wish		
Jupiter	145×10^{6} km	impossible	

<u>JSP77</u>

Jupiter	$\sim$ 400,000 km	0.5×10^{-4} radius	1.25×10^{-2} cts/sec R
Saturn	- no occultation		

Discussion turned on the possibility of obtaining adequate information using the full sun rather than restricting the field of view with a large collimator. Even though the sun might subtend more than a scale height it is possible to unfold the distribution provided no rapid changes occur.

3) Methods of getting CH_4 information in the UV and IR were discussed. Broadfoot and Moos agreed to examine the feasibility of incorporating a 3.3 μ channel. Also to be examined theoretically was the usefulness of the UV absorption near 1200 Å.

4. Theoretical studies by McElroy and McConnell indicate that the vibrational temperature of H_2 may be very large in the atmosphere of Jupiter. This may affect the penetration of UV producing the Lyman fluorescence.

5) McElroy showed that it was possible to determine D/H abundance by comparing HD and H_2 absorption profiles.

6. Dalgarno presented results of calculation on the excitation of H_2 fluorescence by solar UV.

On November 12, 1971 Donahue met with J.E. Blamont and M. Berthaud in Paris to discuss the possibility of producing a single instrument to meet the objectives of both the UVS and UV Lα teams. They concluded that it would not be possible. A memorandum of understanding, submitted to the chairman of the OPGT SSG by them is attached (Appendix A).

3. Studies Funded by NASA Headquarters.

A. At Harvard University in the Center for Earth and Planetary Physics, R. Goody, M.B. McElroy, and J. McConnell have undertaken two main tasks. One is to construct models of the atmospheres of the outer planets using known reaction rate constants, solar fluxes and available data on composition. Models have been constructed using different assumptions concerning the efficiency of transport processes (eddy diffusion). These calculations are essentially complete.

Using these models, with participation by T.M. Donahue, they have predicted the variation of transmitted solar flux at the various wavelengths of interest during sunset and sunrise for the solar occultation phases of the mission. Realistic trajectories and fields of view have been used. It has been verified that useful information can indeed be obtained concerning H, H_2, He and CH_4 distribution from UV occultation measurements. Both IR and UV channels show good promise of producing CH_4 profiles down to and below the expected turbopauses.

B. At Harvard University, Department of Astronomy, A. Dalgarno has in progress detailed quantal studies of collision induced absorption of H_2-H_2 and He-H_2 with the intent of assessing the possibility of deriving the He/H_2 abundance ratio from absorption measurements in the far infrared. The calculations for He-H_2 have been completed and a sample of the results is given in the figure which shows the absorption coefficient as a function of frequency for three different temperatures. The circles are the experimental data. The structure that emerges at low temperatures is of particular interest.

He has also studied the fluorescence of solar radiation by H_2 and HD in the ultraviolet Lyman system. There are coincidences between strong solar lines and molecular absorption lines. Thus a particular line can be absorbed strongly by HD and weakly by H_2. The relative intensity of the resulting fluorescent emission lines by HD and by H_2 can be a measure of the relative abundance ratio HD/H_2. The fluorescence technique may also provide a measurement of rotational and vibrational temperatures. Detailed model calculations will be necessary to determine the spectral resolution necessary. All the molecular data that are required have been assembled and line absorption coefficients have been calculated.

A study has been performed of the intensities of helium emission lines in the dayglow of Jupiter, based on model atmospheres consisting of hydrogen and helium. The intensities depend upon the details of the model atmospheres. Diffusive equilibrium was assumed above 155 km and a He/H_2 mixing ratio of 1:5. Probable typical values for the integrated excitation rates of various levels of helium are listed below.

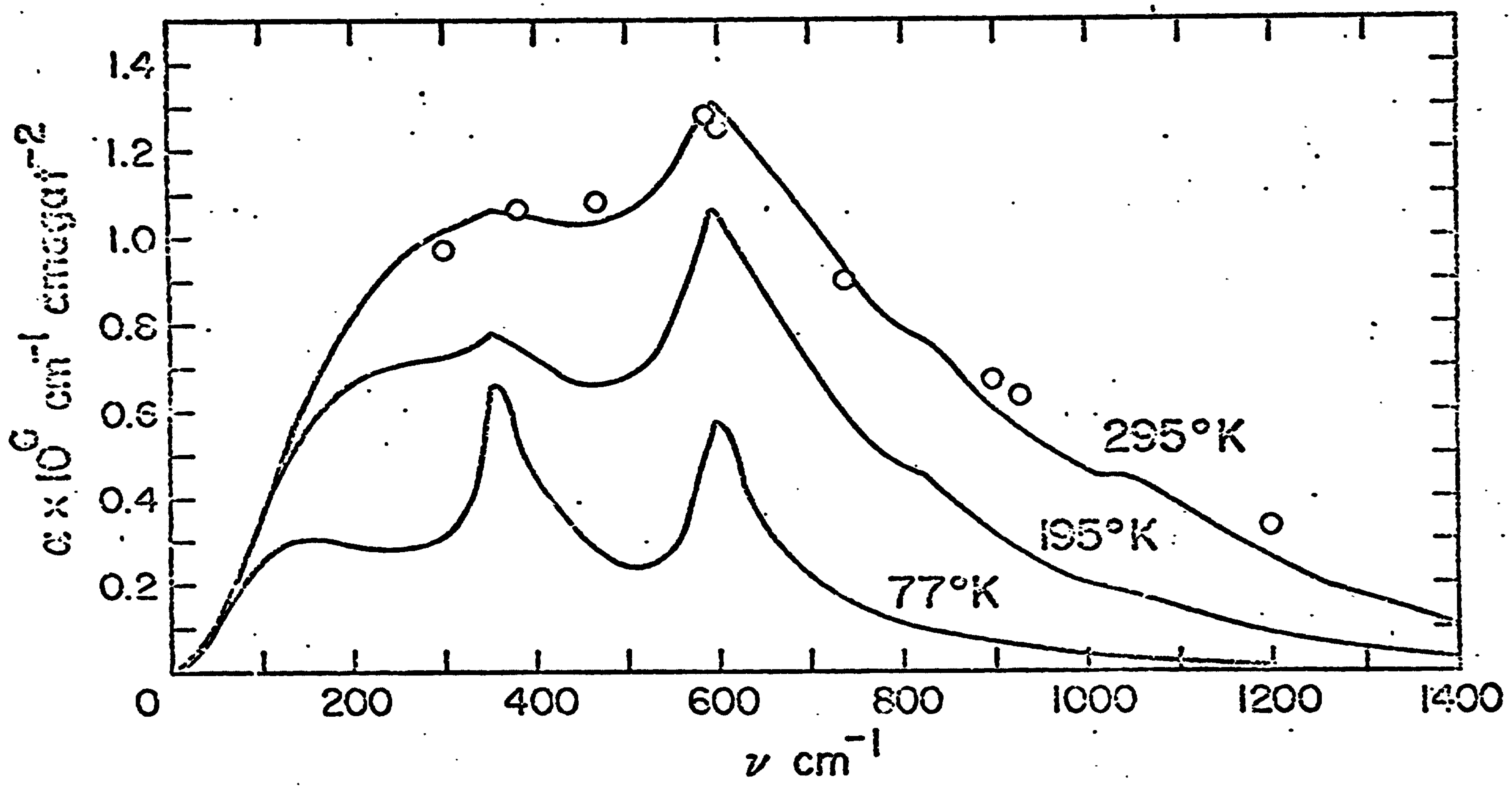
Level	Excitation rate ($cm^{-2}sec^{-1}$)
2^1S	8.5×10^5
2^1P	2.2×10^6
2^3S	6.2×10^5
2^3P	4.6×10^5
3^1P	6.5×10^5
3^3S	1.3×10^5

The excitation rates for all the other levels are less than 10^5 cm^{-2} sec^{-1}. Much of the emission appears in the visible.

The source of the excitation is photoelectrons produced by solar ionizing radiation. A comparison with emission from H_2 can, with suitable analysis, give the mixing ratio of He to H_2 high in the atmosphere.

It should be noted that particle bombardment may be a stronger source of emission. He has constructed programs that simulate the luminosity effects of Jovian auroras. The strongest usual emission line is predicted to be the 3^1P-2^1S line at 5016 Å.

He has calculated the equivalent width of the 0-1 rotational line of HD at 89 cm^{-1}. If he assumes $n(H_2)/n(HD) =$ 2500, the equivalent width in absorption is 5×10^{-2} cm^{-1} for one of the model atmospheres published by Enarenaz and his associates.



The collision-induced absorption of equilibrium H_2-He, using the adjusted dipole moment, at different temperatures.

C. At Kitt Peak National Observatory L. Broadfoot has been engaged in designing the spectrometer. In particular he has been assessing new Channel Electron Multipliers which have been developed at Bendix Corporation. In the new configurations Channel Multipliers are closely packed to form large sensitive areas (micro-channel arrays).

These arrays, in fact, are image intensifiers with proximity focusing allowing a resolution of 30 lines per millimeter. The type of configuration we are interested in would allow closely spaced and aligned sensitive strips which would simulate multiple exit slits and detectors in the image plane of a spectrograph.

This type of multidetector could eliminate the requirement for mechanical motion in many instruments since they will cover the wavelength range from 2 angstroms to 11,000 angstroms by use of appropriate photocathodes. They also imply a large reduction in weight and design complexity which would be important to the Outer Planets Mission.

Test models of these detectors are on order from Bendix Corporation but delivery and assessment will take several months. This investigation is being carried on in close coordination with similar investigations at Bendix Corporation. The state of this work can be determined at any time by contacting L. Broadfoot.

D. The work at The Johns Hopkins University (H. W. Moos) has concentrated on three aspects:

1. The ultraviolet fluorescence of molecules present in the Jovian atmosphere.
2. The evaluation of existing rocket spectra.
3. The evaluation of photon detectors.

These three aspects are surveyed below.

1. He has surveyed the available information both published and unpublished on electron excitation of CH_4, NH_3 and related compounds. Dissociative excitation is the dominant mechanism producing HI 1216 Å ($\sigma \sim 10^{-17}$ -10^{-18} cm^2,) NI 1200 Å ($\sigma \sim 10^{-19}$ Å) and CI 1561 and 1657 Å ($\sigma \sim 10^{-19}$ Å). The $A\,^2\Delta - X^2\pi$ transition of CH (4200-4400 Å) has also been observed with cross sections $\sim 10^{-18}$ cm^2.

   Less is known about the ultraviolet excitation of fluorescence. He has started to construct a simple apparatus for measurements of this type and expect to obtain results over the next few months.

2. The analysis of the Jovian rocket spectrum will be completed in the next thirty to sixty days. Preliminary results indicate:

A. The Ly-α brightness measured in January, 1971 is significantly different from the 4 kR observed in December 1967.

B. The feature reported near 1300 Å in 67 was not observed in 69.

C. There are weak emissions between 1250 and 1600 Å.

D. The decreasing albedo reported by KPNO continues to decrease at wavelengths shorter than 1800 Å. However, it does not go to zero and significant amounts of reflected solar radiation are observed down to ~1650 Å.

4. SCIENTIFIC OBJECTIVES

The purpose of the uv spectroscopy experiment on the Grand Tour of the Outer Planets is to determine the concentration of major constituents in the atmospheres of the planets and their satellites and the dependences of these densities on altitude. Primary attention will be devoted to obtaining these parameters for H, H_2 and He.

The measurements are designed to answer one of the principal cosmogonic questions - probably the principal one - that can be asked of the outer planets. The question is what was the primordial abundunce of the elements - mainly hydrogen and helium - in the solar system. More specifically the question is how these abundances vary among the outer planets and how do they compare with solar and cosmic abundances. The great gravitational fields and low exospheric temperatures of Jupiter and Saturn give assurance that these planets have retained their original allotment of the light gases. This contrasts with the situation on the minor planets where escape of hydrogen and helium during the early stages of planetary evolution as well as through the cons has decoupled the present abundances from the original. Unfortunately terrestrial measurements of H_2 abundances by spectroscopy and atmospheric scale heights by stellar occultations have not been sufficiently precise even for Jupiter to provide meaningful results for the hydrogen-helium ratio. The uv photometric measurements planned for

Pioneers F and G will give the H and He distributions only in the upper atmosphere of Jupiter where gravitational separation will reflect the densities in the mixed atmosphere only if the "turbopause" can be located. Hence the Grand Tour provides our first real opportunity to obtain these most important data.

It is well to mention that the ratio of helium to hydrogen has a cosmological significance as well as a cosmogonic one. The relative amount of helium generated is quite different in the fireball of the big bang than in the slow nucleosynthesis of more steady state like models of creation. Finally measurements of atmospheric density and its variation with altitude provide the kind of reconnaissance data which a flyby mission must attempt to obtain in order to permit the planning of scientific sensors and engineering characteristics of future orbiters and probes.

5. BASELINE INVESTIGATION OBJECTIVES

A. MEASURED PARAMETERS

We propose to obtain the desired information concerning atmospheric densities by two kinds of spectroscopic measurements. The first of these is based on observations of the emission line airglow off the bright limits and on the disc. The second is the variation in absorption of solar radiation at selected wavelengths as the spacecraft passes into and out of solar occultation. In the first kind of observation we propose to observe characteristic optical radiations from the planetary atmosphere with a spectrophotometer pointed perpendicular to the planet-sun axis as the line of sight sweeps toward the limb from about 1000 km above the "surface". The prime spectral lines to be studied are hydrogen Lyman α, the helium resonance line at 584Å and a line in the Lyman band system of H_2 at 1607Å.

Planetary Lyman α will be excited by resonance absorption of solar Lyman α by atomic hydrogen. According to present models this source at Jupiter will vary from about 0.1kR 1000 km from the limb to about 5kR near the limb. Simple, standard radiative transfer analysis will permit these data to be interpreted in terms of atomic hydrogen densities in the diffusive separation region.

Lyman α is also excited in dissociative excitation of He by solar xuv and by Rayleigh scattering. At low altitudes these two sources will yield information concerning the H_2 distribution.

The He 584 planetary line is excited in helium in a fashion analogous to the hydrogen resonance line. The brightness at Jupiter may be as great as 200R at 100 km from the limb. From the height variation of the emission can be deduced the density of helium in the upper atmosphere.

Lines in the Lyman system of H_2 fluoresce in sunlight because of accidental resonances with some strong solar uv lines, including Lyman β. These lines penetrate deeply into the atmosphere and the fluorescence lines will appear at great depths. Thus a line at 1607 Å (excited by Lyman β) will produce about 5kR of airglow signal at Jupiter. From these data the variation with H_2 with altitude will be obtained in a region where comparison with radio occultation data is possible. Thus we will be able to put together pieces of H, H_2 and He variations in regions of gravitational separation as well as mixing to obtain a planetary picture of the hydrogen and helium atmospheric variation.

We expect to be able to cover a dynamic range from about 10R to 10kR with our proposed airglow instrument and to measure densities ranging from 10^5 cm^{-3} for H to 10^{17} or 10^{18} cm^{-3} for H_2. Density values should be reliable to within 20% over most of this range. Clearly the dynamic range of the measurements is set by our need to make observations over several scale heights in the thermosphere and exosphere and down well into the mixed region of the atmosphere. A compromise in sensitivity is dictated by our need to limit the solid angle of acceptance to maintain height resolution below an atmospheric scale height (~ 15 km).

Beyond Saturn the airglow emissions - except Lyman α - become too weak to be detectable because of the decrease in solar flux. For Uranus, Neptune, Pluto and their satellites information about the H, H_2 and He distribution will be obtainable by observing their effect in absorbing solar xuv radiation as the sun goes into occultation. For this purpose we propose to view the sun at 6-8 wavelengths, one on either side of the three absorption edges, 918Å for H, 805Å for H_2 and 504Å for He and near 1216A (Lα) for methane. Our present plans envision using the airglow instrument pointed at a scattering sphere which is in sunlight to obtain these data as the spacecraft goes into and exits from occultation. During cruise the sunlight scattered from the sphere can provide calibration data.

There will be numerous targets of opportunity for this experiment, and these constitute secondary objectives: auroras, comets, interplanetary and interstellar atoms.

B. DERIVED PARAMETERS

For maximum use to be made of the densities derived by uv spectroscopic means this information should be supplemented with information obtained from the radio occultation experiment. Comparison of H_2 profiles with total refractivity profiles will clearly show to what degree the atmosphere is mixed. Our data are also clearly supplementary to the integrated abundance ratios derivable from the infra-red radiometer observations.

The technique proposed is one that has been exploited extensively for the Earth, Mars and Venus. Most recently, the Mariner 6 and 7 uv spectrophometer spectra provided a wealth of data on the abundance of CO_2, CO, O and H in the Martian upper atmosphere.

The instrument being considered for this experiment is virtually a Chinese copy of one now being built for Mariner Venus-Mercury 73 by some members of our team. A diagram of the spectrophotometer is shown in Figure 1. It is an objective grating spectrometer which features a single reflection for both dispersion and imaging. No transmitting materials are used. The mounting is of the Wadsworth type and the 12 or 13 spiraltron detectors will be placed at the proper position in the focal plane to respond to the wavelengths we desire to detect.

C. MAJOR OBSTACLES

Our chief concern is with channeltron lifetime. However, total number of counts will not be large in a three planet mission and the change in sensitivity can be monitored by use of the calibrating sphere. There is also a problem related to the angular diameter of the sun at the distant planets. This is too large to define the absorption scale height properly. Hence it will probably be necessary to use a slit to select a portion of the solar disc. In this case the collimation must be independent of the spacecraft limit cycle.

D. LIKELIHOOD OF SUCCESS

As long as these problems are mastered there seems to be no reason to expect less than complete success for the mission of this experiment.

6. MISSION AND SPACECRAFT REQUIREMENTS

Requirements Imposed on the Spacecraft

<u>Investigation</u>: uv spectrophotometer

1. Weight: 5-10 lbs
2. Power: 3-6 watts
3. Location: Scan Platform
4. Orientation: Planet
5. Viewing: the instrument should be pointed
   a) perpendicular to the sun-planet line for 1000 km before limb passage, at the disc if possible thereafter and either at the sun or at a fixed scattering sphere going into and emerging from occultation.
   b) A roll to take the antenna out of the field of view after encounter seems to be required.
6. Data Rate:
   a) Interplanetary 120 BPS, at 1/sec sample rate once every 0.5 au during celestial sphere scan.
      120 BPS at 1/sec sample rate for calibration ~ 12 times/year.
   b) Planetary: 120 BPS, at 1/sec sample rate.

7. Temperature Operating Range: -20^{0} to $+ 40^{0}C$.

8. Commands: A 12 bit cooled command word (individual HV on-off) (12 HV Pwr. Supplies) Optional pulse routing by command.

9. Source of Interference: Scattered light from booms and edges of antenna.

10. Timing or Interface Signals: spacecraft generated commands.

Preliminary Mission Requirements

1. Trajectory

Planets:

Distance of closest approach - as close as possible both for airglow and occultation. However, data are useable even if obtained from 10 Jovian radii distance. Solar occultation is desired for every planet and essential for Uranus, Neptune and Pluto.

2. Satellites

Distance of closest approach - same as for planets, solar occultation is desired for as many satellites as possible, especially beyond Saturn.

3. Operations Requirements

At encounter a sequence of operations is required from the scan platform. Essential is that during the 1000 km of travel before bright limb passage inbound the experiment be pointed perpendicular to the sun-planet axis, that going into and out of occultation for about 1000 km the experiment be held fixed either pointed at the sun or at some selected point on the space craft. During solar occultation at least one scan of the dark side of the planet is required. Clearly these operations should be automatically sequenced.

Ground commands would be utilized only to actuate calibration sequences or to point toward targets of opportunity such as comets.

4. Articulation of Platforms (See Operations Requirements)
5. A spacecraft maneuver to permit (along with scan platform exercises) a mapping of the celestial sphere is requested at least every 0.5 au.

As presently planned the major shortcoming of the 4 mission set is the lack of planetary and satellite solar occultation passage at Saturn. Thus we would incline to favor a JSUN or simple JS mission to replace JSP77 if JSP76 has successfully passed Saturn on course to Pluto.

7. MINIMUM EXPERIMENT

Experiments of this sort, as we have already indicated have been flown on Mariners 5, 6 and 7 and are on Mariner 9. A very similar experiment - almost identical - is being prepared for MVM73. The instrument in question has been flown repeatedly with high measure of success on sounding rocket by NRL to observe the solar xuv spectrum. Only a change in wavelength selection is planned between MVM73 and OPGT versions and this clearly represents a minor modification.

OPGT MINIMUM INSTRUMENT DESCRIPTION

TEAM U.V.S. DATE Septembe: 24, 1971

INSTRUMENT U.V.S.

PARAMETER	INFORMATION
I. Location	
A. Sensor	Scan Platform
B. Electronics	Scan Platform
II. Weight	
A. Remote	6 pounds
B. Bus	ϕ
III. Size	
A. Remote	4 x 8 x 27 in.
B. Bus	ϕ
IV. Orientation	
A. Field of View	15" x 30'
B. Preferred Viewing Direction(s)	Perpendicular to nalnet sun axis at bright limb passage; toward a body fixed mirror at beginning and end of solar occultation; toward dark disc during and after occultation.
C. Scanning Rates	
D. A/C Stability	Less than 100×10^{-6} radians/sec
V. Power	
A. Remote	2.5 watts
B. Electronics	ϕ

PARAMETER	INFORMATION
VI. Thermal	
A. Sensor	
1. Operating	-20° to +40° C
2. Non-Operating	-20° to +75° C
B. Electronics	
1. Operating	[illegible]° to +40° C
2. Non-Operating	[illegible]° to +75° C
VII. Data	
A. Profile	120 bits at one second sample rate
B. Bits/Sec	120 bits per second
VIII. Mission Sequence	See IV/B
IX. Other Constraints	

4. COST: 4.5 M seems realistic

5. OPTIONS: From the uvs point of view the constraints imposed are not serious. However, the overall problem of determination of abundances below the turbopause would be attacked properly if the payload also contained an IR photometer with a field of view the same as the UVS capable of measuring the solar energy transmitted in the CH_4 7μ band and the HD pressure induced absorption band during solar occultation.