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# Rapid H$\alpha$ Variability in T Coronae Borealis[1]

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**ABSTRACT.** We report on a search conducted for variability in the H$\alpha$ emission line of the recurrent nova T CrB with a time resolution of 10–15 minutes. This is comparable to the timescale of the photometric flickering observed in this object. This is the first time that observations of the short-timescale emission-line variation have been made for this system. On two nights (1999 January 6 and 7), we detected statistically significant variability (at the 99% confidence level) in the H$\alpha$ line profile. This variability is confined to the central part of the emission line ($\pm 100$ km s$^{-1}$), although FWZI(H$\alpha$) $\sim 800$ km s$^{-1}$. The variability in the line profile is accompanied by variability of the total equivalent width, EW(H$\alpha$): $\pm 8\%$ for 1999 January 6 and $\pm 6\%$ for 1999 January 7 (calculated from the mean EW value). Assuming Keplerian motion, the variability is generated at a distance of $\sim 20$–$30\ R_\odot$ from the white dwarf, which is approximately the radius of the ring that the stream of gas forms as it flows away from the L1 Lagrangian point. For three other nights we are only able to put upper limits on the variability, $\Delta$EW(H$\alpha$): $\pm 2\%$ for 1998 April 15, $\pm 4\%$ for 1998 August 2, and $\pm 3\%$ for 1998 August 3.

## 1. INTRODUCTION

The short-term photometric behavior of symbiotic stars has been investigated in many systems (e.g., Dobrzycka et al. 1996; Sokoloski et al. 2001). However, so far there have been no systematic searches for rapid *spectral* variations. Until now, the search for rapid spectral variability has been undertaken in only three symbiotic stars: CH Cyg, MWC 560, and RS Oph. All three are known to exhibit flickering and to have collimated outflows. Rapid spectral variability in the Balmer lines of CH Cyg, on timescales of about an hour, has been detected and is probably connected to blobs ejected from a white dwarf acting as a propeller (Tomov et al. 1996). For RS Oph, Sokoloski (2003) reported variability on timescales of hours in the He II 4686 Å line, although no variability in H$\beta$ was detected. No significant variability has been detected in MWC 560 (Tomov et al. 1995).

In a few cataclysmic variables (CVs), which are closely related to symbiotic stars, rapid spectral changes are visible in optical and ultraviolet lines as the result of a variable accretion disk wind: BZ Cam (Ringwald & Naylor 1998), V592 Cas (Witherick et al. 2003), RW Sex (Prinja et al. 2003), V603 Aql (Prinja et al. 2000a), and BZ Cam (Prinja et al. 2000b). The detection of variability on timescales of tens of minutes in symbiotic stars and cataclysmic variables provides the motivation for this study.

T Coronae Borealis consists of a red giant and a hot component, most probably a white dwarf. T CrB can be classified as a cataclysmic variable, symbiotic star, and recurrent nova, and it accretes at a rate of $1 \times 10^{-8}\ M_\odot$ yr$^{-1}$ (Selvelli et al. 1992). This places it among the cataclysmic variables with the highest accretion rates (see Warner 1995, p. 476), and for such high accretion rates an accretion disk wind could be expected. Here we report on a search for signatures of variability in time-resolved optical spectroscopy in the H$\alpha$ line of T CrB, with a resolution of ~10–15 minutes. This is comparable to the timescale of flickering (see, e.g., Zamanov et al. 2004).

## 2. OBSERVATIONS

The observations were performed with the coudé spectrograph of the 2.0 m Ritchey-Chrétien/coudé telescope at the Bulgarian National Astronomical Observatory, in Rozhen. The spectra have a dispersion of 0.2 Å pixel$^{-1}$. The normal CCD reduction procedures (bias subtraction, flat-fielding, wavelength calibration, etc.) were undertaken using the IRAF environment. A journal of observations is given in Table 1. The signal-to-noise ratio (S/N) achieved on the individual exposures is 35–65. The averaged spectra, normalized to the local continuum, are presented in Figure 1, along with a comparison spectrum of the red giant HD 135530.

## 3. RESULTS

### 3.1. Average, Fractional, and Temporal Variance Spectra

The prominent emission line in Figure 1 is H$\alpha$. On a timescale of years, the intensity of the H$\alpha$ line varies from an equivalent width EW = 0.5 Å up to 35 Å (Iijima 1990; Anupama & Prabhu

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TABLE 1
Hα Observations of T Coronae Borealis

| Date | UT Range | Mid-TJD | Phase | λ Coverage (Å) | $N \times$ Exp. (minutes) | EW(Hα) (Å) | EW Range (Å) |
|---|---|---|---|---|---|---|---|
| 1998 Apr 15 ...... | 22:37–01:43 | 50,919.512 | 0.187 | 6510–6620 | 10 × 15 | 20.84 ± 0.31 | 20.39–21.36 |
| 1998 Aug 2 ....... | 18:50–20:58 | 51,028.328 | 0.665 | 6510–6620 | 12 × 10 | 13.39 ± 0.23 | 12.72–13.81 |
| 1998 Aug 3 ....... | 18:23–21:03 | 51,029.305 | 0.669 | 6510–6620 | 15 × 10 | 13.97 ± 0.25 | 13.63–14.45 |
| 1999 Jan 6 ........ | 02:59–04:13 | 51,185.652 | 0.356 | 6500–6700 | 7 × 10 | 9.77 ± 0.62 | 8.90–10.51 |
| 1999 Jan 7 ........ | 01:50–02:51 | 51,186.598 | 0.360 | 6507–6707 | 3 × 20 | 7.92 ± 0.45 | 7.45–8.36 |

Note.—Listed are the dates of observation, the beginning and the end of spectroscopic observations, and truncated Julian Day. Orbital phase was calculated using the ephemeris of Fekel et al. (2000). The following columns give wavelength coverage, number of exposures each night, and the exposure time of the individual exposures. For EW(Hα) we give the mean and standard deviation, plus the smallest and largest values for each night.

1991; Zamanov & Martí 2000; Stanishev et al. 2004). During our search for rapid variability, we have observed a range of different profiles, an atlas of which is given in Stanishev et al. (2004). In the spectra obtained on 1998 April 15, the line is single peaked and the central absorption dip is not visible. During 1998 August the profile was a little unusual, with three peaks or two absorption dips. During 1999 January, the profile exhibits double peaks with a well-defined central dip, which is partly due to the Hα absorption line of the red giant.

The total Hα equivalent width was measured on each exposure in our sample. The results are presented in Figure 2. For the first three nights the variability is less than 3 times the estimated errors. On 1999 January 6 and 7, it is about 5 times the error of the individual measurements.

The EW measurements depend strongly on the placement of the continuum. The continuum was defined using a straight-line or spline fit, using parts of the spectrum located on both sides of Hα. We used different wavelength intervals to produce different normalizations. This leads to changes in the absolute value of the EW but keeps the relative distributions of the points the same. The EW errors have been calculated from four measurements, with different normalizations.

In order to search for variability in the line profile of the Hα line during an individual night, we calculate the fractional variance spectrum based on all the data for each night:

$$\sigma = \left[ \frac{1}{(N-1)\bar{f}_\lambda^2} \sum_{i=1}^{N} (f_{i,\lambda} - \bar{f}_\lambda)^2 \right]^{1/2}, \qquad (1)$$

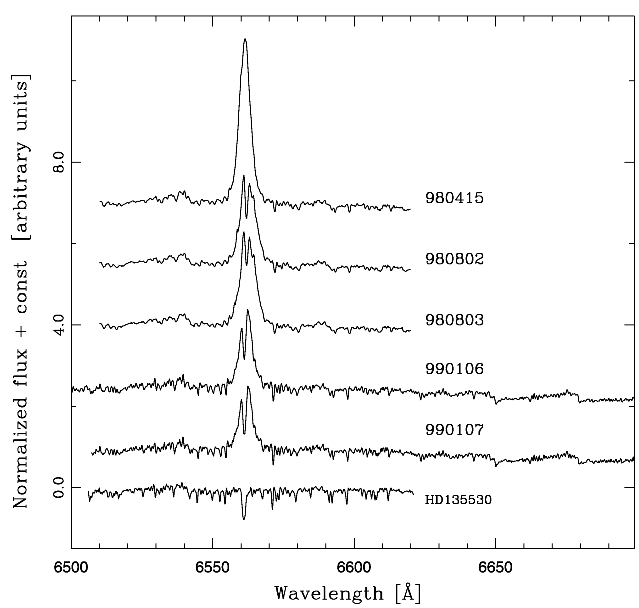


Fig. 1.—Nightly average spectra for all five nights. A spectrum of the red giant HD 135530 (M2 III) is shown for comparison at the bottom.

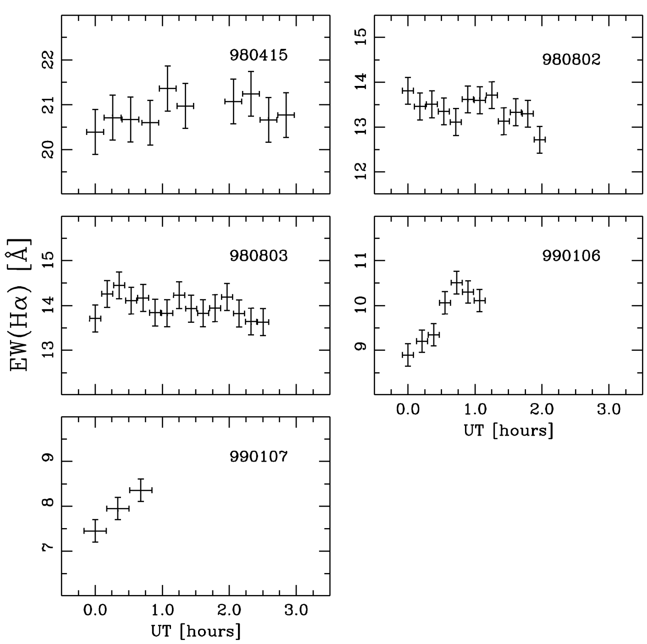


Fig. 2.—Measurements of the Hα equivalent width. The vertical error bars indicate the errors in EW measurements, the horizontal bars the exposure time of the spectra. For the first three nights the variability is on the order of the estimated errors. On 1999 January 6 and 7, it is ∼5 or more times the error of the measurements.

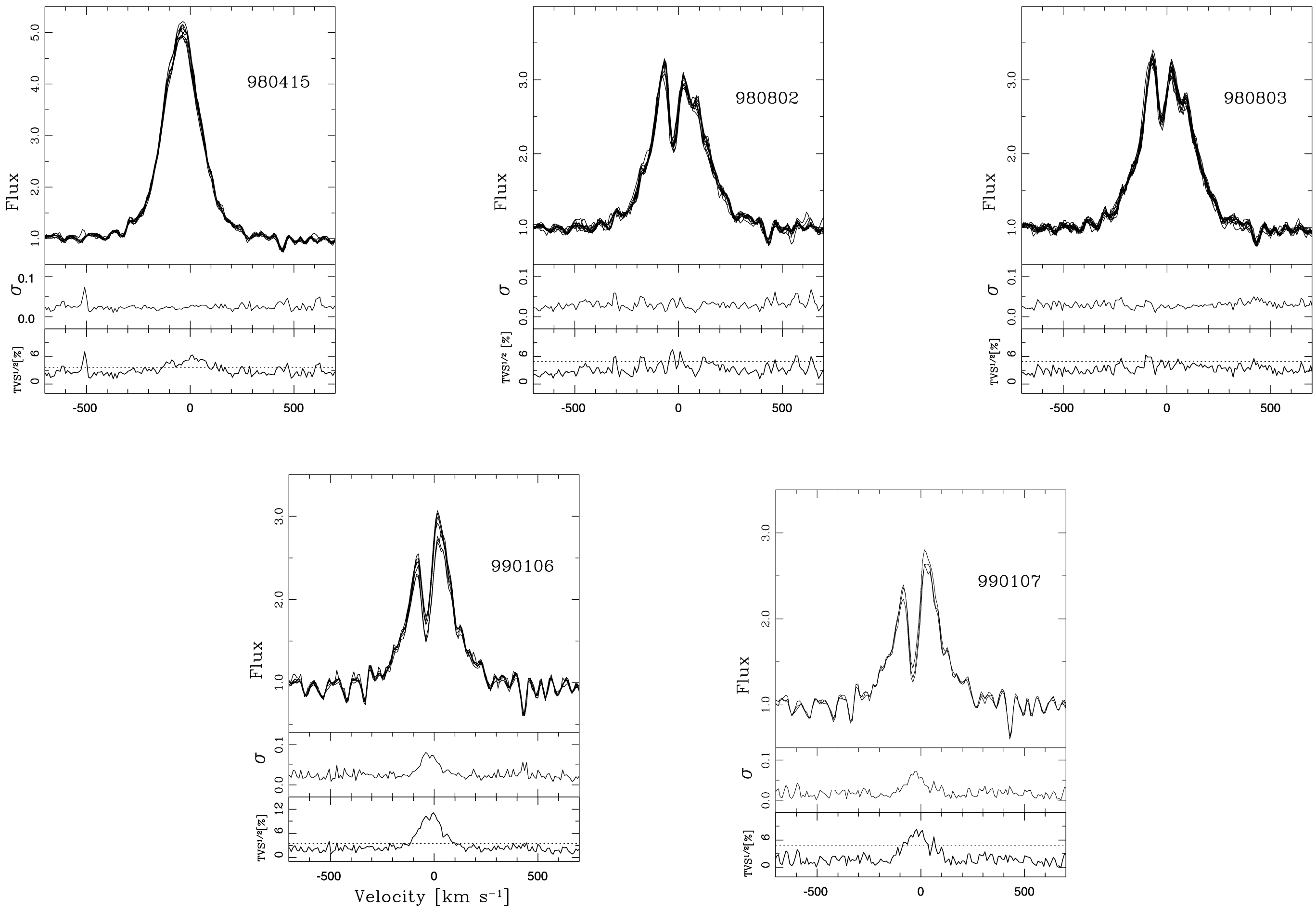


FIG. 3.—H$\alpha$ profiles of T CrB for the five nights of observation, normalized to the local continuum. The $x$-axis is heliocentric velocity. The value of $\sigma$ and the TVS for all nights are plotted. The dotted horizontal lines indicate the 1% threshold for the detection of variability. For the first three nights, $\sigma$ does not indicate any variability, while the TVS is marginally above the 1% significance level on the night of 1998 April 15. On 1999 January 6 and 7, well-defined peaks in both $\sigma$ and the TVS are clearly visible in the central part of the line, corresponding to velocities from $-100$ to $+100$ km s$^{-1}$. This demonstrates that there is statistically significant variability in the profile of the H$\alpha$ line at a time resolution of ∼10 minutes. The probability that this variability is real is ≥99%.

where $N$ is the number of spectra, $f_{i,\lambda}$ is the flux at wavelength $\lambda$ of the $i$th spectrum, and $\bar{f}_\lambda$ is the flux at that wavelength averaged over all spectra. The $\sigma$ in the continuum should correspond to $(\mathrm{S/N})^{-1}$, and hence a peak in $\sigma$ should determine the significance of a variation.

One other statistical technique that is particularly useful to accurately determine the spectral location of variability is the temporal variance spectrum:

$$(\mathrm{TVS})_\lambda = \frac{s_0^2}{N-1}\sum_{i=1}^{N}\frac{(f_{i,\lambda}-\bar{f}_{w,\lambda})^2}{s_i^2 f_{i,\lambda}} \qquad (2)$$

(Prinja et al. 2003; Fullerton et al. 1996), where $\bar{f}_{w,\lambda}$ is the weighted mean of the normalized intensity, $s_i$ is the inverse of the S/N of spectrum $i$ measured in the continuum, and $s_0^2 = (N^{-1}\sum_{i=1}^{N} s_i^{-2})^{-1}$. The results of the calculations are presented, together with all spectra, in Figure 3.

As can be seen, the fractional variance spectra do not indicate variability on the first three nights (1998 April 15 and August 2 and 3); however, the TVS indicates some variability on 1998 April 15. A clear peak in both $\sigma$ and the TVS is visible on 1999 January 6 and 7 at velocity ≈0 km s$^{-1}$.

Following Fullerton et al. (1996), if the TVS for a spectral feature is above a specified level of significance, then the null hypothesis of "no variability" can be rejected. The statistical distribution of the TVS is governed by the reduced $\chi^2$ distribution with $N-1$ degrees of freedom and scaled by S/N ($\mathrm{TVS} \sim s_0^2\chi^2_{N-1}$). For the nights considered here, the statistical significance of 1% corresponds to $\sqrt{\mathrm{TVS}} = 3.6\%$–$5.0\%$, depending on the number of spectra and the S/N. In the central part of the line, the TVS is well above this level for 1999 January 6 and 7 (Fig. 3). The peaks in $\sigma$ correspond practically to the same confidence level of 3 standard deviations from the mean. This clearly shows that on these two nights there is

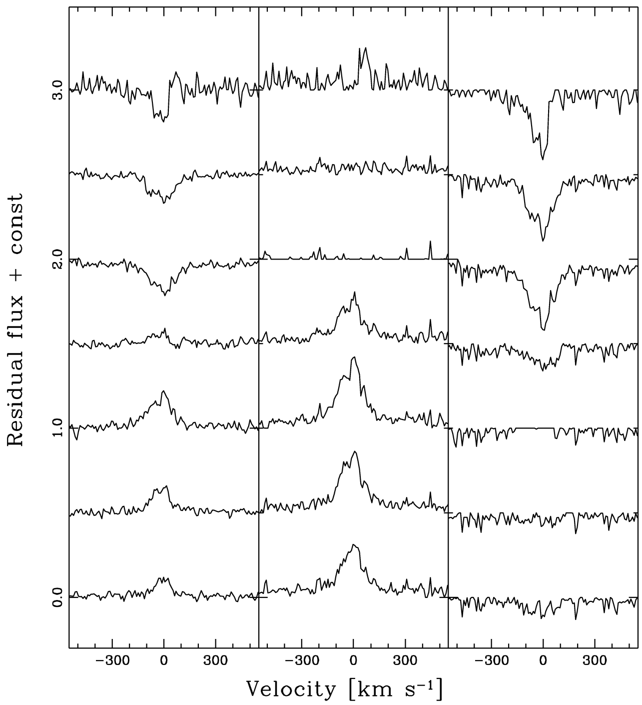


FIG. 4.—Night of 1999 January 6. We have subtracted from the individual spectra the average spectrum (*left*), the minimum spectrum (*middle*), and the maximum spectrum (*right*). Zero on the velocity axis corresponds to the systemic velocity, $\gamma = -27.79$ km s$^{-1}$ (Fekel et al. 2000).

statistically significant variability in the Hα line profile, at a confidence level of 99%, at a time resolution of ~10 minutes.

### 3.2. Variability in 1999 January

For the two nights with detected variability, we subtract from the individual spectra the average spectrum, the minimum spectrum, and the maximum spectrum. The average spectrum is defined as the average of the normalized flux for every pixel. The minimum (or maximum) spectrum is defined as the minimal (or maximal) value for each pixel. We do not know a priori whether we are seeing variability due to pure emission, pure absorption, or a mixture of both. The results for 1999 January 6 are presented in Figure 4. As can be seen, variability is evident in all three panels. This indicates additional absorption or emission with EW of approximately 1 Å, located in the central part of the line.

To exclude the possibility that the observed variability is an artifact of the data reduction, we performed tests with data processing and normalization, which showed that the detected variability on 1999 January 6 and 7 is not an artificial result. Figure 5*b* shows the results from two different extractions and normalizations that have identical $\sigma$ peaks.

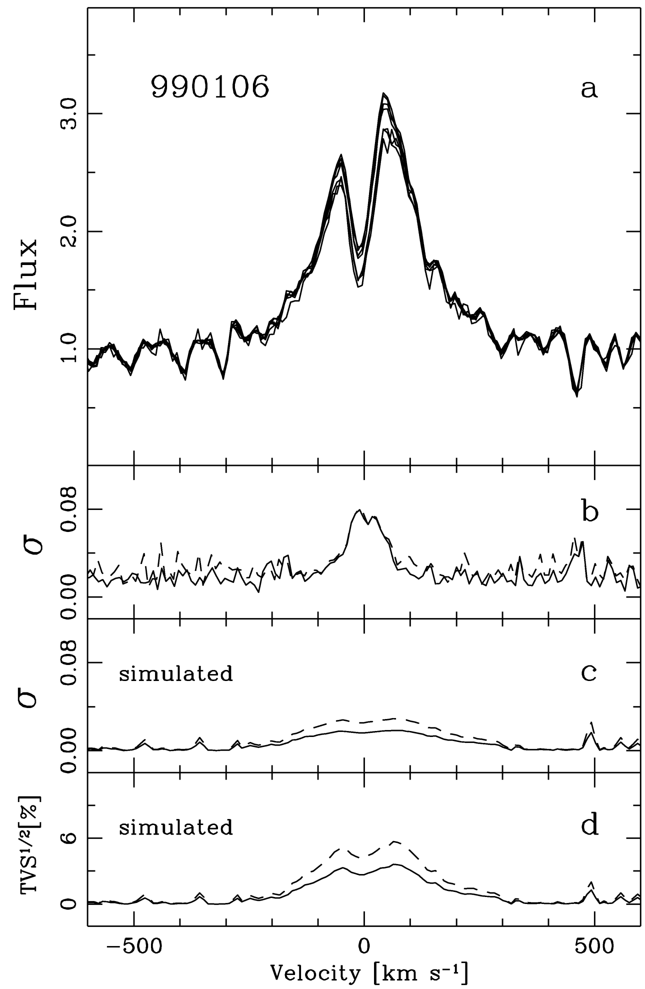


FIG. 5.—(*a*) Hα profiles observed on 1999 January 6 (same as in Fig. 3). (*b*) Values of $\sigma$ for 1999 January 6. Solid and dashed lines are for two deliberately different extraction and normalization procedures. (*c*) Simulated $\sigma$ as a result of hot continuum variability. (*d*) Simulated TVS as a result of hot continuum variability. During the simulation we assumed that the hot continuum contributes 15% of the flux on average and varies by ±30% (*dashed lines*) and ±25% (*solid lines*). Zero on the velocity axis corresponds to the systemic velocity $\gamma$.

Although the sky conditions looked photometric at the time of the observations, we cannot exclude the possibility that the variable atmospheric lines and small wavelength shifts from spectrum to spectrum might have resulted in spurious variability. To test the variability that these effects could produce, we artificially introduced random shifts in wavelength up to 3 km s$^{-1}$ (the largest shifts we detected were under 0.25 pixels, or 2.5 km s$^{-1}$). We also isolated atmospheric absorption lines from a high-S/N spectrum of Spica ($\alpha$ Vir) and introduced variable atmospheric absorption into the spectra. We find that both effects can produce variability, but this variability is lower than the noise in the TVS and $\sigma$ and cannot account for the observed peaks.

It is known (e.g., Zamanov & Bruch 1998) that the hot continuum, which flickers on timescales of minutes with amplitude 0.2–0.3 mag in $U$, contributes about 15% of the average flux in the $V$ band. To check whether the variability detected in H$\alpha$ is due to the changing continuum level caused by the flickering of the hot component, we simulated $\sigma$ in such a case by supposing that the hot continuum flickers with amplitude $\pm$25%–30% and contributes 15% of the flux in the continuum around H$\alpha$. The amplitude ws chosen to be slightly higher than the highest observed in the $U$ band after subtraction of the red giant's contribution (see Zamanov & Bruch 1998). To this variable hot continuum, we add constant red giant and H$\alpha$ emission. The simulated $\sigma$ and TVS are shown in Figure 5. The simulated quantities are different from the "observed" ones in that (1) they have smaller amplitude and (2) they are wider and spread over the whole FWZI of the H$\alpha$ emission while the observed quantities are located in the central part of the line only. This indicates that the detected variability is not due to the continuum variability but is intrinsic to the line.

## 4. DISCUSSION

The FWZI of the H$\alpha$ emission line is 800 km s$^{-1}$, with the wings of the line formed in the immediate vicinity of the white dwarf (see also Stanishev et al. 2004). However, the detected variability appears in the central part of the line and is confined to $\Delta V \approx \pm 100$–120 km s$^{-1}$ from the systemic velocity. This indicates that this variability originates in the outer parts of the H$\alpha$-emitting region. Assuming Keplerian motion, a 1.4 $M_\odot$ white dwarf, and an inclination of 67° (see, e.g., Stanishev et al. 2004 and references therein), this corresponds to a distance $\geq$20–25 $R_\odot$.

Mass accretion in T CrB occurs by means of Roche lobe overflow. As the stream of gas flows away from the L1 Lagrangian point, it forms a ring (see Verbunt 1982). The position of the ring approximately defines the outer edge of the accretion disk. The radius of the ring can be estimated from $r_r/a = 0.0859q^{-0.426}$, where $a$ is the semimajor axis and $q$ is the mass ratio of giant to white dwarf (Hessman & Hopp 1990). For T CrB, $q = 0.82 \pm 0.10$ and $a \approx 210\ R_\odot$ (Stanishev et al. 2004), which places the ring at 20 $R_\odot$. At this location, the Keplerian velocity is about 115 km s$^{-1}$, which is similar to the $\Delta V$ of the detected variability. However, the Keplerian timescale is about 18 days, which is not comparable to the timing of our observations. This suggests that the variability is not produced by an inhomogeneous disk structure.

The observed behavior of H$\alpha$ emission from T CrB with 10–15 minute time resolution is different from that of CH Cyg and of the variable winds observed in some CVs. We do not see ejected blobs, like those observed in CH Cyg (by Tomov et al. 1996), or high-velocity components observed in the variable disk winds of some CVs (Prinja et al. 2003). It might be that they are not detectable in our H$\alpha$ profiles, even though they may exist and could be detected in the ultraviolet, where the hot component is the dominant source of radiation.

One possible explanation for the detected variability could be variable absorption from the wind of the giant or from the accretion stream. It is worth noting that no variability in the line is observed at orbital phases where the line of sight passes through the expected position of maximum absorption from the red giant wind. Another cause could be additional emission from the area where the accretion stream hits the disk (the hot spot). It is possible that a variable component with EW $\leq$ 0.5 Å always exists but is lost in the line when the line is strong (e.g., 1998 April 15).

An additional plausible explanation is that the variable continuum arising from the central part of the accretion disk (where the flickering in $U$ arises) changes the ionization state of the outer regions of the (flared) disk, from which the central parts of the emission lines arise. This possibility deserves further exploration.

## 5. CONCLUSIONS

We have searched for rapid H$\alpha$ variability in the spectra of the recurrent nova T CrB. On two nights out of five, we detect statistically significant variability at a time resolution of 10–20 minutes.

The detected variability is confined to the central part of the line profile at $\pm$100 km s$^{-1}$, which suggests that variations are produced in the outer parts of the accretion disk (>20 $R_\odot$). On these two nights there is evidence for variability of the total EW(H$\alpha$) (in all cases calculated relative to the average value; see Table 1), with amplitude $\pm$8% for 1999 January 6 and $\pm$6% for 1999 January 7, which is approximately 5 times the error of the individual measurements. For the other three nights of observation, we do not detect line profile changes. We place upper limits on the variability of the total H$\alpha$ equivalent width, $\Delta$EW(H$\alpha$), of $\pm$2% for 1998 April 15, $\pm$4% for 1998 August 2, and $\pm$3% for 1998 August 3.

More extensive spectral observations with better time resolution, combined with photometry, are necessary in order to define what influences the H$\alpha$ variability and whether this variability is directly connected to the flickering.

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