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Hα variability in the quiescent spectrum of the recurrent nova T Coronae Borealis

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SUMMARY

The emission lines in the quiescent spectrum of the recurrent nova T Coronae Borealis are variable. Optical spectra recorded during the years 1985–90 show one full cycle of high and low states. After removing the slow variation, an orbital-phase-dependent variation becomes apparent in the Hα line, with maxima around orbital phases 0 and 0.5. The slow variation indicates secular changes in the accretion disc possibly caused by a variable mass transfer rate. Orbital variations can be caused either by geometrical effects or a phase-modulated mass transfer rate. More detailed monitoring is needed to model the system.

1 INTRODUCTION

T Coronae Borealis belongs to the group of recurrent novae, with two recorded outbursts in 1866 and 1946. The outbursts were identical photometrically (Campbell 1948). T CrB is visually the brightest known recurrent nova, reaching a magnitude $m_v \approx 2$ at maximum. The rate of decline of 0.4 mag per day classifies it among very fast novae (Payne-Gaposchkin 1957). Both outbursts were characterized by the appearance, at ~106 d since maximum, of a secondary maximum reaching $m_v \approx 8$ (Pettit 1946; Sanford 1949).

The interacting binary nature of T CrB is well established. It consists of a cool, mass-losing secondary and a hot accreting primary. Radial velocity measurements based on optical data yield an orbital period of 227.53 d with semi-amplitudes $K_1 = 23.32$ km s^{-1} and $K_2 = 33.76$ km s^{-1}, where the subscripts 1 and 2 refer to the secondary and primary respectively. An estimate of 68° for the orbital inclination results in the mass estimates of the secondary and primary as 3.34 ± 0.73 $M_\odot$ and 2.31 ± 0.29 $M_\odot$, respectively (Webbink *et al.* 1987 and references therein). The estimated mass of the primary poses a problem to the thermonuclear models of outburst, which presume a white-dwarf primary. A decrease in the value of K_2 by 8 km s^{-1}, which is within the errors of radial velocity measurements would reduce the mass of the primary to ~1.4 $M_\odot$ allowing for a massive white-dwarf primary (Selvelli, Cassatella & Gilmozzi 1989).

The spectrum in the ultraviolet (UV), as observed by the *International Ultraviolet Explorer (IUE)*, is dominated totally by the hot component that appears to be an accreting white dwarf (Cassatella & Selvelli 1988; Selvelli, Cassatella & Gilmozzi 1989; Gilmozzi, Selvelli & Cassatella 1991). The spectrum consists of high- and low- excitation permitted and intercombination emission lines, P-Cygni profiles and absorption lines of singly ionized metals (Cassatella, Gilmozzi & Selvelli 1985). The UV continuum varies significantly both in slope and intensity, and can be fit by a power-law spectrum $f_\lambda = A\lambda^{-\alpha}$ over the entire *IUE* range. The spectral index α varies from 0 to 2.0 with a mean value of 1.3 (Gilmozzi, Selvelli & Cassatella 1991), which is lower than the value 2.33 for an optically thick steady accretion disc. The integrated UV luminosity varies from 2.6×10^{34} erg s^{-1} at a low state to 2.6×10^{35} erg s^{-1} at a high state. The mean UV luminosity is 2.2×10^{35} erg s^{-1} (Selvelli, Cassatella & Gilmozzi 1989).

The quiescent optical spectrum of T CrB is that of the cool secondary, but with emission lines of H I, He I, He II, [O III], [N III] superposed, similar to the spectra of symbiotic stars (Swings & Struve 1941; Andrillat & Houziaux 1982; Kenyon 1985). The spectral type of the secondary is estimated to be M3III (Berman 1932; Joy 1938), M4.1 ± 0.3III (Kenyon & Fernandez-Castro 1987) and M5III (Duerbeck & Seitter 1989). Emission-line variability was reported by Kenyon & Garcia (1986), the emission lines being bright in 1984 April but faint in 1981 February and 1985 June.

Photometry of T CrB during quiescence has shown variations in the light curve, especially in blue light (Bailey 1975; Peel 1985; Lines, Lines & McFaul 1988; Peel 1990). This was identified as the ellipsoidal variations of the tidally-distorted secondary (Bailey 1975). Peel (1990) has recently analysed several photographic (1892–1911; 1929–35) and visual (1872–1979) light curves of T CrB at quiescence to look for orbital phase consistency in the variations. Minima in the photographic light curve have been detected at phases 0 and 0.5. The minimum at 0.5 phase is shallower and there is a tendency for short-lived brightening to occur at phases

0.45 and 0.58. Lines, Lines & McFaul (1988) detect an additional ~55-d periodicity in the *UBV* bands with the amplitude being maximum in the *U*, which they attribute to semi-regular variations of the secondary. However, these results are disputed by Peel (1990) who suggests that they were an artefact of analysis. The fact that the reported periodicity is exactly one-fourth of the orbital period supports Peel's view.

Variations in the UV continuum and line fluxes (Cassatella *et al.* 1982; Cassatella, Gilmozzi & Selvelli 1985) and in the optical line fluxes (Kenyon & Garcia 1986) have been reported. Correlation of these variations with the orbital phase was, however, not evident since the data were too scanty. The results of optical spectroscopic monitoring with a 5-yr baseline presented here show a long-term variation in the equivalent width of Hα line emission. Superposed on this is an orbital-phase-dependent variation with emission peaks near 0.0 and 0.5 phases.

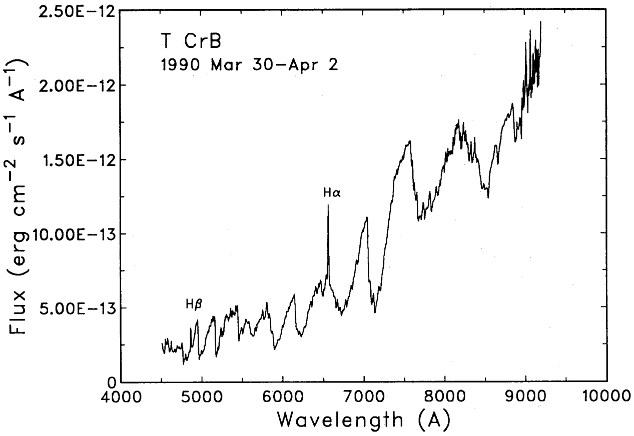

Figure 1. The spectrum of T CrB averaged over four nights between 1990 March 30 and April 2.

2 OBSERVATIONS

T CrB was monitored spectroscopically during the years 1985–90 from the Vainu Bappu Observatory (VBO), Kavalur using the 102-cm reflector. Low-dispersion spectra covering the wavelength range 4400–9200 Å were recorded. During 1985–89 photographic image-tube spectra were recorded. In 1985, spectra at dispersion 200 Å mm^{-1} in the wavelength range 5000–8800 Å were recorded on Kodak IIaD plates. The spectrograms obtained in 1986 and 1987 cover a wavelength range 4600–7100 Å at a dispersion of 86 Å mm^{-1} and were also recorded on Kodak IIaD plates. The data obtained in 1988 and 1989 were recorded on Kodak 103aD plates at a dispersion of 200 Å mm^{-1}, covering wavelength regions 4000–8000 or 5000–8800 Å. The spectrograms were digitized at 5-μm intervals using a PDS 1010M microdensitometer. The digitized spectra were Fourier smoothed using a low-pass filter with cut-off at 12 cycles mm^{-1}. The smoothed spectra were then brought to a relative intensity scale and wavelength calibrated using the Fe + Ne comparison spectrum. The spectra were then normalized with respect to the continuum level and the equivalent widths of the emission lines were measured.

From 1989 December to 1990 April, CCD spectra of T CrB were obtained at 5.5 Å per pixel resolution in the wavelength ranges 4400–7600 and 6000–9200 Å. The CCD frames were individually de-biased, flat-field corrected, and the one-dimensional spectra extracted. An Fe + Ne comparison source was used for wavelength calibration. At least one of the spectrophotometric standards Feige 15, HD 60778, HD 109995, HD 19445, EG 99, HD 117880, HD 161817 and Feige 66 was observed for flux calibration on each night. The contributions due to telluric absorption bands in the infrared region of the spectrum were removed by preparing a mask based on the standard star spectrum. CCD observations of T CrB were generally made as it was rising, at fairly low hour angles. The continuum in the red region of the spectrum was found to be affected by atmospheric refraction since the slit of the spectrograph was aligned almost perpendicular to the atmospheric dispersion. The spectra obtained during 1990 February to 1990 April were corrected for this effect as follows: T CrB was observed on each night with the spectrograph slit opened to ~13 arcsec such that all the light from the star passed through the slit. The flux-calibrated wide-slit spectra were treated as standards and a correction curve determined to scale the narrow-slit spectrum continuum level to match that of the wide slit over the entire range of the spectrum.

All reductions (photographic as well as CCD data) were performed at the VAX 11/780 installation at VBO using the RESPECT (Prabhu & Anupama 1991) software package.

3 THE SPECTRUM

Fig. 1 shows the mean flux-calibrated CCD spectrum of T CrB in the wavelength range 4500–9200 Å obtained by summing the spectra recorded on 1990 March 30, 31 and 1990 April 1, 2. The spectrum has been corrected for interstellar reddening using $E(B-V)=0.15$ (Cassatella, Gilmozzi & Selvelli 1985) and the Savage & Mathis (1979) law. The spectrum is dominated by strong TiO absorption features from the secondary, and superposed Hβ and Hα emission lines. He I emission lines are weak in the spectrum shown in the figure. Spectra obtained during the latter half of 1985, and in 1986 and 1987 show strong He I 5876-, 6678- and 7065-Å lines. He I lines are also seen in some spectra obtained in 1989.

Table 1 lists the equivalent widths of the emission lines Hβ, Hα, He I 5876, 6678 and 7065 Å. The equivalent widths were measured as follows: the spectra were reduced to a continuum level estimated as a smooth curve through the absorption bandheads. The equivalent width of an emission line was measured as the area enclosed by the emission profile above the local continuum which may lie in an absorption band. The equivalent widths are hence the total emission-line fluxes referred to the overall continuum of the star. Scaling the Hα flux observed by Kenyon & Garcia (1986) on 1985 June 1 and 2 by the continuum at the base as shown by their 1984 April spectrum, we obtain an equivalent width of 6.6 Å which may be compared with the value of 9.7 Å from Table 1 on 1985 May 17 (JD 2446202). Assuming that the spectrum does not vary over a time-scale of one day, one may compare the spectra of adjacent days to evaluate the overall error of measurements. The inferred errors for photographic data with T CrB in a high state (Hα equivalent width > 10 Å) are 20 per cent for Hα, Hβ and He I 5876 Å, 30 per cent for

Table 1. T CrB: Emission-line equivalent widths in Å units.

Date (JD) 2440000+	Phase*	Hβ 4861	Hα 6563 Obsd	Hα 6563 Norm	He I 5876	He I 6678	He I 7065
6124.440	62.368		17.09	2.34		1.32	0.67:
6183.332	62.627		8.02	0.96			
6184.309	62.631		8.76	1.04			0.46
6202.275	62.710		9.73	1.09	1.62		
6484.500	63.951		15.42	0.97	1.83		
6493.347	63.989		25.66	1.60	3.58	0.76	
6541.234	64.200		15.97	0.93			
6568.224	64.319	6.56	19.34	1.10	1.33	0.85	
6574.390	64.346	7.65	15.05	0.85	0.94	1.35	1.36
6639.169	64.630	12.80	22.61	1.21	1.83	1.76	
6828.483	65.471	11.51	31.22	1.82	1.29	1.86	0.79
6829.397	65.475	8.77	23.30	1.36	1.54	2.45	2.95
6859.342	65.598	12.42	37.18	2.35	2.11	2.11	2.63
6860.330	65.602	12.86	35.48	2.25	2.40	1.36	1.20
6895.340	65.756	5.42	18.81	1.36	1.31	1.37	
6936.283	65.936	10.94	24.58	2.16	3.20	1.80	
6937.203	65.940	10.59	23.54	2.07	2.18	1.66	
6951.161	66.002	4.30	17.48	1.63	0.92	1.01	1.62
6959.267	66.037	5.38	12.82	1.26			2.37
6964.220	66.059	6.55	19.61	1.96	2.06	1.28	1.87
6965.157	66.063	8.12	25.96	2.60	1.47	1.07	
6999.200	66.213	2.85	8.19	0.96			
7040.120	66.393		9.90	1.36			
7042.126	66.401		3.68	0.50			
7177.470	66.996		7.35	1.50			
7178.476	67.001		5.26	1.07			
7211.367	67.145		4.99	1.10			
7213.368	67.154		5.45	1.21			
7236.357	67.255		7.13	1.70			
7268.400	67.396		7.19	1.85			
7295.250	67.514	5.51	10.22	2.76			
7304.306	67.554		7.07	1.90			
7324.144	67.641		3.15	0.90			
7386.158	67.913		4.69	1.47			
7527.496	68.535		4.89	1.88			
7537.475	68.578		3.41	1.31			
7538.473	68.583		4.28	1.65			
7574.390	68.741	1.26	2.91	1.16			
7575.392	68.745		2.31	0.92			
7616.377	68.925		3.65	1.52			
7617.285	68.929	3.62	6.66	2.77			
7630.291	68.986	2.25	4.93	2.05			
7631.285	68.991		5.61	2.34			
7659.358	69.114		2.31	0.96			
7660.240	69.118		4.27	1.78			
7892.475	70.139	1.42	1.89	0.73			
7894.482	70.147		2.75	1.06			
7904.443	70.191	0.63	2.70	1.04			
7944.438	70.367	1.23	3.29	1.17			
7975.371	70.503	1.70	3.19	1.06			
7981.369	70.529	3.21	7.02	2.34			
7982.344	70.534	2.65	6.75	2.25			
7983.335	70.538		7.99	2.67			
7984.291	70.562		8.85	2.95			

* T_0 = JD 2,431,933.83 (Kenyon & Garcia 1986).

He I 6678 Å, and 100 per cent for He I 7065 Å which falls at the edge of the spectrum. It was possible generally to measure only the Hα equivalent width when T CrB was in a low state (Hα equivalent width < 10 Å). The errors in this case are 30–50 per cent for photographic data, depending on Hα flux, and 10 per cent for CCD data.

The spectrum of the secondary is dominated by TiO absorption bands, the prominent ones being at 4761, 4954, 5167, 5448, 5598, 5849, 6159, 6651, 7054, 7126, 7589, 8430 and 8860 Å. The bands of VO at 7865, 7895 and 7939 Å are also visible. Ca II triplet at 8498, 8543, 8662 Å and Ca I 6472, 6494, 6500 Å are the strongest absorption lines. Following Kenyon & Fernandez-Castro (1987) the spectral type of the secondary can be determined from TiO and VO indices, and its luminosity from the Na I infrared doublet index. The spectrum presented in Fig. 1 yields a $[\mathrm{TiO}]_1$ 6180-Å index of 0.54 corresponding to M3.3, $[\mathrm{TiO}]_2$ 7100-Å index of 0.78 corresponding to M4.3 and [VO] 7865-Å index of 0.22 corresponding to M4.2. The [Na] 8190-Å index of −0.08 lies within the range for giants as given by Kenyon & Fernandez-Castro. Based on the above values, a spectral type M3.9 ± 0.6 III is assigned to the secondary. This value agrees with published estimates referred to in Section 1.

4 EMISSION-LINE VARIABILITY

It is evident from Table 1 that the emission-line equivalent widths vary by a large factor. The Hα equivalent width is available throughout our observations and is plotted in Fig. 2 as a function of time. A slow variation is evident in the figure with a high state around JD 2446800 and a low state after JD 2447400. Superposed on this is a shorter period variability. In order to search for periodicities in the data, a power spectral analysis was carried out following the method due to Press & Rybicki (1989). The most significant peaks were found at 439 ± 26 d and 298 ± 12 d. These coincide with the expected beat periods of 454 d and 305 d due to 1-yr seasonal gaps in the data and the 5-yr baseline. The next peaks in the order of importance were at 122 ± 4 d and 108 ± 4 d. These can be produced by a beat of 113.76 d (half an orbital cycle) period with the 5-yr baseline. These two peaks are of low significance (~ 10 per cent probability) and are flanked on either side by peaks of similar, but slightly lower, significance. This entire structure around 0.5 orbital cycle periodicity was absent in simulated data with either low-frequency variation alone, or random data, spaced according to the epochs of observation. This periodicity hence appears physically significant, and its statistical significance is low due to incomplete sampling.

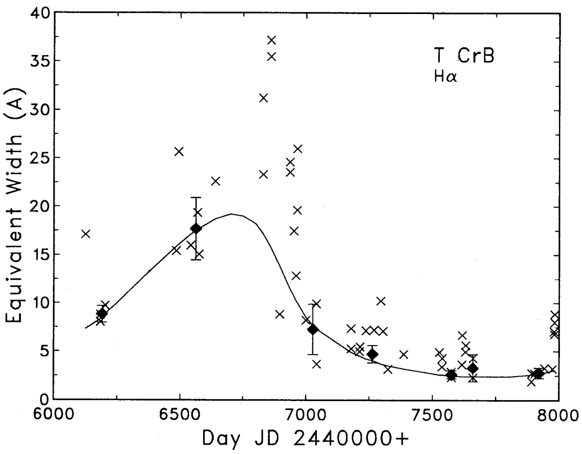

Figure 2. The observed equivalent widths of Hα line (×) as a function of time (JD 2446000.5 = 1984 October 27). The smooth line joins the mean minimum equivalent width in each orbital cycle, the latter are shown (◆) together with ± 1σ error bars.

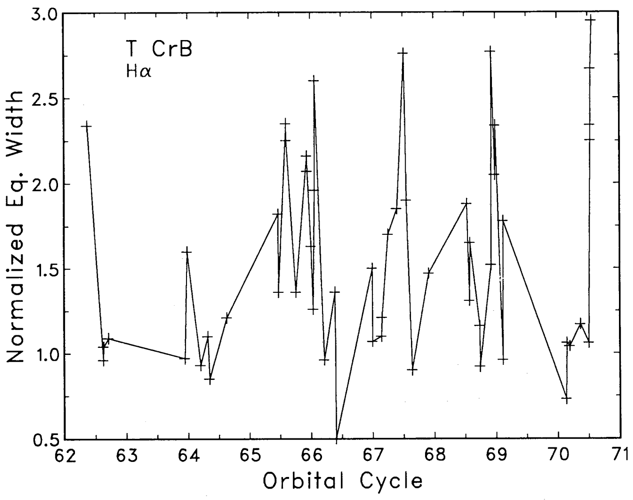

Figure 3. The observed equivalent widths of Hα line, normalized by the smooth curve shown in Fig.2, plotted as a function of orbital cycles. The peaks are close to phases 0.0 and 0.5.

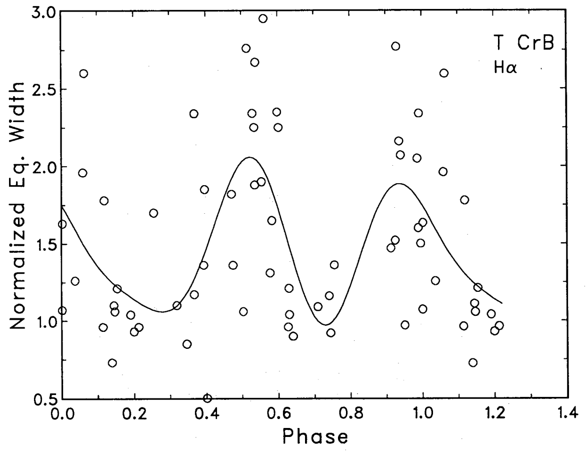

Figure 4. The normalized equivalent widths of Hα line (○) plotted as a function of orbital phase. A truncated Fourier series fit with three lowest frequency components is shown by a smooth line. The scatter of observed points is largely due to cycle-to-cycle variations of equivalent widths and small variations in the phases of the peaks.

In order to examine the 0.5-cycle periodicity further, a baseline of slow variation was removed from the observed equivalent widths. The baseline was defined as a smooth curve passing through the mean minimum equivalent width for each cycle. The adopted mean values and the smooth curve are both shown in Fig. 2. The observed Hα equivalent widths were normalized dividing by this smooth curve, and are plotted in Fig. 3. These data are also listed in Table 1. The phase is reckoned on the ephemeris of Kenyon & Garcia (1986): T_0 = JD 2431933.83, the epoch of inferior conjunction of the M giant. It should be noted that some of the earlier workers chose to use the epoch of superior conjunction and thus their phases differ by 0.5. Enhanced emission at phases 0.0 and 0.5 is evident in this figure except during the cycles when these phases are not adequately covered. The enhancement takes place over a short duration, typically 0.15 in phase. This periodicity is not clearly evident in power spectra due to the fact that many such enhancements were missed in the data.

A Fourier analysis of normalized equivalent widths (*Eqn*) using a three-term truncated Fourier series yields

$$
\begin{aligned}
Eqn = &(1.461 \pm 0.115) - (0.043 \pm 0.134) \cos \phi \\
&- (0.095 \pm 0.188) \sin \phi + (0.428 \pm 0.159) \cos 2\phi \\
&- (0.055 \pm 0.162) \sin 2\phi - (0.100 \pm 0.167) \cos 3\phi \\
&- (0.135 \pm 0.153) \sin 3\phi, \qquad (1)
\end{aligned}
$$

where ϕ is the phase in radians (the errors are standard deviations). The Fourier fit as given by the above equation is plotted in Fig. 4. The light curve shows two well-defined maxima around phases 0.93 and 0.53. The double-peaked nature of the light curve is apparent from the fact that the amplitude of the term with exactly half the orbital period is the most dominant. Most of this amplitude is in the cosine component indicating that the maxima are close to phase 0.0 and 0.5. Components with orbital period and one-third orbital period only change the shapes of these maxima. Ignoring these components, a good fit is possible with a pure cos 2ϕ curve. On the other hand the sharpness of peaks seen in Fig. 3 indicates that the light curve is not purely cosine. The peak near phase 66.0 is clearly double-peaked with peaks at 65.94 and 66.06 flanking the dip at 66.04. No other maximum was, unfortunately, so well covered. The scatter in Fig. 4 may owe its origin to such structures in peaks and in cycle-to-cycle variations in the structure.

One may look for variability of all the emission lines during the high state. Unfortunately the data in Table 1 is sparse during cycles 64–66 when T CrB was in a high state and it was easy to record He I and Hβ lines. Particularly, orbital phases 0.1–0.3 and 0.7–0.9 are not well covered. An average of available data grouped into four epochs indicates that variations are indeed present in all the lines. These are shown in Table 2. He I 7065 Å is not considered because of the large uncertainty in the estimates of equivalent width. The non-detection of He I lines at phase 66.305 implies that the equivalent widths were < 1.3 Å. It should also be noted that the activity of T CrB was steadily decreasing during this period.

5 DISCUSSION

The Hα line equivalent width exhibits a slow variation over the time-scale of years and also an orbital-phase-dependent variation with peaks at 0.0 and 0.5 phase. Photometric monitoring of T CrB during 1981–83 by Lines, Lines & McFaul (1988) showed a ~30 per cent variation in the broad-band *R* flux. This variation is much smaller in magnitude compared to the long-term variation of Hα emission-line equivalent width indicating that the latter variation is dominated by intrinsic variations of line flux. A minimum in the *R*-

Table 2. Average equivalent widths at four epochs in orbital cycles 65 and 66.

Phase	Mean equivalent width (Å)			
	Hβ	Hα	He I	
			5876	6678
65.537	11.39	31.79	1.83	1.94
65.756	5.42	18.81	1.31	1.37
66.009	6.95	19.29	1.66	1.99
66.305	2.85	7.49	< 1.30	< 1.30

band flux has also been detected by Lines, Lines & McFaul (1988) near phases 0.0 and 0.5. This decrease in the continuum flux ($\Delta m < 0.4$ mag) accounts for < 30 per cent of the increase in the Hα equivalent width around these phases. It is hence unlikely that the emission enhancement is due to a decrease in the continuum.

Variations in the UV continuum and line fluxes have been reported in the literature (e.g. Cassatella *et al.* 1982; Cassatella, Gilmozzi & Selvelli 1985). Although the available UV data are scanty, the emission-line fluxes (N v, O I, C IV, He II, Mg II) estimated from *IUE* data (published and unpublished: A. Cassatella; personal communication) suggest a long-term variability. Deep minima exist around JD 2443953 (1979 March 21) and JD 2447587 (1989 March 2). Between these minima, two other minima are clearly present around JD 2445568 (1983 August 22) and JD 2446452 (1986 January 22), and maxima around 1983 May–June, JD 2446133 (1985 March 9) and JD 2446949 (1987 June 3). The maximum in 1987 coincides with the maximum observed in the Hα light curve around JD 2446859, and the subsequent deep minimum agrees with the minimum in the Hα line. It would appear that the UV spectrum varies more strongly during the 'high' state. The UV data also give an indication of increase in the line fluxes between phases 53.34–53.42 and 68.80–68.96, which are near the 0.5 and 0.0 maxima in Hα. The increase during 68.80–68.96 coincides with the Hα flux increase during 68.75–69.11. There are also indications for variations in the electron densities. Based on the density sensitive Si III] 1892-Å/C III] 1909-Å line ratio, we find that the density changed from 3×10^{10} to 5×10^{10} cm^{-3} during phase 53.34–53.42 and from 2×10^{10} to 4×10^{10} cm^{-3} during phase 68.80–68.96. Also, the electron density had a much higher value of 1.8×10^{11} cm^{-3} in 1981 February at phase 55.90. A similar value is already reported by Cassatella *et al.* (1982) based on high-resolution data on N III] 1750-Å line. However, the available UV data are too sparse for an effective comparison of the optical data presented here.

The data presented here are clearly insufficient towards an attempt to infer the cause of these variations. The simplest possible explanation for the slow variation would be a secular change in the structure of the accretion disc, probably associated with variations in the mass transfer rate. A similar explanation for the enhancements at fixed orbital phases would require the mass transfer to be phase modulated. A similar suggestion has been made by Peel (1990) for explaining the structure near the minima in broad-band fluxes. The possible correlation between the UV continuum, line and the Hα line fluxes and the marginal increase in density around phases 0.0 and 0.5 support this suggestion. On the other hand, orbital-phase-dependent variations can be produced by geometrical effects. It has been suggested that the minimum around phases 0.0 and 0.5 in the broad-band light curve is due to ellipsoidal variations in the secondary. However, this cannot explain enhanced emission at these phases unless the emission originates along the shorter axis of the secondary itself. The emission light curve is out of phase with the broad-band light curve. The dips at 0.25 and 0.75 phase in the emission-line curve can be explained if there is a CQ Cephei kind of stream originating from the secondary to the primary whose different portions are occulted by the secondary and primary respectively at the above phases. The situation may be more complex if the system contains a third body as contemplated by Gilmozzi, Selvelli & Cassatella (1991).

The nature of variations in the spectrum of T CrB can be understood better only if multiwavelength observations are obtained with good time resolution over at least one orbital cycle. Of particular interest would be observations of UV continuum for modelling the accretion disc, and of UV and optical lines to derive the physical conditions in the line-emitting region. Observations of emission lines with sufficient velocity resolution will permit isolating different line-emitting components, and also ascertain if one of the components is eclipsed/occulted at quadrature phases.

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