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Continued Observations of the H Ly α Emission From Uranus

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We present four years of observations of the disk-averaged H Ly α emission from Uranus performed with the IUE Observatory. A detailed analysis of the uncertainties of these measurements is discussed, based both on known calibration uncertainties and on a new analysis of the uncertainty in our customized extraction procedure. On the basis of roughly 30 observations we derive an average brightness of 1400 Rayleighs. The larger data base now available has allowed us to perform a more detailed analysis of the character of this emission and its functional relationship with other parameters. The observed extent and time scales of the variability of the emission are presented, and no evidence for correlation with the solar H Ly α variations is found, implying a largely self-excited emission. Limits are derived from the minimum observed brightness and from a modeling of the atmosphere of Uranus for the possible contribution by reflected solar H Ly α emission, which we estimate to be roughly 200 Rayleighs. We therefore interpret the remaining self-excited emission as being produced by charged particle excitation, i.e., an aurora. Studies of possible correlations between the self-excited component of the H Ly α emission and the density and velocity of the local solar wind are presented, based on comparisons with solar wind measurements performed in the vicinity of Uranus from the Voyager 2 and Pioneer 11 spacecraft. No evidence is found for any correlation between the solar wind density and the H Ly α brightness. We estimate an upper limit to the energy of the precipitating particles based on the lack of observed H_2 band emission (which sets a lower limit to the ratio H Ly α/H_2) and by analogy to the auroral precipitation on Jupiter. Finally, an estimate of the total power in the precipitating particles is on the order of 10^{12} watts (comparable to the aurora on Saturn), and the disturbance of the upper atmosphere by the deposited energy is discussed.

1. INTRODUCTION

The initial observations and interpretation of the unexpectedly bright and variable H Ly α emission from Uranus have been presented by *Clarke* [1982] and *Durrance and Moos* [1982], each based on observations performed with the IUE Observatory and utilizing the monochromatic imaging of the instrument within the field of view of the larger of two available apertures. Further observations and additional interpretative calculations have been discussed in two conference proceedings by *Clarke* [1984] and *Durrance and Clarke* [1984]. This paper will summarize four years of IUE observations of Uranus performed using the same observational and data reduction procedures and discuss the more detailed interpretation of this emission made possible by the extended and uniform data base.

The principal excitation mechanisms to produce H Ly α emission from the outer planet atmospheres are (1) resonant scattering of incident solar H Ly α radiation, (2) Rayleigh scattering of solar H Ly α radiation, and (3) charged particle excitation of H and H_2. Observations of Jupiter and Saturn have revealed planet-wide resonant scattered emission, no measurable Rayleigh-scattered emission, pronounced auroral emission from the polar regions of both planets, and weak planet-wide particle-excited H_2 emission which presumably is accompanied by H Ly α emission. Resonant scattering of solar H Ly α radiation by atmospheric H provides a direct measure of the atomic hydrogen column abundance above the methane absorbing layer of the atmosphere. Atomic H is produced both by photodissociation and charged particle dissociation of H_2 relatively high in the atmosphere; the magnitudes of these sources of H atoms can be calculated from the measured solar EUV flux and the expected total energy in precipitating charged particles. The H atoms so produced are lost mainly through a three-body recombination reaction once they are transported to the denser lower atmosphere. The column abundance of H, and hence the atmospheric reflectivity to solar H Ly α radiation, is an indication of the degree of upper atmospheric mixing (which is expressed as an eddy diffusion coefficient).

Rayleigh scattering of incident solar H Ly α radiation competes directly with resonant scattering to increase the planetary albedo at 1216 A, but Rayleigh scattering by H_2 would also produce a Raman-shifted emission at 1280 A which has thus far not been observed from any of the outer planets. Charged particle excitation can also produce H Ly α emission, both by direct excitation of H and by dissociative excitation of H_2. The particle-excited emissions are important tracers of magnetospheric activity at Jupiter and Saturn. In the case of Uranus, the interpretation of the bright, variable component of the H Ly α emission as auroral (i.e., particle-excited) in nature has provided the first evidence for the existence of an active magnetosphere

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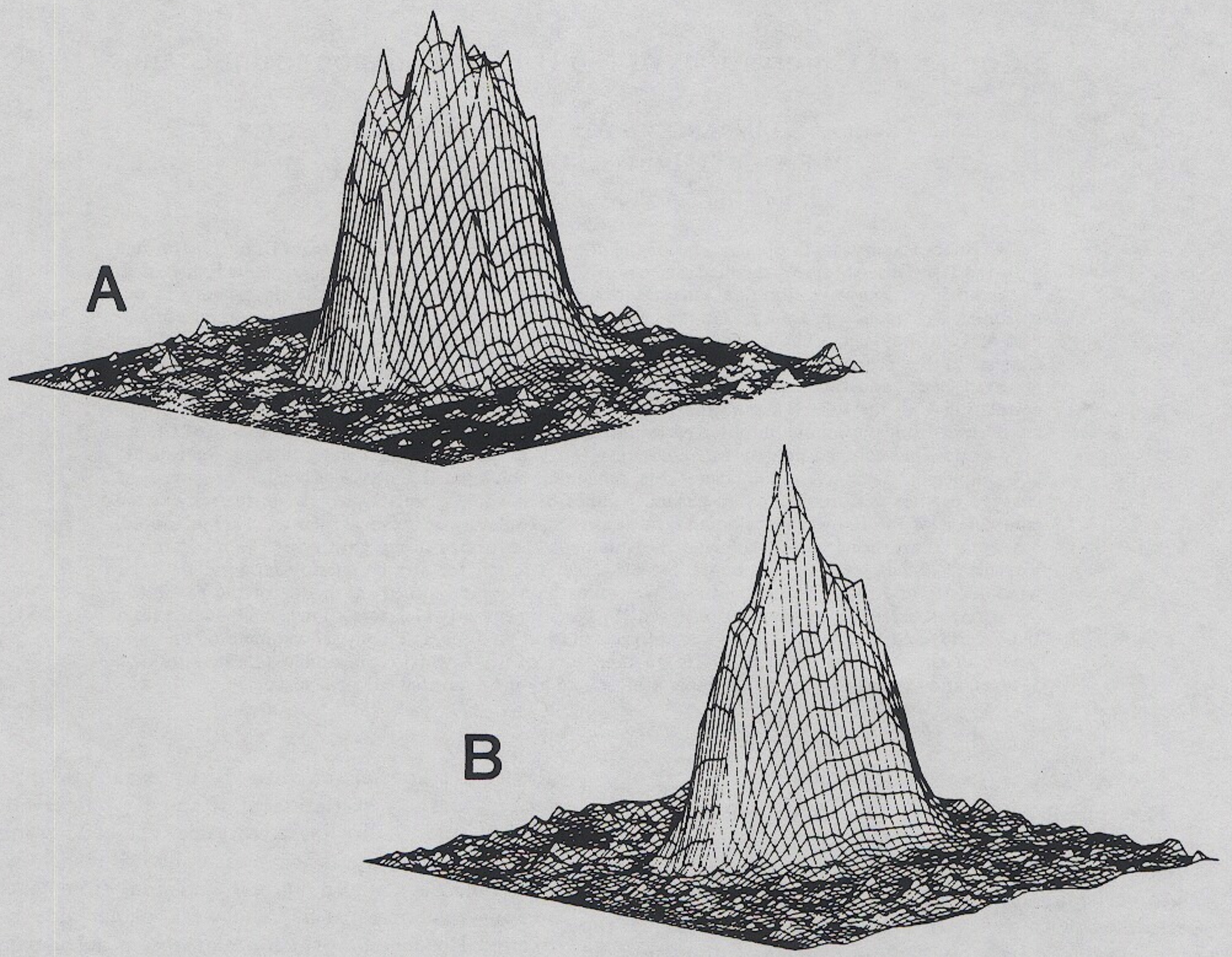

Fig. 1. Three-dimensional plots of the raw data from exposures showing the (*a*) faintest and (*b*) brightness H Ly α emissions from Uranus obtained with the IUE to date. In these plots the horizontal plane represents the detector camera face, and the intensity of H Ly α emission imaged onto the detector is plotted in the vertical direction. The large elliptical features are the sky background H Ly α emission filling the roughly 10 x 20 arc sec aperture, with the point source (5-6 arc sec FWHM) emission from Uranus centered in the aperture in both cases.

at Uranus by analogy to Jupiter and Saturn. In addition, the energy input to the atmosphere from charged particle precipitation can result in significant heating and H atom production in the precipitation regions. Enhanced thermospheric heating and H abundance could also be possible at nonauroral latitudes.

2. Observations and Estimates of Uncertainties

The two initial sets of measurements reported in 1982 were performed using the same observational technique but the data were reduced by slightly different procedures. In all cases, the roughly 4 arc sec diameter disk of Uranus was centered in the 10 by 20 arc sec elliptical IUE spectrograph aperture for integration periods on the order of 1-2 hours (for a description of the IUE Observatory, see *Boggess et al.* [1978]). The IUE point source response function has a full width at half maximum (FWHM) of 5-6 arc sec, and at least three resolution elements are achieved along the long axis of the aperture (which runs perpendicular to dispersion). Plots of the raw data showing the Uranus emission above the extended background are presented in Figure 1 for the faintest and brightest Uranus emissions observed to date (see section 4). The general procedure for separating the emission from Uranus from the background geocoronal and interplanetary H Ly α emissions filling the aperture is to scale and subtract an image of sky background H Ly α emission pixel by pixel from each Uranus image. The resulting background-subtracted array is summed over a region of roughly 9 arc sec diameter centered on the Uranus emission peak to yield the planetary H Ly α signal in uncalibrated units of IUE flux numbers (FN's). This summing region was chosen to include the flux from the 4 arc sec Uranus disk folded through the 5-6 arc sec instrument response function. The conversion to absolute flux was performed in both initial data sets using the calibration of *Bohlin et al.* [1980] and the size of the Uranus disk at the time of each observation.

For the present paper the original data have been re-reduced, along with a substantial number of new observations made by the various authors. The new reduction technique is similar to the original method, except for the following improvements. In an attempt to improve the accuracy of the background subtraction, the scaling of the

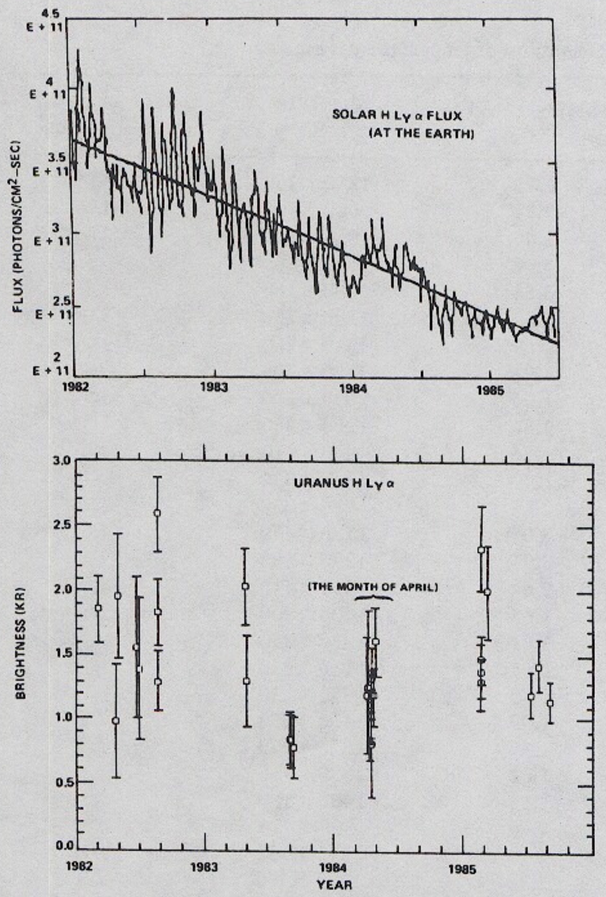

Fig. 2. The disk-averaged H Ly α brightness of Uranus from all measurements performed to date with the IUE (bottom) and the solar H Ly α flux at the earth over the same period, as measured by the SME spacecraft (top). The determination of the error bars on the Uranus observations is discussed in some detail in section 2, and the best linear fit to the solar H Ly α flux is superimposed on those data. The time scale in the April 1984 observations has been expanded (see Figure 3).

background image has been accomplished by a least squares fitting routine which compares the regions of sky background emission within the aperture pixel by pixel (i.e., omitting the central pixels). Two additional corrections have been made to earlier-reported data in our reanalysis of all of the data obtained to date. First, the absolute calibration of the IUE at 1216 A has been revised as reported by *Holm et al.* [1982] to increase all previously reported flux values by 16% of their earlier values. Second, the initial brightness values of *Clarke* [1982] were derived using the photometrically corrected image segment from the standard NASA/IUE guest observer tape to achieve maximum angular resolution, and the conversion from the integer tape pixel values to FN's as published in a draft of the IUE Image Processing Information Manual (version 2.0) was later learned to be too low by a factor of 2. The originally published brightness values of *Clarke* [1982] must therefore be doubled to account for this.

The uncertainties involved in deriving the H Ly α brightness of Uranus from these observations therefore include systematic errors from the absolute calibration of the IUE, from the size of the summing region, and possibly from the subtraction of the sky background image. Random errors are the counting statistics and detector noise affecting both the subtraction of the background image and the Uranus H Ly α signal. The absolute calibration is reported to be accurate to within 15% [*Bohlin et al.*, 1980; *Holm et al.*, 1982]. The exclusion of flux by using summing regions of different sizes has been tested by simply varying the diameter of the summed region on the same bright Uranus image and comparing the derived fluxes with the variation expected from the modeled point spread function convolved with the 4 arc sec diameter Uranus disk: we estimate that the 9 arc sec region excludes no more than 5% of the flux from Uranus. It should also be noted that the position of Uranus within the aperture is confirmed in each exposure by the presence of longer wavelength (1800–2000 A) Rayleigh-scattered continuum emission and its relationship to the aperture field of view.

The estimation of the random and systematic errors is complicated by the knowledge that there exist both fixed pattern and variable noise on the IUE SEC vidicon detectors. To understand the nature of the uncertainties in the reduced brightness values for Uranus it will be necessary to briefly discuss the noise characteristics. In addition to permanent sensitivity variations from pixel to pixel, which are removed by a flatfielding procedure, there appear variable features which appear in the data as "hot spots" consistently at the same physical location but varying in intensity. There is also evidence that oversaturation of the cameras produces temporarily higher noise levels, presumably due to the decay of the ultraviolet to visible conversion phosphor, on a time scale of days. Due to bright geocoronal emission, the region of the detectors illuminated by H Ly α is commonly saturated by large factors during long exposures of faint astronomical objects. We have evidence from our own data that the noise pattern on the Ly α region of the camera varies noticeably from month to month and year to year as the result of continued saturation. This would imply that our Uranus measurements have a higher relative accuracy on short time scales than on long time scales.

We feel that the most realistic approach to quantitatively estimating these uncertainties is to empirically compare images taken with and without Uranus in the aperture and separated by different time intervals. Random and systematic errors in the subtraction of the sky background have therefore been tested by reducing a series of exposures of empty sky (at exposure levels similar to the Uranus images) by the same procedures used to derive the brightness of the Uranus image in the aperture (i.e., scaling and subtracting one sky background exposure from another). We find that the mean residual brightness derived for a 3.8 arc sec disk when none is present is 0.4% of the sky background brightness with a standard deviation of ±15.5%, based on 11 background exposures randomly distributed over the four years of the observing program. In addition, we have reduced five exposures taken over two days time with no intervening saturation of the detector, and find a mean residual brightness of 10% with a standard deviation of ±10.6%. Since we have used the same background summed image in all reductions, for the presentation of the whole data set we have corrected the Uranus brightness values by the systematic error of 0.4% and listed 1σ errors of ±15.5% (as listed in Table 1 and plotted in Figure 2).

TABLE 1. IUE Observations of Uranus H Ly α Emission

Date	SWP	Exposure Time, min	Background H Ly α, kR	Uranus H Ly α, R	Solar Flux at Earth, x 10^{11} ph/cm^2 s
March 3, 1982	16468-69	240	1.70	1860 ± 260	3.8
April 21, 1982	16808-10	208	2.88	980 ± 450	3.2
April 23, 1982	16821-23	191	3.09	1950 ± 480	3.4
June 19, 1982	17262-64	190	3.62	1560 ± 560	3.5
June 20, 1982	17272-74	205	3.64	1390 ± 560	3.4
Aug. 23, 1982	17738	120	1.47	1290 ± 230	3.0
	17739	120	1.69	1840 ± 260	
	17740	90	1.91	2590 ± 300	
April 29, 1983	19847-49	140	1.96	2030 ± 300	3.5
April 30, 1983	19855-57	196	2.30	1290 ± 360	3.3
Sept. 1, 1983	20880	120	1.36	840 ± 210	2.6
	20881	120	1.50	840 ± 230	
Sept. 2, 1983	20882	120	1.62	790 ± 250	2.7
April 23, 1984	22822	120	3.05	1190 ± 470	2.8
	22824	120	3.71	1270 ± 580	
April 24, 1984	22825	120	2.64	810 ± 410	2.8
	22826	120	1.68	1200 ± 200	
	22827	120	1.61	1330 ± 250	
	22828	120	1.61	1110 ± 250	
	22829	120	1.39	1030 ± 220	
April 25, 1984	22830	120	1.59	1190 ± 250	2.7
April 26, 1984	22831	120	1.77	1620 ± 270	2.8
Feb. 26, 1985	25316	120	1.02	1320 ± 160	2.3
	25317	120	1.14	1480 ± 180	
	25318	120	1.39	1390 ± 220	
	25319	90	2.14	2340 ± 330	
March 4, 1985	25358	90	2.38	2010 ± 370	2.3
July 18, 1985	26441	120	1.20	1200 ± 190	2.3
Aug. 5, 1985	26550	120	1.27	1420 ± 200	2.5
Sept. 9, 1985	26656	120	1.00	1150 ± 160	2.3
Sept. 24, 1985	26722	120	1.02	1110 ± 160	2.3

We further regard the mean residual of 10% in the set of five exposures as simply representing a temporary zero-level offset within the 15.5% one sigma range, and the short-term standard deviation of ±10.6% as the correct relative uncertainty to apply when comparing exposures taken within 2–3 days and without intervening camera saturation.

Finally, the random error in the counting statistics from the Uranus flux is small compared to the random error in the sky background subtraction. In principle this random error should scale as $\sqrt{N}$, where N is the total number of counts in the background. Due to the limited dynamic range of the IUE and our own efforts to always expose the camera near the optimum level, however, the random error in the background subtraction is nearly a constant fraction of the sky brightness from exposure to exposure. We therefore assume uncertainties of the constant percentages of ±15.5% of the sky brightness when comparing widely separated observations and ±10.6% when comparing observations taken close in time.

All IUE observations of the disk-averaged H Ly α brightness of Uranus are plotted in Figure 2, with a listing of these values given in Table 1. We derive an average brightness of 1400 ± 450 Rayleighs from these data, where this standard deviation refers to the dispersion in measured values. These observations have all been reduced using the same software and the same summed sky background image for scaling and subtraction, and therefore are directly comparable. Examining the data in Figure 2 as variations about a time-invariant mean with the plotted uncertainties, the long-term variability appears significant but at a low level. In this data set, 47% of the measurements are within 1σ of the mean value, 80% within 2σ of the mean, and 97% within 3σ of the mean. Compared to values of 68% within 1σ and 95% within 2σ of the mean expected for a randomly varying sample, the Uranus emission appears consistently variable at roughly the 2σ confidence level. There exist several short-term variations which are at much higher levels of confidence, however. Applying the short time scale uncertainty to the observations in April 1982, August 1982, and February 1985 yields variations on time scales of from two days to four hours of 3.1σ, 7.2σ, and 5.1σ, respectively. In view of these highly significant short time scale variations, we regard the emission from Uranus as having occasional significant variations about a mean which appears constant at the several hundred Rayleigh level.

3. CONTRIBUTION FROM REFLECTED SUNLIGHT

Possible contributions to the observed emission from resonant scattering or from Rayleigh scattering have been studied and upper limits to these components set by two different analyses. The Solar Mesospheric Explorer (SME) makes daily measurements of the full disk solar irradiance

TABLE 2. Atomic Hydrogen Abundances on Uranus

	Nominal Cases		
	Case 1 (Equator)	Case 2 (Mid-Latitude)	Case 3 (High Latitude, 82°)
H above $\tau_{CH_4} = 1$, cm^{-2}	1.5×10^{15}	2×10^{15}	2.3×10^{16}
$\tau_{CH_4} = 1$ level at Z (km)	470	390	375
N, cm^{-3}	4.3×10^{14}	2.6×10^{15}	3.5×10^{15}

In all above cases, $K = 10^6$ cm^2 s^{-1} at the homopause. $T_{trop} = 55$ K; $T_{photolysis} = 95$ K. Downward flux of H from the ionosphere included. Z is altitude above the 100-mbar level; N is atmospheric density.

Variations are as follows: With K: for $K = 10^4$ cm^2 s^{-1}, above values of H are higher by approximately 25%. For $K > 10^6$, H abundances are smaller. $K = 10^4$ appears to be unacceptably low; $K > 10^6$ is also unreasonable. With T_{photo}: for photolysis region temperature, $T_{photo} = 154$ K, and H abundances are higher by 50% compared to the values in the table. With T_{ex}: with exospheric temperature $T_{ex} = 200$ K, a possibility that cannot be ignored, H abundances are from 25 to 50% higher than those in the table.

at H Ly α. Figure 2 shows the SME solar H Ly α data for the period January 1982 to July 1985 as obtained from the SME data base (G. J. Rottman, University of Colorado, unpublished data, 1985). The highly significant short-term variations in the Uranus brightness are not matched by corresponding variations in the solar flux, and dividing each Uranus value by the corresponding solar flux does not reduce the overall level of variation observed. There is also a slow decrease in the solar flux toward solar minimum, shown in Figure 2 with a linear fit, which represents a roughly 40% decrease from the 1982 flux by mid-1985. The Uranus data are more consistent with a time-invariant mean than with such a decrease, especially when comparing the 1982 and 1985 average brightness levels (the intermediate points are somewhat lower, but also represent measurements which were closely spaced in time). As with the variability in general, we conclude that the Uranus brightness does not follow the solar flux level, with a higher significance derived from the short-term variations in the Uranus brightness than from the longer-term trend. This in turn limits the contributions from resonant and Rayleigh scattering to the observed Uranus emission.

An upper limit to Rayleigh scattering by H_2 can be set independently by the nondetection of the Raman-shifted feature at 1280 A. We derive an upper limit to the flux in a 8-A FWHM line at 1280 A of 30 Rayleighs from the spectrum to be discussed in section 6 (see also Figure 5), which corresponds to an upper limit to H Ly α emission of roughly 100 Rayleighs [*Brandt*, 1963; *Dalgarno and Williams*, 1962]. An upper limit to the contribution from resonant scattering by H can be set independently from the minimum observed brightness to date, assuming that the Uranus atmospheric H Ly α albedo and solar flux both change slowly compared to the variability of the bulk of the observed emission from Uranus, and recognizing that some of this emission may be due to charged particle excitation. This sets an upper limit of 800 Rayleighs to the resonant scattered component, and this experimental upper limit can then be compared with current models for the upper atmosphere of Uranus.

Current understanding of the upper atmosphere of Uranus is summarized by the model in Table 2. The expected resonant scattered fluxes for different H column abundances above the homopause can be derived by comparing the values from Table 2 with Figure 2 of *Clarke* [1982], using the T=135 K curve of growth. Considering the Uranus spin orientation, a range of 2×10^{15} to 5×10^{15} cm^{-2} for the H column abundance (which is an average for middle to high latitudes) can be assumed using the entries in Table 2. These column abundances correspond to an H Ly α disk-averaged brightness of 70 Rayleighs, assuming the solar flux measured by the SME in April 1982. For contrast, a simple scaling by $1/R^2$ from the 800-Rayleigh equatorial H Ly α brightness observed from Saturn with the IUE [*Clarke et al.*, 1981] yields an expected resonant scattered brightness of 200 Rayleighs, and we take 200 Rayleighs to be a conservative estimate for the contribution to the Uranus brightness from resonant scattering. A hot, extended exosphere more similar to that of the earth (as modeled in the 1200-K example in Figure 2 of *Clarke* [1982]) could reflect a significantly larger fraction of the incident solar H Ly α radiation, but the observed FWHM of 5–6 arc sec for the Uranus emission (which is comparable to the 5–6 arc sec point source response of the IUE) suggests that the emitting region is equal to or smaller than the 4 arc sec diameter of Uranus rather than larger.

4. EXTENT AND TIME SCALE OF THE VARIABILITY

The largest short time scale variations observed to date remain the factor of 2 increase over a period of 8 hours in August 1982 and a factor of 1.7 increase over a 4-hour period in February 1985. This degree of short-term variability has not been observed in the solar H Ly α flux (see Figure 2) and must be due to variability in the intrinsic emission from Uranus. The extreme brightness values of 800 Rayleighs minimum and 2.6 kR maximum indicate a total range of a factor of 4 variability in the auroral emission if we assume 200 Rayleighs underlying emission due to reflected sunlight. This range is comparable to the range of variability normally observed from Jupiter's aurora with the IUE, although as high as a factor of 30 or greater variation was observed from Jupiter's aurora over a

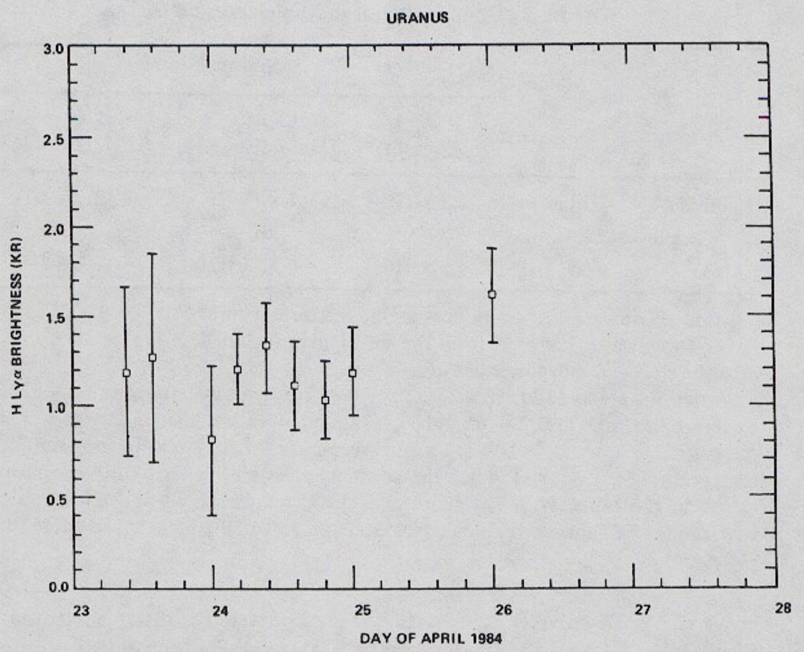

Fig. 3. IUE observations of the Uranus H Ly α brightness over the concentrated set of observations in April 1984 (see discussion in section 5).

5-month interval in 1978–1979 [*Skinner et al.*, 1984; *Clarke et al.*, 1980]. For comparison with the FUV emissions from the earth's aurora (principally O I 1304 A), observations with the imaging photometer on the Dynamics Explorer spacecraft have shown the integrated flux from the northern auroral oval to increase by a factor of 3.5 over a 1-hour interval, and selected regions of the auroral oval have been seen to vary by factors of 25 to 50 on time scales of 10 to 20 minutes (J. Craven, personal communication, 1985). Although the earth auroral observations have not yet been reduced to give the planet-averaged auroral brightness as a function of time for a direct comparison with the IUE observations of Jupiter and Uranus, it appears that the earth's auroras are at least as variable and may be more variable than those observed on Uranus. Nonetheless, the degree of variability observed on Uranus is the least ambiguous evidence for the interpretation of the bulk of the emission from Uranus as auroral in nature. A more quantitative analysis of the degree of variability observed is discussed in the following section.

In addition to the randomly timed observations plotted in Figure 1, a set of observations performed in April 1984 provided measurements approximately every 2 1/2 hours for a period of 20 hours to look for pronounced short-term variations that might occur on the time scale of the spin period of the planet. A scenario for such variability could be a situation comparable to the off-axis nondipolar magnetic field of Jupiter, which might interact either with the solar wind or some source of plasma internal to the magnetosphere. Since the Uranus rotational pole has been pointed within 15 degrees of both the sun and the earth during these observations, the entire polar cap has always been within the field of view. If the magnetic pole is located near the rotational axis, any likely auroral zone would also be completely within the field of view, and variations in the H Ly α emission due to changes in the observing geometry as the planet rotates (such as those observed on Jupiter and modeled by *Skinner et al.* [1984]) would not be expected from Uranus. This data set is plotted in Figure 3, and can be compared with the 15- to 17-hour rotation period of Uranus [*Brown and Goody*, 1977; *Belton and Terrile*, 1984]. It is apparent from Figure 3 that no systematic variation with the rotation period was observed, and we do not believe that we have measured any spin-controlled modulation of the H Ly α intensity.

5. CORRELATIONS WITH THE SOLAR WIND

The approaches of the Pioneer 11 and Voyager 2 spacecraft toward Uranus have provided a unique opportunity to observe the strength of the H Ly α emission from Uranus under known values of the velocity and density in the local solar wind without large extrapolations from solar wind conditions in the inner solar system. We have monitored the solar wind proton velocity and density measurements made by these spacecraft since spring 1984, both to compare the H Ly α brightness of Uranus with the local solar wind properties and to be able to plan IUE observations in the event of any particularly large burst in the solar wind. The largest increase in both particle velocity and density to date was observed in Pioneer 11 plasma measurements [cf. *McKibben et al.*, 1977] on April 15, 1984 (see Figure 4), and the predicted arrival time at Uranus based on the observed velocity jump occurred just after the IUE observations discussed in section 4 which had been previously scheduled for April 23 and 24. We then requested (and the IUE Project very responsively granted) two additional observations over the following 3 days in an attempt to detect any correlated variation in the H Ly α emission after the disturbance had arrived at Uranus (see Figure 3). Based on Pioneer solar wind data alone and extrapolating out over 3.4 AU to Uranus, our last observation on April 27 appeared to be after the time

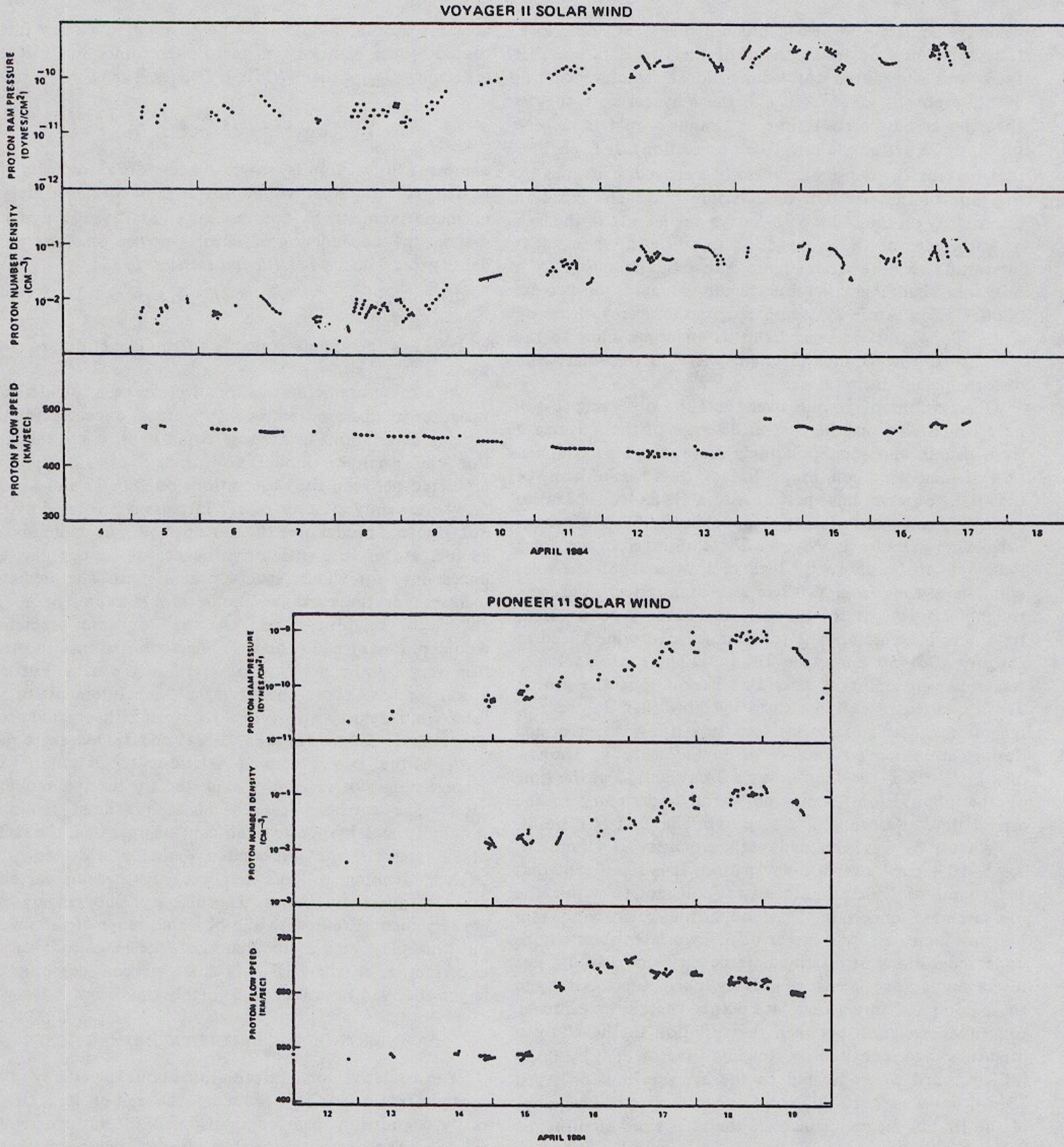

Fig. 4. Solar wind parameters as measured by the Pioneer 11 and Voyager 2 spacecraft during the burst in density and velocity observed at both spacecraft in April 1984 (see section 5).

of arrival of the disturbance at Uranus if there were little difference between the solar wind conditions along the lines of sight to Pioneer and Uranus (i.e., assuming only the radial travel time delay and corotation in the solar wind). The expected arrival time of the solar wind velocity increase was near the beginning of April 25 and no later than about 1500 UT on that day.

In April 1984 the Pioneer 11 was 3.4 AU from the orbit of Uranus and 16° above the plane of the ecliptic, with a corotation difference of 1/2 day between the line to Pioneer 11 and the line to Uranus. Voyager 2 was very close to the line of sight to Uranus and 5 AU away. Following the hurried IUE observations, the Voyager 2 solar wind data [*Bridge et al.*, 1977] for the same period were reduced (Figure 4). It was immediately apparent that a major disturbance had passed both spacecraft, but the character of the event at Voyager 2 was quite different from that at Pioneer 11, with Voyager 2 measuring a much smaller velocity increase and also a much earlier density increase. It is apparent from comparison of the two data sets that there was substantial three-dimensional structure to this event, even out at 15 AU, and the Voyager data suggest that the earliest arrival time at Uranus would have been on April 28 (after the last IUE observation). It is possible that part of the density increase had arrived at Uranus by the time of the last IUE observation, but there exists an uncertainty on the order of 2–3 days due mainly to the lack of knowledge of the propagation speed of the shock. It is interesting to note from Figure 3 that the Uranus H Ly α brightness had increased by roughly a factor of two by 0000 UT on April 27 compared to the average level on April 23–24, but we regard this as an upper limit to the response of the Uranus magnetosphere to the solar wind disturbance up to that time.

Observations of Uranus over the 1985 observing season have benefited from the shorter distance of the Voyager 2 from Uranus and correspondingly more accurate extrapolation of solar wind conditions. In fact, the focus of many of the IUE observations performed in 1985 has been to observe Uranus on a target of opportunity basis when the solar wind pressure at Voyager 2 was observed in the quick look data to be unusually high or low. In 1985 the solar wind travel time from Voyager 2 to Uranus decreased from roughly 10 days at the time of the February observations to 4 days in September at the average solar wind speed of roughly 400–450 km/s (see Table 3). The proton velocity was relatively constant over this period, but the proton density varied in extreme cases by more than an order of magnitude. The observation on July 18 was performed during an extended period of low density at Uranus, measuring 5.8 x 10^{-3} cm^{-3} over a 3-day period at the time of the observation (compared to an uncertainty in the arrival time at Uranus of ±2 hours). The next IUE point, on August 5, was obtained with a density at Uranus of 3.9 x 10^{-2} cm^{-3} over a 3-day period. It is significant that the Uranus H Ly α brightness was constant to within the measurement uncertainty, although the solar wind ram pressure increased by a factor of 6. Two later observations under conditions of intermediate density similarly did not reveal any large-scale change in H Ly α brightness. Although these comprise only a few data points, there is no evidence for any correlation between the variation in the H Ly α brightness had increased by roughly a factor of 2 by 0000 UT on April 27 compared to the average level on April 23–24, but we regard this as an upper limit to the response of the Uranus magnetosphere to the solar wind disturbance up to that time.

We can compare the lack of observed variability of the auroral H Ly α emission from Uranus with the predicted variability of that emission based on different assumptions about the potential response that a Uranus magnetosphere might have to the local solar wind. We have considered two cases: (1) an earthlike system in which the auroras are driven by the solar wind energy, and (2) the proposed Faraday disk dynamo model of *Hill et al.* [1983] in which the auroras are driven by a combination of solar wind and planetary spin. The detailed physics of how the earth's auroras are produced is a controversial subject (see the review by *Burch* [1974] and references therein). Assuming simply that in an earthlike system the average power available for aurora is equal to the solar wind energy intercepted by the planetary magnetosphere times a conversion efficiency ϵ_{earth}, then [*Hill and Dessler*, 1985]

$$P_{uv} = 2\pi\, \epsilon_{earth}\, (2/\mu_o)^{1/3}\, \rho^{2/3}\, v^{7/3}\, M^{2/3}$$

expressed in MKS units, where ρ and v are the density and velocity of the solar wind protons and M the planetary magnetic moment. By contrast, in a Faraday disk dynamo system the dependence of auroral power on solar wind density and velocity is [*Hill and Dessler*, 1985]

$$P_{uv} = 16\pi/3\, \epsilon_{disk}\, (2\mu_o)^{-2/3}\, \rho^{1/3}\, v^{-1/3}\, \Omega^2\, M^{4/3}$$

where Ω is the angular velocity of the planet due to rotation.

With these predicted relations we can then calculate the variation in observed emission brightness expected for the measured variations in the solar wind density and velocity. For the earthlike model an increase of 3.0 times is predicted between the observations on July 18 and August 5, whereas only a factor of 1.9 increase is predicted by the disk dynamo model over the same period. The data indicate an increase of 15% with a significance of 1σ, applying the uncertainty for widely spaced observations. The predicted increase for the earthlike model would represent a 13σ change in brightness, and the disk dynamo prediction would represent a 6σ increase. These variations are therefore very significantly not observed in the data. Furthermore, we have taken the Voyager 2 measurements of the solar wind density and velocity covering the period from day 100, 1983, to day 365, 1984, and folded these data through the two predicted relations to determine the average ranges of variability expected for the two modeled cases. The earthlike case yields a predicted range of variability which appears significantly larger than the factor of 4 range in the self-excited emission observed from Uranus, tending to rule out even further an earthlike magnetosphere at Uranus. The disk dynamo range is not entirely inconsistent with the observed range of variability, but this may be a coincidence of the magnitude of the uncertainties in the IUE data since we consider only the larger observed variations to be highly significant.

6. Energy of the Precipitating Particles

We can derive some information about the energy of the precipitating particles producing the self-excited Uranus H Ly α emission from comparison of the ratio of H and H_2 emission strengths with those of the much better studied aurora on Jupiter. From the accumulated measurements of Uranus with IUE we derive an average auroral H Ly α brightness of 1200 ± 450 Rayleighs. A possible detection of H_2 Lyman band emission from Uranus with the IUE has been reported by *Caldwell et al.* [1983], and we have re-reduced these same data in an attempt to further constrain the possible brightness of any auroral H_2 emission. The time-weighted average of exposures SWP 9478, 8765, and 7680 is plotted in Figure 5 (top), and a comparison with a spectrum of Jupiter's aurora (Figure 5, middle) shows the potential H_2 feature at 1570 A. We have subtracted from this spectrum a summed spectrum of exposures of empty sky of comparable length to remove

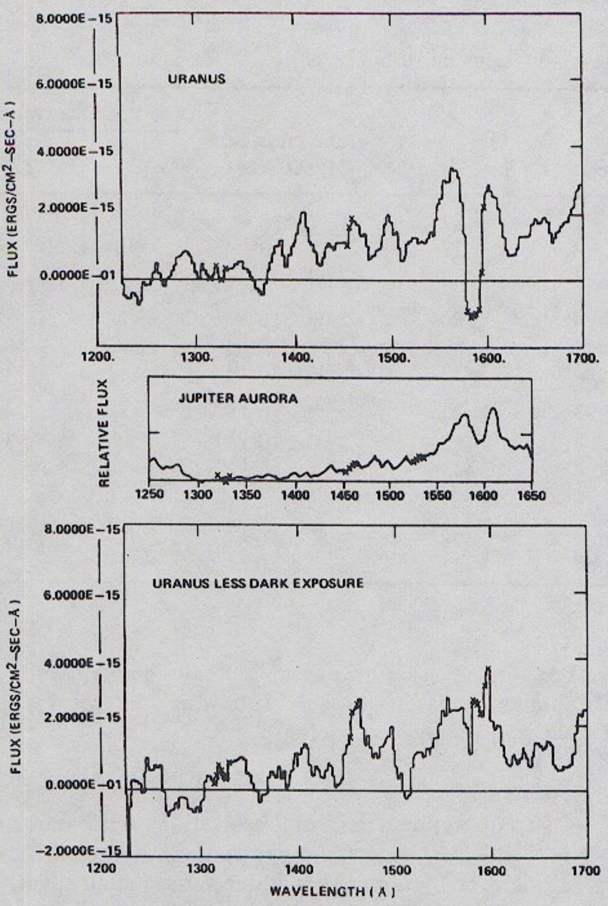

Fig. 5. IUE spectra of Uranus (top) attempting to detect the H_2 Lyman band emissions previously seen from the aurora on Jupiter (middle) and Saturn. After subtracting an empty sky exposure of comparable length, the suggestion of an emission at 1570 A is less pronounced (bottom), and we use this spectrum to derive upper limits to the H_2 brightness and the strength of any Raman-shifted feature at 1280 A.

possible detector features, which are known to contribute to the noise in the SEC vidicon cameras used in the IUE. After subtraction of the dark exposure (Figure 5, bottom) the potential H_2 feature is much less pronounced, and further long observations of Uranus have not yielded any detections of H_2 emission features (J. Caldwell, personal communication, 1985). We therefore take 3σ in the noise level at 1550–1650 A in the spectrum in Figure 5 (bottom) as an upper limit to the strength of any H_2 auroral emission, giving a flux in a 9-A FWHM line of $\leqslant 1.1 \times 10^{-14}$ erg/cm^2 s and corresponding to $\leqslant$ 500 Rayleighs disk average from the integrated H_2 bands longward of H Ly α (assuming the same relative H_2 spectrum as observed from Jupiter's aurora). Although the H Ly α and H_2 observations were not simultaneous, they each represent time averages in the Uranus emission.

The average ratio of H Ly α/H_2 brightnesses from the initial observations of Jupiter [*Clarke et al.*, 1980; *Durrance et al.*, 1982; *Skinner et al.*, 1984] is roughly 0.5. The lower limit that we derive for this ratio from Uranus is 1200/500 or 2.4, indicating that this ratio is significantly higher for the emissions from Uranus than for those from Jupiter. The interpretation of this ratio involves the relative densities of H and H_2 in the upper atmosphere and their variation with altitude, the energy and mass of the incoming particles, and the atmospheric absorption of the escaping UV emission. *Yung et al.* [1982] have modeled two color ratios in the IUE spectra of Jupiter's aurora, the ratio

$$R_1 = \text{H Ly } \alpha / H_2(1230\text{–}1650 \text{ A})$$

$$R_2 = H_2(1230\text{–}1300)/H_2(1557\text{–}1619)$$

They find that R_2 is most sensitive to methane absorption in the lower atmosphere, whereas for a constant R_2, R_1 is most sensitive to the energy of the incoming particles (i.e., their depth of penetration). Yung et al. derive a best estimate of 30 keV for the energy of precipitating electrons producing the Jovian aurora, and given the present uncertainties about the atmospheric composition and structure of Uranus, we wish to point out that a significantly higher ratio R_1 from Uranus suggests that the precipitating particles are likely to be less energetic than those at Jupiter.

7. Total Power and Effect on the Atmosphere

The extended base of IUE observations have provided an accurate time average for the brightness of the self-excited H Ly α emission from Uranus of 1200 ± 450 Rayleighs. We have converted this emission brightness to an estimate of the power in the precipitating particles necessary to produce the emission by the following analysis. In view of the evidence that methane is largely condensed out of the upper atmosphere of Uranus [*Danielson*, 1977], we assume that the majority of the H Ly α radiation escapes from the atmosphere (specifically that only 1/3 of the photons are absorbed before leaving the atmosphere). For lack of any observations of the nightside, we calculate the energy required for the cases of no emission from the nightside and emission equal to that observed on the dayside. The 1200-Rayleigh disk-averaged brightness then corresponds to a radiated power of 2.7×10^{10} watts, and assuming a 5% efficiency of production yields an input power of 5×10^{11} watts (or 10^{12} watts if the nightside is equally bright). We have further assumed that no significant fraction of the emitted H Ly α radiation is absorbed by interplanetary H en route from Uranus to the earth, since the relative motion of the interplanetary hydrogen toward the earth of roughly 25 km/s from the general direction of $\alpha = 17^h$, $\delta = -20°$ will Doppler shift the absorption line off most of the Uranus line. For comparison, the power estimates for the aurora on Saturn are a few times 10^{12} watts and roughly an order of magnitude higher for the aurora on Jupiter. In view of the much greater distance of Uranus from the sun, this again suggests that the Uranus emission might either be powered by internal processes (similar to the case of Jupiter) or by a more efficient coupling with the solar wind than the other planets. In any event, the power estimate indicates a substantial energization mechanism at Uranus, which is most likely an active magnetosphere.

A preliminary model of the effect of energy deposition on the atmosphere reveals that substantial heating and H_2 dissociation are likely in the thermosphere, at least in any auroral zones. For example, if it is assumed that, as on Saturn, the Uranian band is narrow (3° to 5° wide) and confined to high latitudes (75° to 85°), then a power input

TABLE 3. Voyager 2 Solar Wind Measurements in 1985

Voyager Data		Arrival Time at Uranus					IUE Observation	
Day of Year	Time, UT	Day of Year	Time, UT	Density, cm^{-3}	Speed, km/s	Ram Pressure, $dynes/cm^2$	Day of Year	Time, UT
191	1346	198	0846	5.0×10^{-3}	427	1.52×10^{-11}		
192	1722	199	0912	5.5×10^{-3}	427	1.68×10^{-11}	199	0400
193	1434	200	0130	7.0×10^{-3}	437	2.24×10^{-11}		
209	0930	215	2340	3.83×10^{-2}	394	1.00×10^{-10}		
210	0601	216	2330	4.30×10^{-2}	389	1.10×10^{-10}	217	0200
211	1645	217	1840	3.53×10^{-2}	422	1.06×10^{-10}		
247	0120	251	1544	10×10^{-3}	447	3.42×10^{-11}		
248	0308	252	2234	9.5×10^{-3}	427	2.90×10^{-11}	252	1800
249	1456	254	0451	20.0×10^{-3}	445	6.6×10^{-11}		
263	0247	266	2340	6.5×10^{-3}	473	2.44×10^{-11}		
264	0335	267	2350	12.5×10^{-3}	473	4.68×10^{-11}	267	2200
265	0712	269	0017	13.7×10^{-3}	491	5.56×10^{-11}		

of 10^{12} watts would imply an energy flux of 5 to 10 erg/cm^2 s. This flux is of the same order as in the auroral regions of Jupiter, and at least a factor of 10 greater than that at Saturn. If the Uranian emission is caused by keV electrons, then the local exosphere is expected to be heated to roughly 2000 K by 1-keV electrons and 3000 K by 10-keV electrons, similar to that at Jupiter. An interesting consequence of such high temperatures is a relatively high population of the vibrationally excited H_2 which would provide a rapid sink to the topside ion (H^+), thus substantially reducing the electron concentrations at auroral latitudes [*Atreya*, 1984; *Atreya and Ponthieu*, 1983]. The charged particle dissociation of H_2 at the Uranian auroral latitudes is expected to produce between 5 x 10^{10} and 5 x 10^{11} H atoms/cm^2 s. By way of comparison, the solar EUV produces only 10^8 H atoms/cm^2 s. Should an auroral band at Uranus be larger than that at Saturn, the above-mentioned atmospheric effects would be less dramatic. An extreme situation is where the emitting region is of the same dimension as the planet. This is tantamount to saying that the power is spread uniformly over the entire atmosphere. In this situation, the average energy deposition would be on the order of 0.12 to 0.18 erg/cm^2 s. Solution of a simple one-dimensional heat conduction equation (see, for example, *Atreya et al.* [1981] for Jupiter) then yields a range of 320 to 400 K for the Uranian exospheric temperature (the solar EUV alone would result in a 100- to 150-K range). The enhanced H abundance would range from 1 x 10^{17} to 3 x 10^{17} cm^{-2}, resulting in a disk-averaged H Ly α brightness of 100–300 Rayleighs due to resonant scattering alone. These values should be regarded as upper limits since, as mentioned earlier, the Uranian emission is probably smaller than the planet, in which case the energy would not be spread uniformly over the entire planet with a 100% efficiency. The previously mentioned minimum level of 800 Rayleighs observed thus appears to be greater than the maximum possible emission due to resonant scattering, supporting our assumption that part of the 800 Rayleighs is due to charged particle excitation.

In summary, it is evident that irrespective of the size of the emitting region at Uranus, some significant effect on the global thermospheric energy budget and the H abundance is inescapable following the precipitation of energetic charged particles.

8. CONCLUSIONS

The extended base of observations of Uranus obtained over the past 4 years supports the initial identification of a bright H Ly α emission which varies independently of the solar H Ly α flux. By analogy to the other planets studied to date, and in view of existing knowledge of the physics of the upper atmospheres of these planets, the most plausible interpretation of this emission is that it is produced by precipitating charged particles. The H Ly α emission exhibits a range of variability similar to the aurora on Jupiter, being essentially always detected at an average level of 1400 Rayleighs (of which we estimate roughly 200 Rayleighs may be due to reflected sunlight). Recent observations of the H Ly α emission under known solar wind conditions at Uranus have not indicated any correlation between the brightness of the emission and the solar wind density. The upper limit to H_2 emission gives a lower limit to the ratio of H Ly α/H_2 emissions of roughly 2.4, which suggests that the precipitating particles may be significantly less energetic on Uranus than those responsible for the relatively well understood aurora on Jupiter. Finally, we estimate an average power in precipitating particles of 5 x 10^{11} to 10^{12} watts, suggesting that the Uranus emission may be comparable in total power dissipated to the Saturn aurora.

Having concluded that the self-excited component of the Uranus emission is produced by charged particle excitation, and in view of the similarities between the variability and total power of the Uranus emission and the polar aurora on Jupiter and Saturn, we consider it likely that Uranus also possesses an active magnetosphere. If this proves not to be the case, then Uranus must produce H Ly α emission by some process which is thus far unprecedented in our study of the giant planets. We look forward with great interest to the Voyager 2 encounter with Uranus.

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