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A study of the upper atmosphere of Uranus using the IUE*

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Summary. The 1750 Å band of C_2H_2 has been detected in an IUE spectrum of Uranus recorded in 1980. The derived C_2H_2 column density is $6.8 \pm 3.4\ 10^{16}\ \mathrm{cm}^{-2}$. Eddy diffusion coefficients of $10^4\ \mathrm{cm}^2\ \mathrm{s}^{-1}$ or smaller at the homopause result in an abundance of photochemically produced C_2H_2 which is too low compared to the measurements. On the other hand, the results with $K = 10^5$ or $10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ are virtually undistinguishable from each other but give acceptable agreement with the data. The observed C_2H_2 is controlled by photochemistry and not by saturation, which takes place at lower altitudes.

Key words: planets and satellites – Uranus, Jupiter, Saturn – abundances – atmospheres

1. Introduction

In spite a large number of observations in the visible, IR and radio ranges, our knowledge of the upper atmosphere of Uranus, above the region of minimum temperature, is still poor. Some information about the stratosphere (at pressure levels ranging from 1 to 10 microbar) has been derived from stellar occultation measurements (French et al., 1983; Sicardy et al., 1985). Below this atmospheric region, our information comes from infrared observations, coupled with radiative transfer calculations by Courtin et al. (1978), Wallace (1980), and Appleby (1980). From these studies, the atmosphere above the minimum temperature level, at about 100 mb, has a positive temperature gradient that is significantly smaller than for the other giant planets. However, recent airborne observations in the far infrared are not fully consistent with these results (Moseley et al., 1985). On the other hand, the atmospheric region probed in the visible and near-infrared range is located at the tropopause and below, and cannot provide additional constraints on the lower stratosphere.

It has been known for several years that the atmosphere of Uranus behaves differently from the other giant planets. The absence of radiation from Uranus at 12 micron, in the C_2H_6 band, where the Neptune emission is very strong, was the first indication that the upper atmospheres of these two planets are different (Macy and Sinton, 1977; Gillet and Riecke, 1977). The reason could be a lower stratospheric temperature, combined with a possible smaller vertical mixing on Uranus, which would result in a lower abundance of gaseous C_2H_6 due to its condensation on Uranus (Atreya, 1984). As we shall see, this possibility can be tested by spectroscopic observations in the UV.

Other important differences exist between the two planets; First, the internal energy of Uranus is very small, if not zero, while the energy of Neptune is equal to about 2 times the amount of solar energy absorbed (Orton and Appleby, 1984; Pollack et al., 1986). Second, the peculiar inclination of Uranus, with its rotational axis nearly in the ecliptic plane, is likely to induce an atmospheric structure different from that of the other giant planets. Moreover, peculiar seasonal effects are possible. In particular, some variations could have occurred during the past 20 years, since the rotational axis has gradually moved into an orientation towards the Sun in 1986, leading to a situation where most of the southern hemisphere has a 100% insolation and the northern hemisphere is always in the dark.

The study of the reflected, absorbed or scattered UV radiation is a powerful tool for probing the upper atmosphere of Uranus. The region probed is the same as in the infrared emission lines at 12–13 micron (1–100 mb) but, in contrast to the thermal range, the strengths of UV absorption features depend upon the abundance of the absorber and not upon the temperature. Thus, the search for the C_2H_2 absorption band at 1700 Å in the spectrum of Uranus, could provide a powerful indicator of the characteristics of the lower stratosphere: e.g., if the C_2H_2 band is present on Uranus in significant amounts, it will imply that the absence of C_2H_6 on Uranus at 12 microns is most probably caused by low stratospheric temperature, rather than a low C_2H_6 abundance.

In this paper, we present the result of monitoring Uranus between 1980 and 1984, using the International Ultraviolet Explorer IUE satellite. The observations were made in the spectral range 1600–2000 Å since C_2H_2 exhibits diffuse absorption bands between 1650 and 1800 Å. Jupiter and Saturn were observed for

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* Based on observations collected at the Villafranca Satellite Tracking Station and at the Goddard Space Flight Center with the International Ultraviolet Explorer

** Work done while on sabbatical at Université de Paris comparison. Spectra of Neptune were also recorded over this period, but the signal to noise ratio below 1800 Å was not good enough for the data to be conclusive (Encrenaz, 1982; Caldwell et al., 1984). In the present study, we first analyse the IUE observations (Sect. 2); in Sect. 3, the C_2H_2 abundances are determined on Uranus, Jupiter and Saturn; in Sect. 4, these results are interpreted in terms of the structure and composition of the Uranus atmosphere. Part V summarizes the results.

2. The IUE data

Below 2000 Å, the reflection spectra of the giant planets roughly follow the slope of the solar spectrum, which drops by a factor of about 40 between 2000 and 1600 Å. As a consequence, several IUE spectra had to be taken with different exposure times, in order to record the complete spectrum of Uranus between 1600 and 2000 Å. For the short wavelength range of the spectrum, exposures of more than 10 h were recorded with IUE, using ESA/NASA combined shifts. The SWP camera was used in the low resolution mode, corresponding to a spectral resolution of about 7 Å in the case of the $3''$ circular aperture, and 10 Å in the case of the $10'' \times 20''$ aperture.

Table 1 lists the Uranus data recorded in the 1650–1900 Å region between 1980 and 1984. Other data corresponding to shorter exposures were also recorded. Before 1983, most of the data were recorded with the $3''$ aperture centered on Uranus. Then it was realized that a significant part of the flux was lost, due to Point-Spread-Function ($\sim 5''$ FWHM) and variable focus and the $10'' \times 20''$ aperture has been used since 1983. In the present paper, we selected the 1980 and 1984 data which have the best quality; we ignored the 1983 data which were affected by cosmic radiation hits.

As discussed in detail by Caldwell et al. (1984), there are several limitations on deriving the reflecting spectrum below 2000 Å. The first limitation comes from the choice of the solar spectrum taken as calibration: the measurements are difficult, and moreover the solar spectrum shows variations with time below 1900 Å. Several attempts were made to observe the Moon, Mars or solar-type stars, but they did not yield good results. We finally selected two solar spectra: Kjeldseth-Moe et al. (1976), and Mount and Rottman (1981, 1983). The two sets of data were used for determining the C_2H_2 abundances. The second limitation arises from the scattered light in the SWP, coming from the long wavelength radiation of the object. In the case of solar-type objects, the flux increases steeply toward longer wavelengths, so that this effect is not negligible. The correction due to the long wavelength scattering has been applied according to the procedure described in Caldwell et al. (1984).

We first searched for a detection of the individual C_2H_2 absorption bands. Since these bands are separated by about 15 Å, they can be resolved with the spectral resolution of IUE. The best range to search for C_2H_2 is the 1725–1850 Å interval: below 1725 Å, the signal to noise ratio is too low in the planetary data, while, at wavelengths longer than 1850 Å, the cross-sections of C_2H_2 become too small (Nakayama and Watanabe, 1964).

Figures 1 and 2 show the 1980 Uranus data, divided respectively by the solar data of Kjeldseth-Moe et al. (1976) and Mount and Rottman (1981). Jupiter and Saturn spectra are also shown for comparison. C_2H_2 bands seem to be present in the Uranus spectrum, at 1727 Å, 1753 Å, and 1775 Å, in both Figs. 1a and 2; however, the error bars are large, compared with the modulation of the spectrum, so that this identification is marginal. A more convincing indication of the presence of C_2H_2 is given by the general slope of the spectrum, which decreases continuously from 1900 Å to 1700 Å. The slope is comparable for Jupiter and Uranus, while it is much greater for Saturn, indicating the presence of a large amount of C_2H_2 on Saturn, as reported by Moos and Clarke (1979).

By analysing the different Uranus data from 1980 to 1984, we searched for a possible change with time in the C_2H_2 abundance. The 1984 data, which give the best signal to noise ratio, still do not provide unambiguous evidence for the presence of the individual C_2H_2 bands (Fig. 3). Owing to possible changes in the solar

Table 1

Year	Planet	Exposure time	Aperture	Image
1979	Uranus	1^h30	Large ap.	SWP 5746
	1^h	1^h30	SWP 5745	
1980	Uranus	14^h	Small ap.	SWP 9478
	5^h	14^h	SWP 7680	
	6^h30	14^h	SWP 8765	
1982	Uranus	6^h30	Small ap.	SWP 17425
	2^h25	6^h30	SWP 17419	
1983	Uranus	3^h30	Large ap.	SWP 20502
	6^h	3^h30	SWP 20503	
	13^h	3^h30	SWP 20505	
	6^h15	3^h30	SWP 20737	
1984	Uranus	10^h	Large ap.	SWP 23477
	10^h	10^h	SWP 23478	
1979/80	Jupiter	− 90 min	Lg + sm. ap.	Ref: Wagener et al. (1985)
1979/80	Saturn	− 20–360 min	Large ap.	Ref: Winkelstein et al. (1983)

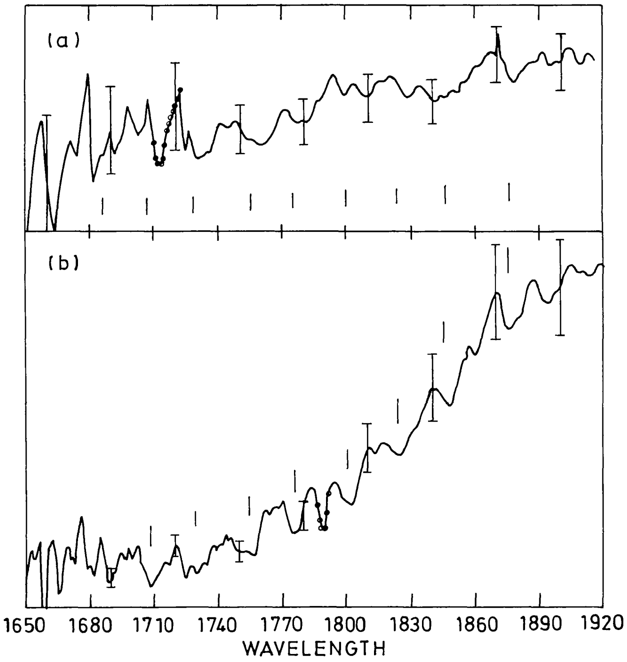

Fig. 1a and b. IUE spectra of **a** Uranus (1980) and **b** Saturn between 1650 and 1900 Å. The data have been divided by the solar spectrum of Kjeldseth-Moe et al. (1976)

spectrum during this same time interval, the case for variability of C_2H_2 absorption on Uranus is not yet obvious.

3. Determination of the C_2H_2 abundances on Jupiter, Saturn and Uranus

For each of these 3 giant planets, we measured the optical depth between 1700 Å and 1900 Å, every 50 Å, by smoothing the observational curves, and we used the cross-sections measured by Nakayama and Watanabe (1964) to derive, at each wavelength, a C_2H_2 column density.

The continuum level was assumed to be a horizontal line, as expected if due to Rayleigh-Raman scattering, and extrapolated from the level of the spectrum at 1950–2000 Å, where no absorption by C_2H_2 is expected to occur (see Fig. 2). In the case of Jupiter, the continuum was fitted at 1850 Å, because, above this wavelength, another absorption is visible, due to NH_3. In the case of Uranus, C_2H_2, which is the major dissociation product of CH_4, is expected to be the first compound responsible for the UV absorption. Other absorptions in the same wavelength range, due to other minor species are probably less important and should not affect the continuum level very much.

In order to reduce the uncertainty arising from the slope of the solar spectrum, we used both the Kjeldseth-Moe et al. spectrum (1976) and the Mount and Rottman spectrum (1981). Both reductions gave results in agreement within 10 % or less. The mean values of τ are given in Table 2 for each planet. The error bars on the column density include the uncertainty in the definition of the continuum level. For each planet, the air mass factor was estimated from the sizes of the planetary disks and the aperture used. The large error bars of the Jupiter and Uranus results come from the dispersion of the values obtained at different wavelengths; they illustrate that the "reflecting layer model", used in the present study, is not fully adequate because scattering effects are not taken into account.

Our results, in the case of Jupiter and Saturn, can be compared with previous determinations. For Jupiter, Owen et al. (1980) derived from the same C_2H_2 band an acetylene abundance of $3.5\ 10^{-3}$ cm-Am, which corresponds to a column density of $9.4\ 10^{16}\ \mathrm{cm}^{-2}$, in good agreement with the present study which gives $1.3 \pm 0.6\ 10^{17}$ (Table 2). The mixing ratio derived by Owen et al. is $2.2\ 10^{-8}$, assuming that the penetration level at 1750 Å is defined by Rayleigh scattering. This mixing ratio is in agreement with the determination of Wagener et al. (1985), as well as previous determinations derived from the C_2H_2 emission bands at 13 microns (Combes et al., 1974; Tokunaga et al., 1976; Orton and

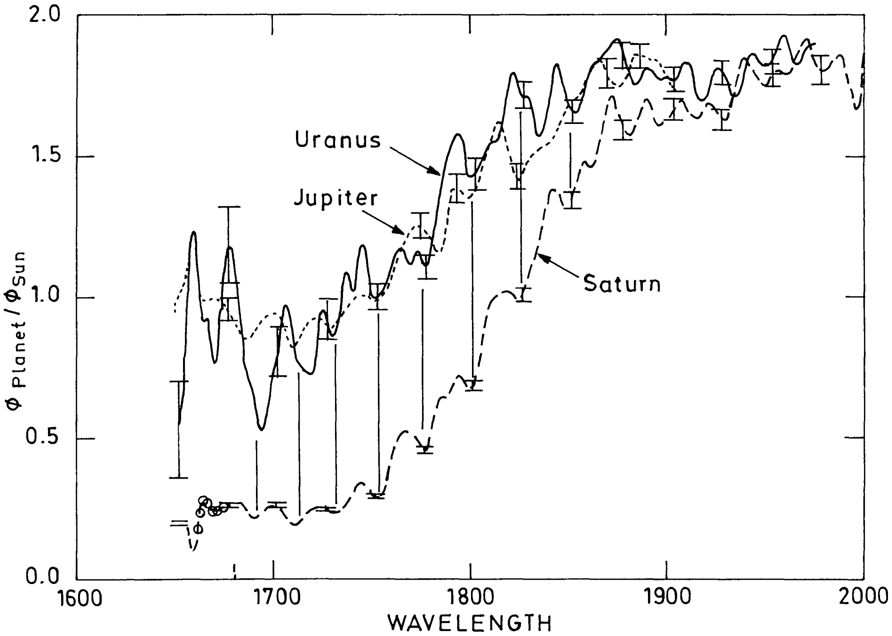

Fig. 2. IUE spectra of Jupiter, Saturn and Uranus between 1600 and 2000 Å. The data have been divided by the solar spectrum of Mount and Rottman (1981). The Uranus spectrum is composed of spectra from 1979, 1980, and 1982, smoothed with a 5 Å FWHM Gaussian filter

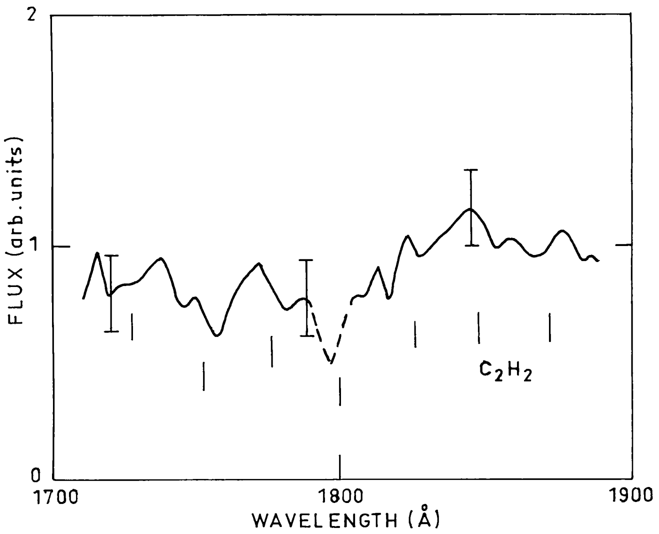

Fig. 3. IUE spectrum of Uranus (1984) between 1710 Å and 1890 Å, divided by the solar spectrum of Kjeldsetz-Moe et al. (1976)

Aumann, 1977). In the case of Saturn, our value of the C_2H_2 column density is in good agreement with the first estimate of $7\ 10^{17}\,\mathrm{cm}^{-2}$ made by Moos and Clarke (1979), also from IUE data. The good agreement obtained between our results and previous estimates, in the case of Jupiter and Saturn, gives us confidence that our simple model can be reliably used in the case of Uranus.

4. Discussion

Information about certain atmospheric characteristics is essential for theoretical interpretation of the measured C_2H_2 abundance on Uranus. Of particular concern is the atmospheric thermal structure. Unlike Jupiter and Saturn, the temperature is quite critical in determining the maximum allowable gaseous C_2H_2 in the atmosphere. Radiative convective models, such as those of Courtin et al (1978) and Wallace (1980) provide thermal structure up to about the 1 mb pressure level, and models of Orton et al. (1983) up to 0.1 mb. Between 0.1 mb and 1 microbar, the situation is less satisfactory, and is also not likely to improve substantially even after the Voyager observations. Thermal models of Appleby (1980) have a range of temperature gradients which differ widely from one another in the this pressure range. Around the microbar level, visible stellar occultations give the temperature information. Since C_2H_2 is produced in the photochemistry of CH_4, the temperature structure throughout the photolysis region should be known. It is, however, found from sensitivity studies done for Jupiter and Saturn (Atreya et al., 1981, 1984) that a 10 to 20 K change in the stratospheric temperature does not have any significant effect on the distribution and abundance of CH_4 and its photochemical products. Following the experience with Jupiter and Saturn, therefore, we have adopted a linear temperature gradient between the 0.1 mb and 1 microbar levels. The temperatures, H_2 densities and the saturated C_2H_2 mixing ratios for the adopted model atmosphere are listed in Table 3 for several altitudes of interest to the present discussion.

Another important quantity in photochemical studies is the vertical eddy diffusion coefficient K. Considering that Uranus possesses virtually no internal heat source, that it receives only 0.25% of the solar energy incident on the Earth, and that its globally averaged auroral energy input is perhaps small, it would seem that the strength of turbulent mixing at Uranus is small compared to Jupiter and Saturn. A value of 10^4 to $10^6\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ for K at the homopause of Uranus is likely. We adopt a nominal value of $10^5\,\mathrm{cm}^2\,\mathrm{s}^{-1}$ and assume its variation as $K \propto M^{-1/2}$, where M is the atmospheric density. Actually, as discussed later, the effect of K on C_2H_2 in the region of interest to the IUE observations is quite small unless K is very low.

The only other parameter of interest for the present discussion is the latitude. IUE observations represent a more or less hemispherical average, since the apertures used are comparable to or greater than the angular size of Uranus. Although the south pole of Uranus presently points to the Sun (and the Earth), it was oriented less so in 1980. The IUE observations reported here could be weighted more toward contributions from C_2H_2 at high latitudes. This effect, however, has been found to be quite localized. For example, the "bright spot" in C_2H_2 seen on Jupiter is narrow (less than a couple of latitude degrees wide) and has a well

Table 2

		Saturn		Uranus 1980		Jupiter	
λ	σ cm^2	τ	N cm^{-2}	τ	N cm^{-2}	τ	N cm^{-2}
1900	2.0(−19)	0.3	1.5 (18)	0.0	–	0.0	–
1850	4.0(−19)	0.7	1.75(18)	0.05	1.2(17)	0.07	1.7(17)
1800	8.0(−19)	1.4	1.75(18)	0.15	1.8(17)	0.22	2.7(17)
1750	1.1(−18)	2.0	1.8 (18)	0.49	4.4(17)	0.44	4.0(17)
1700	1.3(−18)	2.5	1.9 (18)	–	–	–	–
Mean value			1.75(18)		2.4(17)		2.8(17)
Planet size			16″		3.4″		40″
Aperture			10 × 20″		3.4″		3″ + 10 × 20″
Air mass factor η			2.7		3.5		2.2
Column Density			$6.5 \pm 1.2\ 10^{17}$		$6.8 \pm 3.4\ 10^{16}$		$1.3 \pm 0.6\ 10^{17}$

Table 3. Model atmosphere

Z(km)[a]	T(K)	H_2(cm^{-3})	fC_2H_2[b]	P(mb)
0	53.5	$1.2\ 10^{19}$	$5\ 10^{-16}$	100
25	56.0	$4.4\ 10^{18}$	$9.2\ 10^{-16}$	38.4
50	58.8	$1.7\ 10^{18}$	$3.9\ 10^{-14}$	15.5
75	64.6	$6.3\ 10^{17}$	$1.4\ 10^{-11}$	6.3
100	74.4	$2.5\ 10^{17}$	$2.0\ 10^{-8}$	2.9
110	80.1	$1.8\ 10^{17}$	$5.2\ 10^{-5}$	2.2
125	87.9	$1.1\ 10^{17}$	$2.3\ 10^{-5}$	1.5

[a] Altitude reference is at the tropopause, located at a mean pressure level of 100 mb where the temperature is approximately 53.5 K

[b] fC_2H_2 represents the saturated vapor mixing ratio of C_2H_2

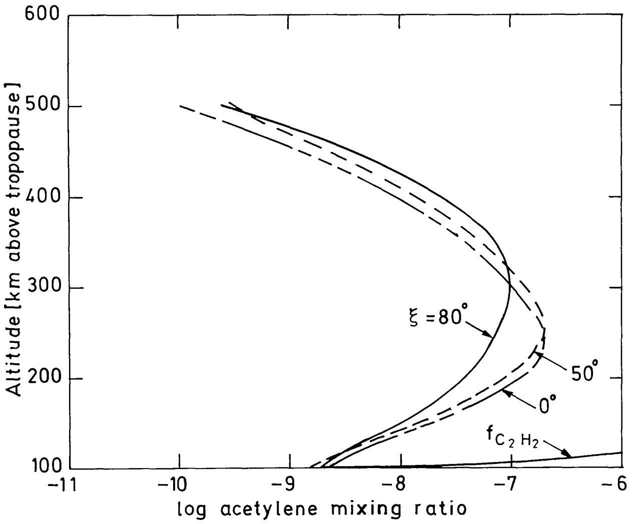

Fig. 4. Photochemical profiles of C_2H_2 at Uranus with $K = 10^5\ cm^2\ s^{-1}$ and solar zenith angles of 80°, 50° and 0°. Also shown is the curve for saturated vapor mixing ratio of C_2H_2 ($f\ C_2H_2$). See Table 3 for the atmospheric model

defined location (Kim et al., 1985; Drossart et al., 1986). For the present observations, therefore the photochemical interpretation can be regarded as quite appropriate. The latitude effect in the photochemical models can be simulated by choosing the appropriate solar zenith angle. The first photochemical calculations for the atmospheres of the giant planets were done by Strobel (1973, 1975). CH_4 photochemical calculations for Uranus are done in the same manner as those for Jupiter and Saturn (Atreya et al., 1981, 1984), and as the earlier preliminary calculations for Uranus (Atreya and Ponthieu, 1983; Atreya, 1984).

Typical C_2H_2 photochemical profiles for the case with a nominal value of $K(10^5\ cm^2\ s^{-1})$ at the homopause, and for 3 different latitudes, are shown in Fig. 4. The 3 latitudes are 2° N (solar zenith angle $\zeta = 80°$), 40° N ($\zeta = 50°$) and 80° ($\zeta = 0°$). At all these latitudes, the one-way optical depth in C_2H_2 (τ), (at the km level where C_2H_2 condensation begins) is found to lie between 0.05 and 0.06 at wavelengths between 1670 Å and 1750 Å. The value of τ is not found to change appreciably between 100 and 130 km. A range of 0.07 to 0.05 for τ is found with $K = 10^6\ cm^2\ s^{-1}$, and 0.04 to 0.02 with $K = 10^4\ cm^2\ s^{-1}$, all other parameters being the same. The C_2H_2 column abundances corresponding to the above optical depths are $4\ 10^{16}\ cm^{-2}$ for $\tau = 0.05$ and $5.4\ 10^{16}\ cm^{-2}$ for $\tau = 0.07$. Both values lie within the statistical range of the measured C_2H_2 abundance ($6.8 \pm 3.4\ 10^{16}\ cm^{-2}$). The higher mean value of τ is however preferred since it gives a mean C_2H_2 abundance in the best agreement with the measurement. There is approximately 50% uncertainty in the calculation of τ. The very low value of $K(10^4\ cm^2\ s^{-1})$ produces the least satisfactory agreement with the measurements, whereas it is difficult to discriminate between the cases with $K = 10^5$ and $10^6\ cm^2\ s^{-1}$. The range of C_2H_2 volume mixing ratios in the 100 to 130 km altitude interval (where $0.05 \leqq \tau \leqq 0.07$) turns out to be $3\ 10^{-9}$ to $8\ 10^{-9}$ (Fig. 4), not accounting for the uncertainty in the determination of τ. With the latter included, the above C_2H_2 volume mixing ratios would be correct to within a factor of 2. Here, it is important to point out that a factor of 2 decrease in the solar Lyman α flux between 1980 and 1984 would result in approximately 30% decrease in the photochemically produced C_2H_2 abundance. This decrease, however, will be partially compensated by the increased C_2H_2 production rate due to the pole turning toward the Sun in the same period. The H_2 densities in the above altitude range lie between $2.5\ 10^{17}$ and $1\ 10^{17}\ cm^{-3}$. The unit optical depth due to Rayleigh scattering by H_2 (τ_R) occurs for a H_2 column density of $6\ 10^{24}\ cm^{-2}$, corresponding to a density of $2\ 10^{18}\ cm^{-3}$ in the Uranus atmosphere. This level corresponds to an altitude of 50 km. Thus, it can be concluded safely that the C_2H_2 detected by IUE lies well above the level of $\tau_R = 1$ on Uranus.

Another important question is whether the detected C_2H_2 is simply the saturated vapor abundance of C_2H_2. This is most likely not the situation, because the saturated vapor mixing ratio is always greater than the photochemical mixing ratio (Table 3 and Fig. 4), hence condensation of C_2H_2 would not occur. Below 100 km, the saturated vapor pressure decreases rapidly so that the condensation of C_2H_2 is likely. Below 100 km, therefore, the saturated vapor pressure of C_2H_2 would not produce the needed optical depth for its detection. Above 100 km, the C_2H_2 abundance is mostly controlled by photochemistry, and not by saturation. Small differences in the stratospheric thermal models should not therefore affect the C_2H_2 abundances in the relevant height range of 100 to 130 km, since here C_2H_2 is photochemically controlled.

5. Conclusion

In this paper, we have searched for the 1700 Å C_2H_2 band in the UV spectra of Uranus obtained between 1980 and 1984. Our conclusions can be summarized as follows:

1. The C_2H_2 band is present in the 1980 spectrum and corresponds to a column density of $6.8 \pm 3.4\ 10^{16}\ cm^{-2}$.

2. The interpretation of the 1980 observations seems to rule out an eddy diffusion coefficient $K \leqq 10^4\ cm^2\ s^{-1}$ at the homopause. Models cannot discriminate between the C_2H_2 abundances obtained with $K = 10^5$ or $10^6\ cm^2\ s^{-1}$; both models yield reasonable agreement with the data.

3. The C_2H_2 observed in the 1980 IUE spectrum is produced by photochemical reactions, and not controlled by saturation. However, models predict that saturation is expected to occur just below the 100 km level; this C_2H_2 haze layer is likely to be the penetration limit, well above the Rayleigh penetration level at 1700 Å.

Finally, we can compare the K value derived for Uranus in this paper with the Jupiter and Saturn values. The Uranus value appears to be comparable to Jupiter's, while Saturn's value is 10 to 100 times higher. It is likely that C_2H_2 is mixed at higher altitudes on Saturn, implying that more C_2H_2 is observed in the UV spectrum; this is what we observe in the IUE spectra.

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Note added in proof: A preliminary estimate of the C_2H_2 abundance from the Voyager UVS experiment is 2 $10^{16}\,\mathrm{cm}^{-2}$ at the 0.3 mbar level (Broadfoot et al., to appear in *Science*, 1986)