

Flickering variability of T Coronae Borealis

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Accepted 2004 February 18. Received 2004 January 10; in original form 2003 November 11

ABSTRACT

We present electro-photometric *UBV* and high-speed *U*-band flickering observations of the recurrent nova T CrB during a period when its *U* brightness varies by more than 2 mag. The *V* band is dominated by the ellipsoidal variability of the red giant; however, the variability of the hot component also causes ~ 0.15 -mag variations in *V*. We define a set of parameters that characterize the flickering. The Fourier spectra of all 27 nights are similar to each other. The power spectral density of the variations has a power-law component ($\propto f^{-1.46}$ on average). We do not detect a dependence of the Fourier spectra and autocorrelation function on the brightness of the object. Having subtracted the contribution of the red giant, we show that the flickering amplitude correlates with the average flux of the accreting component. A comparison with CH Cyg and MWC 560 indicates that the flickering of T CrB is more stable (at least during the time of our observations) than that in these jet-ejecting symbiotic stars. The data are available in electronic form from the authors.

Key words: binaries: symbiotic – stars: individual: T CrB – novae, cataclysmic variables.

1 INTRODUCTION

T CrB (HD 143454) is an interacting binary star which consists of a red giant and a white dwarf (Selvelli, Cassatella & Gilmozzi 1992, and references therein). The star has undergone two nova eruptions (Nova CrB 1866, 1946) and is thus classified as a recurrent nova (and, due to the presence of the cool giant, plus emission lines seen at outburst, also as a symbiotic star). The red giant fills the Roche lobe, and thus the accretion flow onto the white dwarf (WD) is via L_1 , which is typical for cataclysmic variables. Sharing the characteristics of three (partly overlapping) types of interacting binaries, T CrB is an important object for our understanding of the various processes taking place in interacting binaries.

Stochastic brightness variations (flickering), occurring on time-scales of seconds to minutes with amplitudes ranging from a few millimagnitudes up to more than an entire magnitude, are a phenomenon typical of cataclysmic variables, and one that is rarely observed in symbiotic stars. For example, to date it has been detected in only eight of the 220 known symbiotics (Dobrzycka, Kenyon & Milone 1996; Belczyński et al. 2000; Sokolowski, Bildsten & Ho 2001). In T CrB, flickering with an amplitude of $\Delta U \sim 0.1$ – 0.5 mag has been observed on a time-scale of minutes (Ianna 1964; Lawrence, Ostriker & Hesser 1967; Bianchini & Middleditch 1976; Walker 1977; Bruch 1980). The flickering amplitude is somewhat smaller in the *B* and *V* bands (Raikova & Antov 1986; Hric et al. 1998). In

addition, on some occasions such flickering disappears (Bianchini & Middleditch 1976; Oskanian 1983; Mikołajewski, Tomov & Kolev 1997). In our previous investigation (Zamanov & Bruch 1998) we showed that the flickering of T CrB is indistinguishable from the flickering observed in dwarf novae, in spite of the vast difference in the geometrical size of the systems.

The exact origin of the stochastic variations is not clear, but they are considered to be a result of accretion onto the WD through a disc. Possible mechanisms include unstable mass transfer, magnetic discharges, turbulence and instability in the boundary layer (e.g. Warner 1995; Bruch 1992).

Here we present new *UBV* and high-speed flickering observations of T CrB, estimate the contribution of the red giant, analyse the *U*-band variability, search for relations between the flickering quantities and the brightness of the object, and compare the behaviour of T CrB with that of two other symbiotic stars (the ‘nanoquasars’ CH Cyg and MWC 560).

2 OBSERVATIONS

Observations were performed with the 60-cm telescope of NAO Rozhen equipped with a single-channel photometer. The comparison stars were HD 142929 and BD+26°2761, the check star was GSC 2037.1228, and the integration time was 1 or 10 s. The observations with 1-s integration time were binned in 10 s. APR software (Kirov, Antov & Genkov 1991) was used for data processing. The accuracy of the *UBV* photometry is better than 0.03 mag, and the results are given in Table 1.

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Table 1. UBV observations of T CrB.

JD-2400000	V	B	U	JD-2400000	V	B	U	JD-2400000	V	B	U
50476.655	10.309	11.570	11.568	50698.295	10.146	11.298	11.089	51008.314	10.062	11.393	11.681
50476.659	10.311	11.564	11.620	50698.301	10.142	11.269	10.979	51009.304	10.026	11.318	11.574
50477.556	10.299	11.476	11.367	50739.236	9.946	10.960	10.655	51009.308	10.072	11.403	11.720
50477.559	10.280	11.507	11.496	50739.242	9.943	11.075	11.105	51015.323	10.055	11.343	11.526
50478.580	10.276	11.490	11.363	50741.222	9.773	10.777	10.349	51015.327	10.073	11.353	11.442
50478.583	10.274	11.446	11.314	50741.227	10.036	11.950	12.671	51016.308	10.080	11.387	11.566
50479.660	10.315	11.558	11.515	50828.591	10.213	11.245	11.087	51016.313	10.086	11.395	11.643
50479.663	10.311	11.579	11.517	50828.595	10.188	11.217	11.144	51027.320	10.124	11.412	11.531
50480.651	10.322	11.693	11.780	50864.466	10.104	11.346	11.600	51027.324	10.160	11.413	11.497
50480.654	10.370	11.615	11.639	50864.470	9.852	11.226	11.508	51034.298	10.215	11.468	11.602
50504.566	10.198	11.558	11.850	50865.491	10.015	11.294	11.476	51034.302	10.231	11.470	11.583
50504.572	10.162	11.425	11.676	50865.499	9.993	11.280	11.406	51226.574	9.848	11.063	11.085
50520.518	10.025	11.456	12.039	50867.519	9.974	11.322	11.550	51226.582	9.911	11.167	11.328
50520.524	10.040	11.433	11.970	50867.523	9.958	11.313	11.484	51239.592	10.041	11.356	11.555
50628.448	9.982	11.084	10.809	50877.603	9.974	11.373	11.658	51239.597	10.012	11.303	11.387
50628.453	9.972	11.048	10.766	50877.609	10.023	11.387	11.660	51401.292	10.054	11.095	10.714
50651.337	9.911	11.184	11.319	50877.620	10.023	11.414	11.773	51401.297	10.019	11.040	10.637
50651.342	9.906	11.191	11.328	51005.484	9.841	10.828	11.412	51404.314	10.224	11.539	11.637
50652.325	9.820	10.919	10.714	51005.485	9.853	10.833	11.371	51404.318	10.274	11.649	11.787
50652.329	9.785	10.919	10.730	51007.487	10.095	11.390	11.691	51408.289	10.249	11.712	12.123
50654.307	9.844	10.948	10.766	51007.493	10.074	11.415	12.143	51408.294	10.267	11.689	12.070
50654.311	9.733	10.908	10.811	51008.310	10.090	11.440	11.715				

For the flickering observations, the reduction to the standard U band is better than ± 0.04 mag, and the internal accuracy of the data (standard deviation from the average of 10 consecutive measurements) is 0.015–0.030 mag. The control of the atmospheric conditions and performance of the system were done by observing the check star before and after T CrB, and carefully tracing the comparison star counts. (The comparison star was observed every 20–30 min.) In the subsequent data processing, two nights were rejected because of the ‘doubtful’ behaviour of the comparison and/or check stars. A journal of the flickering observations and the main characteristics of the U -band variability for each run are summarized in Table 2.

The errors in the magnitudes (U_{\max} , U_{\min} , U_{av}) are calculated by dividing every run into two parts and calculating the quantities separately for each part, and in this way assessing the possible errors of the run. Fig. 1 is a plot of the orbital modulation in V , Fig. 2 shows the long-term U -band curve and the flickering observations, and Fig. 3 gives two examples of the flickering.

3 CONTRIBUTION OF THE RED GIANT

3.1 V band

In symbiotic stars, the mass donor is a red giant. In the case of T CrB, its contribution is not negligible in the UBV bands. The V -band variability of T CrB is dominated by the ellipsoidal variability of the red giant (Peel 1985; Lines, Lines & McFaul 1988). The V -band data from the long-term light curve (see Stanishev et al. 2004, and references therein) are plotted in Fig. 1, folded with the orbital period.

A three-term truncated Fourier fit to all data gives

$$\begin{aligned}
 V = & 10.056(0.003) \\
 & + 0.007(0.004) \cos 2\pi\phi - 0.026(0.004) \sin 2\pi\phi \\
 & - 0.161(0.004) \cos 4\pi\phi - 0.036(0.004) \sin 4\pi\phi \\
 & + 0.016(0.004) \cos 6\pi\phi - 0.037(0.004) \sin 6\pi\phi,
 \end{aligned}$$

where ϕ is the orbital phase (hereafter the numbers in parentheses refer to the errors). This fit is plotted in Fig. 1. The typical deviation of the points from the fit line is ± 0.10 mag.

In Fig. 1 we have plotted with different symbols the points at which the object is brighter or fainter at shorter wavelengths (open circles refer to $U < 12$ and filled circles to $U \geq 12$). It is clear that the filled circles are displaced downwards slightly relative to the open ones. The U -band brightness is dominated by the hot component. We can also deduce that the variability of the hot component of about 2 mag in U (see also Stanishev et al. 2004) also contributes to that in V . To define this contribution we performed simple fits (using only the main terms) to the open and filled symbols. The coefficients obtained are

$$V = 10.157(0.005) - 0.194(0.007) \cos 4\pi\phi \quad \text{for } U \geq 12,$$

$$V = 10.029(0.003) - 0.163(0.004) \cos 4\pi\phi \quad \text{for } U < 12.$$

The mean values of the U -band magnitudes are $U = 12.3 \pm 0.3$ and $U = 11.2 \pm 0.4$ for the fainter and brighter points respectively. Therefore, an increase of the system U -band brightness by 1.1 mag results in an increase of the V -band brightness by 0.128 (equations 3 and 4). We derive a relative contribution $R(V) = 0.205 \pm 0.035$, where $R(V) = F_{\text{hot}}/F_{\text{gM}}$ is the relative contribution of the accreting object compared with that of the red giant at $V = 10.056$. The corresponding orbital light curve of the red giant is plotted as a dashed line in Fig. 1. The calculated contribution is very similar to that obtained by Zamanov & Bruch (1998) on the basis of the average colours of the flickering source in cataclysmic variables.

Although the data in Fig. 1 are spread over 22 yr, the typical deviation of the points from the fit line is ± 0.10 mag. This points to the fact that the V -band light curve has not changed in its main features over the last 22 yr. This in turn indicates that the M giant is not variable. Indeed, we can put an upper limit on its possible variability of $\Delta V < 0.05$ –0.10. The stability of the red giant is better defined in IR observations (Yudin & Munari 1993; Shahbaz et al. 1997), where an upper limit of variability $\Delta J < 0.02$ has been found.

Table 2. Journal of flickering observations in the *U* band. Date is given in format YYMMDD, TJD is the truncated Julian day of the start of the observation, N is the number of points in the run, IT is the integration time (in seconds). D is the duration of the run in minutes. U_{\max} , U_{\min} , and U_{av} are the maximum brightness during the night, the minimum, and the average of this quantity, respectively. σ is the standard deviation. U_{av} is calculated averaging the corresponding fluxes. The power spectra in each night are fitted with a linear fit (A and γ are the parameters of the fit, see text). γ is the power spectrum slope in the interval 3–160 cycles h^{-1} . The e-folding time of the ACF is given for the original run (τ_0), and after subtraction of a spline fit (τ_1).

Date	TJD _{start}	N×IT [s]	D min	U_{\max} [mag]	U_{\min} [mag]	U_{av} [mag]	σ [mag]	A	γ	τ_0 [s]	τ_1 [s]
930228	49046.5117	448 × 10	122	12.260 ± 0.03	12.578 ± 0.01	12.387 ± 0.04	0.084	3.41	−1.77	789 ± 35	65 ± 7
940410	49453.4621	266 × 10	49	12.652 ± 0.02	12.945 ± 0.05	12.820 ± 0.05	0.081	3.59	−1.71	516 ± 72	54 ± 10
950613	49882.3317	242 × 10	45	11.713 ± 0.11	12.222 ± 0.07	11.952 ± 0.08	0.121	3.19	−1.32	257 ± 49	143 ± 21
950620	49889.3496	520 × 10	102	11.798 ± 0.06	12.353 ± 0.10	12.081 ± 0.05	0.099	2.14	−1.47	181 ± 25	107 ± 10
960110	50092.6671	150 × 10	31	11.826 ± 0.07	12.236 ± 0.03	12.002 ± 0.03	0.092	3.70	−1.38	138 ± 87	98 ± 17
960228	50141.5088	772 × 10	162	11.161 ± 0.02	11.714 ± 0.01	11.406 ± 0.02	0.121	2.23	−1.51	292 ± 18	130 ± 36
960229	50142.4900	9304 × 1	190	11.460 ± 0.01	12.065 ± 0.07	11.770 ± 0.05	0.105	1.74	−1.40	1253 ± 82	131 ± 12
960325	50167.5358	3956 × 1	63	12.017 ± 0.01	12.323 ± 0.02	12.146 ± 0.00	0.052	3.04	−1.68	132 ± 30	105 ± 21
961216	50433.6246	2190 × 1	57	11.051 ± 0.00	11.397 ± 0.03	11.272 ± 0.02	0.078	1.52	−1.06	152 ± 21	132 ± 18
961218	50435.6354	1292 × 1	38	11.111 ± 0.04	11.368 ± 0.03	11.262 ± 0.04	0.066	2.50	−1.41	66 ± 6	78 ± 7
970128	50476.5542	674 × 10	128	11.181 ± 0.05	11.632 ± 0.10	11.456 ± 0.07	0.101	2.70	−1.45	675 ± 89	174 ± 10
970129	50477.5717	522 × 10	98	11.307 ± 0.01	11.607 ± 0.02	11.469 ± 0.02	0.070	2.56	−1.47	378 ± 47	144 ± 22
970130	50478.5983	425 × 10	81	11.333 ± 0.07	11.614 ± 0.04	11.461 ± 0.05	0.068	2.98	−1.54	785 ± 204	50 ± 8
970131	50479.5537	704 × 10	137	11.354 ± 0.05	11.631 ± 0.04	11.488 ± 0.04	0.060	2.95	−1.67	416 ± 25	185 ± 13
970201	50480.5379	8318 × 1	151	11.443 ± 0.01	11.828 ± 0.02	11.658 ± 0.04	0.093	2.42	−1.54	626 ± 61	169 ± 17
970721	50651.3508	547 × 10	119	11.200 ± 0.02	11.457 ± 0.01	11.326 ± 0.01	0.064	2.52	−1.43	799 ± 38	50 ± 5
970722	50652.3379	96 × 10	21	10.533 ± 0.01	10.762 ± 0.03	10.669 ± 0.03	0.068	3.80	−1.73	114 ± 13	135 ± 16
970827	50688.3313	207 × 10	46	10.561 ± 0.06	10.939 ± 0.07	10.758 ± 0.06	0.086	3.57	−1.67	280 ± 60	123 ± 22
980220	50864.5092	837 × 10	168	11.464 ± 0.01	11.779 ± 0.02	11.604 ± 0.01	0.071	2.14	−1.40	571 ± 44	124 ± 12
980224	50868.5383	407 × 10	81	11.296 ± 0.06	11.700 ± 0.07	11.505 ± 0.05	0.094	3.11	−1.58	498 ± 45	139 ± 23
980713	51008.3217	256 × 10	52	11.540 ± 0.01	11.774 ± 0.00	11.660 ± 0.00	0.062	2.76	−1.28	212 ± 25	256 ± 46
980714	51009.3188	362 × 10	74	11.504 ± 0.04	11.840 ± 0.02	11.670 ± 0.05	0.078	2.94	−1.43	257 ± 216	89 ± 10
980720	51015.3342	304 × 10	64	11.335 ± 0.02	11.621 ± 0.00	11.477 ± 0.01	0.072	3.34	−1.67	191 ± 14	125 ± 18
980721	51016.3208	319 × 10	64	11.435 ± 0.03	11.770 ± 0.05	11.613 ± 0.02	0.059	2.72	−1.41	105 ± 14	91 ± 11
980802	51028.3125	344 × 10	69	11.400 ± 0.06	11.759 ± 0.02	11.595 ± 0.04	0.079	2.19	−1.09	387 ± 118	106 ± 14
980803	51029.3217	298 × 10	61	11.521 ± 0.02	11.737 ± 0.02	11.614 ± 0.01	0.042	2.81	−1.38	87 ± 25	40 ± 10
990107	51185.6225	406 × 10	76	11.646 ± 0.07	12.074 ± 0.05	11.847 ± 0.05	0.086	2.33	−1.40	495 ± 144	54 ± 5

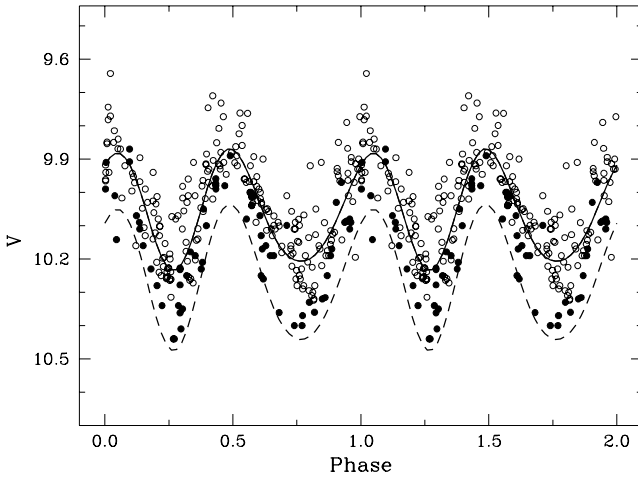


Figure 1. Johnson *V*-band observations of *T CrB* folded with a 227-d period. The solid line is our fit to all data. The open circles refer to the epochs when the object is brighter than $U = 12$, and the filled circles refer to the epochs when it is fainter than this. The dashed line is the calculated contribution of the red giant.

3.2 Red giant contribution to *U*-band flux

The latest definitions of the spectral type of the red giant in *T CrB* are M4III (Zhu et al. 1999) and M4.5III (Mürset & Schmid 1999).

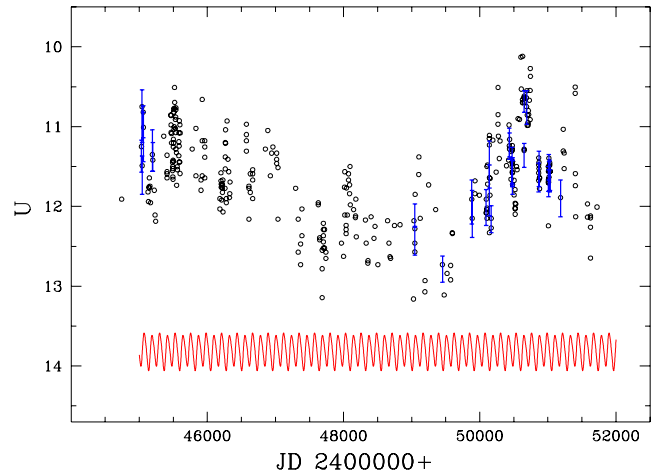


Figure 2. Long-term variability in *U*-band magnitudes and the flickering observations, with the corresponding amplitude. The cosine wave (bottom) is the calculated contribution of the red giant.

Both are obtained on the basis of IR spectra and with typical uncertainty ± 1 spectral subtype. The expected colour of a M4.5III star is $(U - V)_{\text{M4.5III}} = 3.16 \pm 0.10$ (Lee 1970), $(U - V)_{\text{M4.5III}} = 3.28 \pm 0.10$ (Schmidt-Kaler 1982), or $(U - V)_{\text{M4.5III}} = 3.25 \pm 0.10$ (calculated using the tables of Fluks et al. 1994). The New ATLAS9

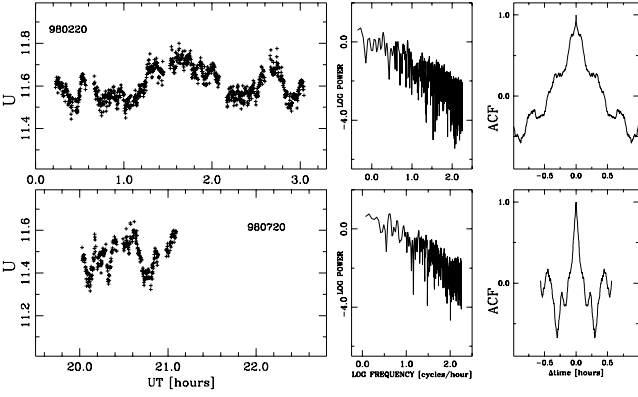


Figure 3. Two examples of our observations (for dates 980220 and 980720). The left panels represent the flickering behaviour of T CrB in U, mid-panels the power spectra, and right panels the autocorrelation function.

model atmospheres (Pietrinferni et al. 2004) for a star with $T_{\text{eff}} = 3500$ K and $\log(g) = 1.0$ give $(U - V) = 3.18$ for $[\text{Fe}/\text{H}] = 0.2$, $(U - V) = 3.26$ for $[\text{Fe}/\text{H}] = 0$, and $(U - V) = 3.42$ for $[\text{Fe}/\text{H}] = -1.5$.

Using $R(V) = 0.222$ at $V = 10.029$ (as derived in Section 3.1), the fit to V (equation 1), $E_{B-V} = 0.15$, and $(U - V)_{\text{M4.5III}} = 3.25$, we can calculate the contribution of the red giant to the U band. The light curve of T CrB, our flickering observations, and the red giant contribution (as a sine wave) are plotted in Fig. 2.

One way to check the calculated U brightness of the red giant is by IR photometry, supposing that the red giant is the only source in the J band. The J brightness of T CrB varies in the interval $J = 5.90\text{--}6.19$ (Kamath & Ashok 1999). Interpolations in the tables of the colours of red giants give $(U - J)_{\text{M4.5III}} = 7.75 \pm 0.25$ (from Lee 1970), $(U - J)_{\text{M4.5III}} = 7.14 \pm 0.2$, combining $(U - V)$ from Schmidt-Kaler (1982) and $(V - J)$ from Ducati et al. (2001), and $(U - J)_{\text{M4.5III}} = 7.34 \pm 0.2$ (from Fluks et al. 1994), where the calculated uncertainties refer to ± 0.5 spectral type. The model atmospheres give $(U - J)_{[\text{Fe}/\text{H}]=0.2} = 7.24$, $(U - J)_{[\text{Fe}/\text{H}]=0} = 7.13$ and $(U - J)_{[\text{Fe}/\text{H}]=-1.5} = 6.52$ (Pietrinferni et al. 2004).

Shahbaz et al. (1999) modelled the M giant spectrum, with enhanced abundance of lithium but normal abundances of the other metals; however, they used a higher gravity, inconsistent with the last orbital solution.

If we suppose that the red giant is the only source in J , using the above $(U - J)$ colours and $E_{B-V} = 0.15$ we could expect a value of $U \sim 14.4\text{--}13.3$, which is consistent with the supposed contribution of the red giant to the U band (see Fig. 2).

4 FLICKERING QUANTITIES

The U magnitudes were converted into fluxes, adopting a flux for a zero-magnitude star of $F_0(U) = 4.194 \times 10^{-11} \text{ W m}^{-2} \text{ nm}^{-1}$ (Bessell 1979). In addition to our data, we used data from Bruch (1992) and Oskanian (1983). Bruch's data are reddened with $E_{B-V} = 0.12$ and were corrected for the difference in the adopted zero-point of the flux scale. For Oskanian's data, we assumed that the instrumental difference $\Delta u = 0$ corresponds to magnitude $U = 11.83$. We have used only positive detections of the flickering. After the observed flux during a given night was corrected for the contribution of the red giant the following quantities were calculated:

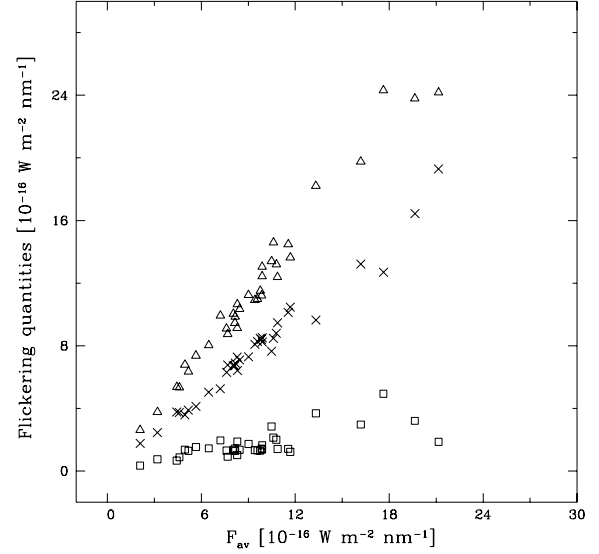


Figure 4. Measured flickering quantities versus the average flux F_{av} of the hot component. Triangles refer to F_{max} , crosses to F_{min} and squares to F_{fl} . The axes are in units of $10^{-16} \text{ W m}^{-2} \text{ nm}^{-1}$.

F_{av} – the average flux of the hot component;

F_{max} – the maximum flux of the hot component;

F_{min} – the minimum flux of the hot component;

F_{fl} – the average flux of the flickering, $F_{\text{fl}} = F_{\text{av}} - F_{\text{min}}$.

Fig. 4 plots the flickering quantities versus the average flux of the hot component. It is obvious they have to be connected; however, it is not clear a priori how the different quantities will depend on each other. The least-squares fits to the data in Fig. 4 give

$$F_{\text{max}} = -0.22(0.07) + 1.252(0.006)F_{\text{av}}, \quad (1)$$

$$F_{\text{min}} = -0.32(0.56) + 0.858(0.054)F_{\text{av}}, \quad (2)$$

$$F_{\text{fl}} = +0.19(0.42) + 0.156(0.042)F_{\text{av}}. \quad (3)$$

4.1 Power spectra

For each run we also calculated the power spectrum and the autocorrelation function. Two examples are shown in Fig. 3. Over a wide range of frequencies the power spectra of T CrB light curves follow the power law $P(f) \propto f^\gamma$, where P is the power and f is the frequency. Such a power-law shape is commonly observed in the light curves of cataclysmic variables and is attributed to the flickering. The power-law index γ was determined in the frequency interval from 3 to 160 cycles h^{-1} . We fitted the power spectra over this interval with a log-log scale with a least-squares linear fit: $\log(P) = A + \gamma \log(f)$. A and γ are given in Table 2. The typical errors are $\Delta A = \pm 0.8$ and $\Delta \gamma = \pm 0.25$. A visual comparison/inspection shows that all power spectra are very similar. This is confirmed from the fits. They give an average value of $\bar{\gamma} = -1.46 \pm 0.17$. There are two runs where γ is ≈ -1.1 . In both cases two stronger flashes are visible in the variability with amplitude ~ 0.2 mag.

The power-law spectrum of the type observed in T CrB is expected in the model of flickering proposed by Yonehara, Mineshige & Welsh (1997). They proposed as the origin of flickering a self-organised critical state of the disc in which seemingly chaotic fluctuations can be produced. Such a model implies $\gamma \simeq -1$ to -2 . Our observations of T CrB do not contradict this model.

The correlation analysis shows no correlation of A and γ with U_{av} or F_{av} ($r_P < 0.2$), indicating that the flickering is ‘stable’, i.e. without considerable changes in the nature of the power spectrum in spite of the variability.

This is not, however, the situation in the symbiotic star CH Cyg, where the power spectrum changes dramatically. There are even moments when CH Cyg’s power spectrum cannot be fitted with a simple power law, as a result of an unstable disc and disruption of the inner disc during the jet ejection (Sokoloski & Kenyon 2003b). We did not observe instabilities in T CrB like those in CH Cyg.

4.2 Autocorrelation function (ACF)

Another objective way to investigate flickering behaviour is through the ACF (see Bruch 2000). The ACFs were calculated according to Edelson & Krolik (1988) for unevenly spaced data.

The typical time-scale of the flickering may be defined as the time shift at which the ACF first reaches the value $1/e$. Thus determined correlation times are influenced by the presence of periodic brightness variations or trends in the data. As Robinson & Nather (1979) and Panek (1980) note, these correlation times can be additionally biased by the presence of weakly correlated noise and the process of trend removal (if applied).

The e-folding time is given in Table 2. The errors are determined from the errors of the autocorrelation coefficients. We calculated e-folding times in two different ways: (i) the e-folding time of the ACF of the original data in each run (τ_0); and (ii) after subtraction of a spline fit (τ_1). Operation (ii) was performed in order to obtain the typical time of the flickering on shorter time-scales. A tension spline interpolation was undertaken. We subtracted this spline fit through the mean points in non-overlapping bins of length about ~ 20 min in a way that is identical to that applied to TT Ari by Kraicheva et al. (1999).

The e-folding time of the ACF varies over a wide interval. The average value, standard deviation of the average, and median value of the e-folding time are $\bar{\tau}_0 = 394 \pm 287$, $\langle \tau_0 \rangle = 292$, $\bar{\tau}_1 = 115 \pm 48$, $\langle \tau_1 \rangle = 123$, where all values are in seconds. The values of τ_1 are similar to the values of TT Ari as defined in Kraicheva et al. (1999).

The correlation analysis showed that there are no correlations between the so-defined e-folding times and the brightness of the object, or the flickering quantities (F_{av} , F_{fl} , or the size of the boundary layer). The linear Pearson correlation coefficient and Spearman’s rank correlation give values between 0 and 0.2, indicating that there is no dependence of the time-scale of variability on the luminosity of the hot component, i.e. the characteristic time-scales of the flickering are not connected with the brightness of the object.

4.3 Boundary layer

The origin of flickering is still not clear, although this phenomenon is observed for many stars. Bruch (1992) and Bruch & Duschl (1993) identify the boundary layer between the accretion disc and the white dwarf as the most probable place for the origin of flickering. Bruch & Duschl (1993) consider that the ratio F_{fl}/F_{min} is connected with the size of the boundary layer between the white dwarf and the accretion disc.

In T CrB, F_{fl} is well correlated with F_{min} (see Fig. 5). Pearson’s correlation coefficient is $r_P = 0.72$ and Spearman’s rank correlation $r_S = 0.56$. Assuming that the deviation of the points from the fit lines (Fig. 2 and equations 3, 4, 5) is due only to the errors of the measurements, the fits (equations 3, 4, 5) indicate that, in spite of

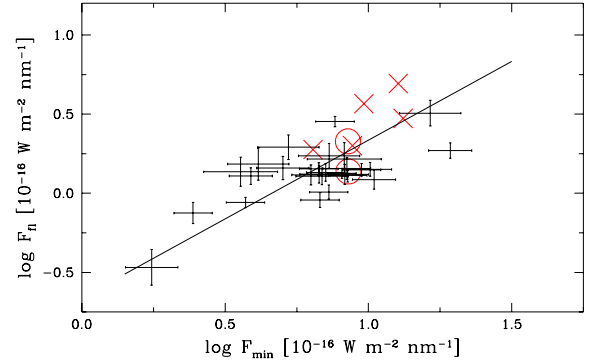


Figure 5. The average flux of the flickering, F_{fl} , versus the quiescent flux of the hot component in a light curve, F_{min} . The solid line is a linear least-squares fit $F_{fl} \propto F_{min}^k$, where $k = 0.995 \pm 0.015$. Our data are plotted with the corresponding errors, the circles represent data from Bruch (1992), and crosses(×) data from Oskanian (1983).

variations in F_{av} (which we suppose are related to the mass accretion rate), the ratios F_{fl}/F_{min} and F_{max}/F_{min} do not change markedly. According to Bruch & Duschl (1993), this means that the size of the boundary layer remains almost constant independently of changes in the mass accretion rate. Here, adding more data (see Fig. 5), we confirm the conclusion of Zamanov & Bruch (1998) that F_{fl} increases linearly with increasing F_{min} . This, within the limits of Bruch & Duschl’s model, means that the size of the boundary layer in T CrB remains almost constant, independently of changes in the mass accretion rate.

5 FLICKERING AMPLITUDE

Flickering amplitude ($\Delta F = F_{max} - F_{min}$) has also been measured for CH Cyg (Mikołajewski et al. 1990) and MWC 560 (Tomov et al. 1996). The flickering amplitude versus the average flux of the hot component, after subtraction of the red giant contribution, is presented for all three stars in Fig. 6.

5.1 T CrB

The data in Fig. 6 show that the flickering amplitude depends on the average hot-component flux. The correlation is well defined, with $r_P = 0.72$ and $r_S = 0.56$. Searching for a dependence of the type $\Delta F \propto (F_h)^k$, we obtain a best fit for T CrB with $k = 1.09 \pm 0.11$. The fit and the corresponding error have been calculated in two ways: (1) using the errors in corresponding quantities as given in Table 2; (2) bootstrapping simulations (e.g. Efron & Tibshirani 1993) over the points plotted in Fig. 5, i.e. taking ~ 20 subsamples from our points. Using only our own and Bruch’s points (i.e. data well calibrated in U) we obtain $k = 1.03 \pm 0.09$. Using different subsamples of the whole sample we obtained values $0.93 \leq k \leq 1.22$. An error in the subtraction of the M giant contribution of 25 per cent will cause an error in k of about 0.05.

5.2 CH Cyg

A dependence of the flickering amplitude on brightness has been reported for CH Cyg by Mikołajewski et al. (1990). Their results show that the flickering amplitude in CH Cyg is a power-law function of the hot-component luminosity, i.e. $\Delta F \propto (F_h)^k$, where $k = 1.40 - 1.45$. Here, using their data, we subtracted the contribution of the red giant, and the resulting points are plotted in Fig. 6. To subtract

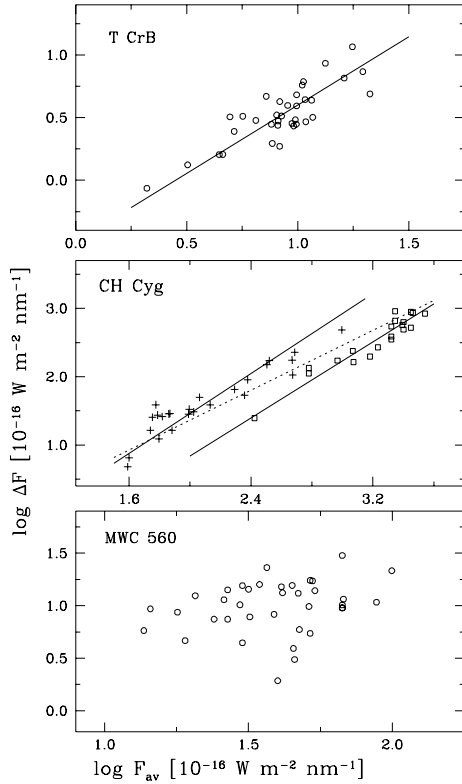


Figure 6. The flickering amplitude versus the flux of the hot component in the U band for T CrB (our data), CH Cyg (Mikołajewski et al. 1990: the plus signs refer to the propeller, the squares to the accretor stage), and MWC 560 (Tomov et al. 1996). The axes are in units of $10^{-16} \text{ W m}^{-2} \text{ nm}^{-1}$. In all cases the contribution of the red giant has been removed. For T CrB, the line is the best linear fit. For CH Cyg the solid lines are for the propeller and accretor stages, and the dashed line is to all points. For MWC 560 the correlation is weak and no fit was performed.

the contribution of the red giant we assume that at the minimum of V flux all the light is due only to the red giant, and has a colour corresponding to $(U - V)_{\text{M6III}} = 2.43\text{--}2.70$ (Lee 1970; Schmidt-Kaler 1982; Fluks et al. 1994). The minimum brightness of CH Cyg is $V = 10.0$ (Mikołajewski et al. 1996), and we adopt a contribution of the red giant of $U = 12.45$. We will not go into details as to whether the system is a triple (Hinkle et al. 1993; Skopal et al. 1998) or binary (Munari et al. 1996). Here we only note that an error of ± 0.7 mag in the subtraction of the flux of the red star(s) would influence the obtained slope by less than ± 0.02 .

The analysis gives a very high correlation between F_{av} and ΔF . r_P and r_S are always about 0.88–0.94, using (1) all points, (2) the propeller-state observations, and (3) the accretor-state observations (for further discussion of propeller and accretor states in CH Cyg, see Mikołajewski et al. 1990).

After the subtraction of the red giant contribution we obtain $k = 1.08 \pm 0.05$ if we use all points, $k = 1.48 \pm 0.05$ for propeller-state points only, and $k = 1.41 \pm 0.05$ for the accretor state only. It has to be noted that the fit $\Delta F \propto (F)^{1.08}$ obtained on the basis of all points is very similar to the value for T CrB.

5.3 MWC 560

For MWC 560 the minimum brightness is $V = 10.2$ (Tomov et al. 1996) and the red giant is classified as M5.5 III (Schmid et al. 2001). Using $(U - V)_{\text{M5.5III}} = 2.80\text{--}2.95$ (Lee 1980; Schmidt-Kaler

1982; Fluks et al. 1994), we adopt a contribution of the red giant equivalent to $U \approx 13.0$. It should be noted that the calculated red giant contribution in MWC 560 and CH Cyg is considerably smaller than that in T CrB, which is in accordance with the fact that in these two objects the V -band variability is dominated by the hot component (and not by the red giant as in T CrB).

The flickering amplitude versus F_{av} for MWC 560 is plotted in Fig. 6 (lower panel). The correlation is not very significant ($r_P = 0.25$, $r_S = 0.27$ – although, if we delete three points with $\log \Delta F < 0.6$, we can obtain a moderate correlation up to $r_P \sim 0.4$).

During the time of these observations MWC 560 was in the process of jet ejection, and the jet was even precessing (Iijima 2002). The lack of significant correlation between the flickering amplitude and hot-component flux is probably a result of the outflow; that is, the jet ejection destroys the innermost parts of the accretion disc, where the flickering originates.

The connection between the jet and flickering is not investigated in MWC 560; however, it is visible in the 1997 jet launch in CH Cyg (Sokoloski & Kenyon 2003a). The discs and jets are also connected in quasars and microquasars (see Livio, Pringle & King 2003, and references therein). In this sense, the fact that the correlation between ΔF and F_{av} is loose in MWC 560 is probably due to the outflow and its connection with the accretion disc.

6 DISCUSSION OF FLICKERING AMPLITUDE

In all three symbiotic stars, the flickering amplitude shows a tendency to increase with increasing hot-component flux. If we accept that there are no different states in CH Cyg and all points lie on the same line, this means that the obtained value of the slope is very similar to that for T CrB, which in terms of the Bruch & Duschl (1993) model means that in both stars the size of the boundary layer remains constant (see Section 5). In MWC 560 the flickering is (probably) influenced by the outflow and ΔF depends weakly on F_{av} , and the correlation is not well defined.

The other possibility, that the flickering amplitude of CH Cyg lies on two parallel lines, would give different values of k in the relationship $\Delta F \propto (F)^k$. One of the reasons for this difference could be connected with the magnetic field of the WD. Here we want to point out that the flickering amplitude could be connected with the magnetic field. The most probable place for the origin of the flickering is the inner parts of the accretion disc. If the flickering is a result of turbulence in the inner parts of the disc then the energy available in the turbulence will be proportional to the density where the flickering forms (Bruch 1992). If the WD is magnetic, the inner parts of the accretion disc will be destroyed by the magnetic field. Various types of instability can then appear at the inner edge of the disc. These instabilities permit the accreting material to be absorbed from the magnetosphere as blobs. The energy releasing will be unsteady, and we suppose that the amplitude of the flickering will be proportional to the typical mass of the blobs, and that the mass of the blobs will in turn be proportional to the density at the inner edge of the disc. The density in the disc can be estimated as (Lipunov 1992)

$$\rho_{\text{in}} \approx \alpha^{-1} \left(\frac{R}{H} \right) \frac{\dot{M}_a}{4\pi R^{3/2} \sqrt{2GM}}, \quad (4)$$

where (R/H) is the ratio between the radius and the vertical size of the disc: (R/H) is usually adopted to be a constant of order 0.01–0.1. M is the mass of the WD.

If the WD is non-magnetic, the inner radius of the disc will be approximately equal to the WD radius (for a thin boundary layer),

and consequently the density at the inner edge is given by $\rho_{\text{in}} \propto \dot{M}_a$. The same relationship will be fulfilled if the boundary layer is not thin and its size does not change. If the WD is magnetic, the radius R_0 of the inner disc edge can be expressed as (Lamb, Pethick & Pines 1973)

$$R_0 = N(GM)^{-1/7} \mu^{4/7} \dot{M}_a^{-2/7}, \quad (5)$$

where N is a constant of order 1, and μ is the WD magnetic moment. In this case (from equations 4 and 5),

$$\rho_{\text{in}} \propto \dot{M}_a^k, \quad k = \frac{10}{7}, \quad (6)$$

where $k = 10/7 = 1.43$ is in agreement with the behaviour of CH Cyg (Mikołajewski et al. 1990, see also Section 5.2), if the suppositions (1) $\Delta F \propto \rho_{\text{in}}$, and (2) accretor–propeller states in CH Cyg (Mikołajewski et al. 1990) are correct.

The data for T CrB are consistent with $k = 1$, as expected for a low- or non-magnetic WD; that is, the position of the inner edge of the accretion disc does not depend on the mass accretion rate.

The presence of a magnetic WD in CH Cyg is not a certain fact. Sokoloski & Kenyon (2003a), Crocker et al. (2001), Ezuka, Ishida & Makino (1998) cast doubts on the presence of such a magnetic WD in CH Cyg. However, the magnetic propeller model of (Mikołajewski & Mikołajewska 1988) still remains the most promising for the variability of this object.

If the differences in the behaviour of the flickering in T CrB, CH Cyg, and MWC 560 are not connected with the magnetic field and jet ejection, other possible reasons may be changes of the energy distribution, or the mechanisms generating the flickering in these objects.

7 CONCLUSIONS

We have analysed the U -band variability of the recurrent nova and symbiotic star T CrB, and compared its behaviour with two other symbiotic stars, CH Cyg and MWC 560. During the period of our observations, T CrB brightness varied between $U = 13$ and $U = 10$ mag. The analyses we performed lead to the following conclusions.

- (i) The V brightness during the last 22 yr is dominated by the ellipsoidal variability of the red giant; however, the hot-component variability with $\Delta U \gtrsim 2$ mag introduces a shift in V of about 0.15 mag. No sign of variability of the red giant has been detected.
- (ii) The power spectrum of the flickering does not change during our observations, remaining always with slope $\gamma \approx -1.5$ in spite of the changes in U . We do not detect changes in the power spectrum like those observed in CH Cyg.
- (iii) The calculated e-folding time of the ACF does not show dependence on the changes in U .
- (iv) The flickering amplitude is strongly correlated with the average flux of the hot component.
- (v) The differences in the dependence of the flickering amplitude between T CrB, CH Cyg and MWC 560 could be connected with jet ejection and the possible presence of a magnetic WD in the last two.
- (vi) In general, in T CrB we have observed flickering, which does not notably change its characteristics (at least during the time of our observations).

In the future it would be very interesting to determine the behaviour of the flickering amplitude, ACF, power spectra, etc. of other symbiotic stars with flickering (in particular RS Oph, RT Cru, o Ceti), as well as the flickering of MWC 560 during phases without outflow,

and also the connection of flickering with jet precession. Simultaneous spectral and photometric observations over a wide spectral range from UV to IR could be very useful in investigating in detail the flickering behaviour and its connection with accretion disc instabilities and jet ejections.

ACKNOWLEDGMENTS

This work is based on observations obtained in NAO Rozhen, Bulgaria. Use was made of SIMBAD, IRAF, and Starlink. RZ is supported by a PPARC Research Assistantship, and MFB is a PPARC Senior Fellow.

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