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#### Publication date

1994

#### Published in

Astronomy and Astrophysics Supplement Series

[Link to publication](#)

#### Citation for published version (APA):

Augusteijn, T., Heemskerk, M. H. M., Zwarthoed, G. A. A., & van Paradijs, J. A. (1994). Periodicities in the optical brightness variations of the intermediate polar TV Col. *Astronomy and Astrophysics Supplement Series*, 107, 219-233.

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# Periodicities in the optical brightness variations of the intermediate polar TV Columbae<sup>\*</sup>

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Received February 3, 1993; accepted February 20, 1994

**Abstract.** — We present extensive observations in the Walraven (*VBLUW*) photometric system of the intermediate polar TV Col over the period 1985-1988. We find, apart from the photometric variations at the three previously known periods, long-term brightness changes between groups of observations of up to  $\Delta B_J \sim 0.4$  mag. During the periods of highest mean brightness the source shows 1-2 mag outbursts, of which we detected four during our observations. No photometric variations are detected at the X-ray pulse period, or at its orbital or 5.2 hr period sidebands. We derived a new ephemeris for the orbital period, and we determined arrival times of maximum light at the 5.2 hr and 4 day photometric periods. We are unable, using the arrival times from our own data and those listed in the literature for the 5.2 hr light curve, to determine any constant-period ephemeris to fit all the observations. We suggest that the 5.2 hr period is in fact not stable and can vary non-monotonically. Because the 4 day period is the beat period between the orbital period and the 5.2 hr period, this also applies to the variations at this period. We investigate the changes in the optical light curve as a function of the 4 day cycle and discuss their cause.

**Key words:** accretion, accretion disks — stars: TV Col — stars: cataclysmic variables — X-rays: stars

## 1. Introduction

The high-latitude hard X-ray source 2A 0526-328 was discovered with the *ARIEL V* satellite (Cooke et al. 1978), and optically identified with the  $V \sim 14$  magnitude star TV Col by Charles et al. 1979 on the basis of its accurate HEAO-1 position (Schwartz et al. 1979) and its optical emission-line spectrum.

Motch (1981) found that the optical brightness of TV Col varies with periods of 5.2 hr and  $\sim 4$  day. The radial velocities derived from the emission lines show a 5.5 hr variation (Hutchings et al. 1981). Reanalysis of the data taken by Motch (1981) showed that the optical brightness is also modulated with the 5.5 hr spectroscopic period; this 5.5 hr modulation is dominant in the blue and UV (Bonnet-Bidaud et al. 1985). The spectroscopic 5.5 hr period is generally thought to be the orbital period ( $P_{\text{orb}}$ ). The 4 day period ( $P_{4\text{d}}$ ) is the beat period between the 5.2 hr period ( $P_{5.2\text{hr}}$ ) and the orbital period ( $P_{4\text{d}}^{-1} = P_{5.2\text{hr}}^{-1} - P_{\text{orb}}^{-1}$ ). Recently Hellier et al. (1991; hereafter H91) detected the presence of a previously unnoticed eclipse recurring with the 5.5 hr period, confirming that this is the orbital period. They showed that the eclipse

is the result of a partial occultation of the accretion disk by the secondary; the primary is not eclipsed. Apart from these three regular photometric variations also three  $\sim 2$  mag outburst have been detected for TV Col, one of which was simultaneously observed in the UV (Szkody & Mateo 1984; Schwarz et al. 1988).

In addition to the optical variations, Schrijver et al. (1985, 1987) detected a 1911 sec X-ray period, which they identified with the rotation period of a magnetic white dwarf, placing TV Col among the intermediate polar subclass of cataclysmic variables.

In this paper we present the results of extensive photometry of TV Col in the Walraven (*VBLUW*) photometric system obtained in 1985, 1987 and 1988. The two large-amplitude ( $\sim 2$  mag) outburst detect during the 1987 observations have been discussed by Schwarz et al. (1988). In Sect. 2 a short description of the observations and the reduction of the data is given. On the basis of these data we derive in Sect. 3 a new ephemeris for the orbital period and compare the photometric variations at the 5.2 hr and 4 day periods in our data with the ephemerides given in the literature. In Sect. 4 we present a search for the presence of the 1911 sec X-ray period in the optical. In Sect. 5 we discuss our results in more detail. A summary is given in Sect. 6.

<sup>\*</sup>Based on observations made at the European Southern Observatory, La Silla, Chile

**Table 1.** Summary of observations

year	$T_{\text{start}}$ (HJD) -2440000	Duration (day)	No. of obs.	year	$T_{\text{start}}$ (HJD) -2440000	Duration (day)	No. of obs.
1985	6402.59806	0.22673	280	1987 I	7133.56899	0.27677	668
	6403.56794	0.27317	325		7134.55958	0.28363	780
	6405.61981	0.05003	140		7135.77349	0.07338	213
	6405.78982	0.05376	134	1987 II	7144.58519	0.20624	435
	6406.61523	0.01247	48		7146.59103	0.20346	528
	6408.58015	0.09291	258		7147.64797	0.19383	536
	6409.54654	0.22953	612		7148.58334	0.21252	616
			7149.64568		0.19856	577	
1987 I	7120.60728	0.22432	429	7150.58755	0.20926	618	
	7121.58556	0.11409	307	7151.58818	0.20416	590	
	7122.57930	0.26310	678	7153.57951	0.22134	609	
	7123.57898	0.11668	300	7155.56916	0.21758	614	
	7124.57911	0.25456	652	1988	7481.66361	0.18616	452
	7125.57083	0.26868	746		7482.63720	0.20330	492
	7126.57401	0.26056	742		7483.64429	0.19186	444
	7127.56731	0.27018	792		7484.65604	0.18556	453
	7128.56551	0.26977	746		7486.66084	0.17290	268
	7129.56603	0.27777	830		7487.62326	0.20388	544
	7130.56204	0.27347	804		7488.68301	0.13493	371
	7131.56185	0.26640	292				
	7132.67274	0.10491	310				

## 2. Observations and reduction

We observed TV Col on 38 nights between 3 December 1985 and 23 November 1988 using the Walraven photometer attached to the 0.91-m Dutch telescope at the European Southern Observatory (ESO). A summary of the observations is given in Table 1.

The Walraven photometer provides simultaneous measurements in five passbands ( $V$ ,  $B$ ,  $L$ ,  $U$  and  $W$ ) with effective wavelengths between ( $W$ ) 3255 and ( $V$ ) 5467 Å which are defined in Rijf et al. (1969) and Lub & Pel (1977). The source was monitored for several hours each night with a break about every half hour to measure the sky background and nearby comparison stars. For all the observations an integration time of 16 s was used. To avoid contamination of the light from a star located  $\sim 10''$  to the North-West of the source, an 11.5" diaphragm was used. The photometric data on TV Col were reduced differentially with respect to a nearby comparison star (located  $\sim 1.1'$  to the South and  $\sim 1.3'$  to the West of TV Col;  $V_J = 10.67$ ,  $(B-V)_J = 0.423$ ). The timing of each measurement was taken at the middle of the exposure and the heliocentric timing correction was applied. The comparison star was checked for variations by calculating the ratio of the sky subtracted signal of this star with respect to that of a second comparison star. This ratio was constant to within  $\sim 1\%$  during each night, except for the observations in 1988 when the variations in this ratio was  $\sim 2\%$ ; the average value per night was constant over the whole observing period to within 0.5%.

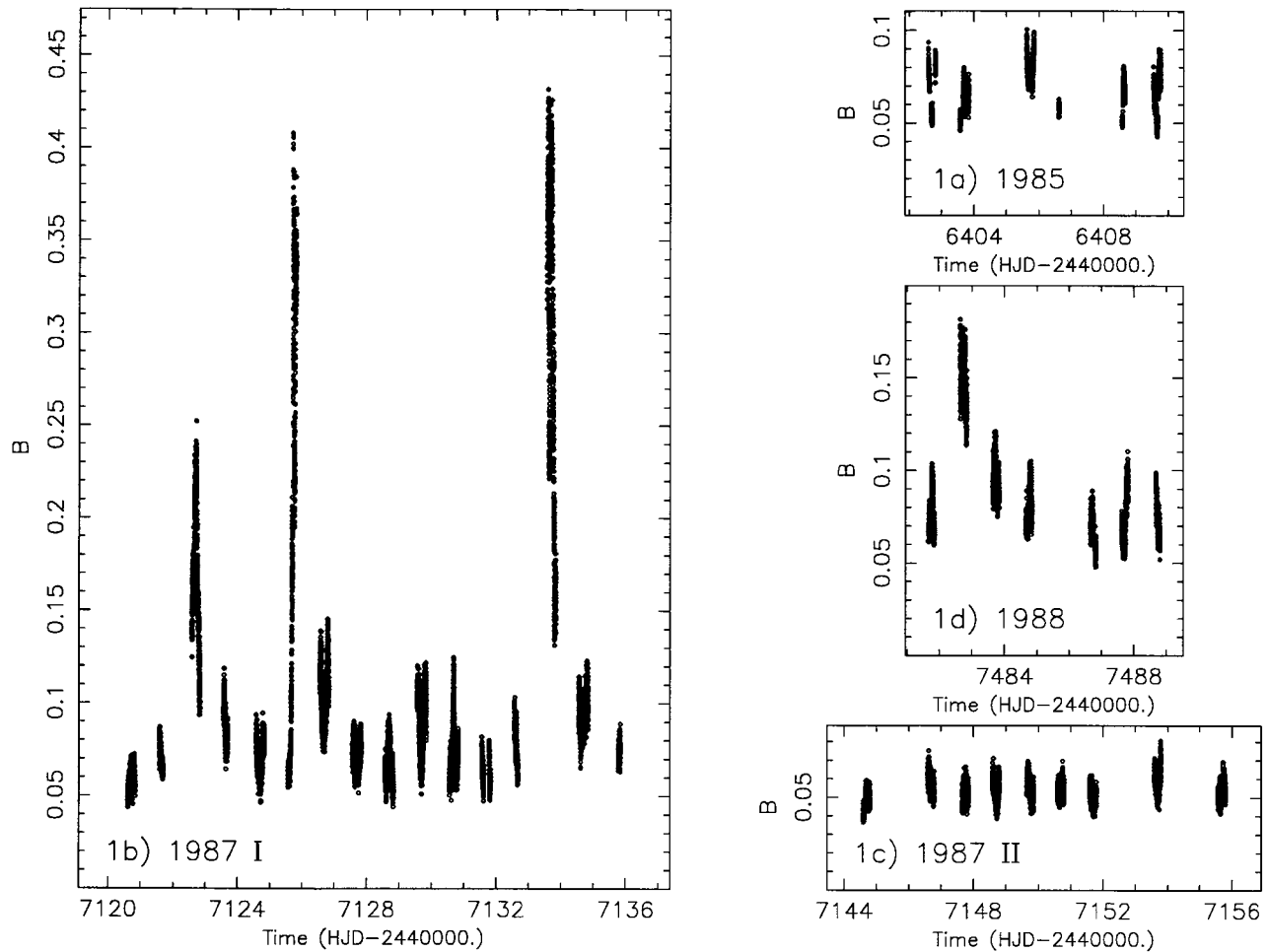
## 3. Results

We divided the 1987 observations in two parts. For the remainder of this paper we will refer to the observations from the first and second part as the 1987 I and 1987 II observations, respectively (see Table 1). In Fig. 1 we show the intensity (in units of the comparison star intensity) of TV Col in the  $B$  band as a function of time for the four observing periods. Note that the intensity scale is the same throughout the figure. It can be seen that the source, apart from the “outbursts”, is not only variable from night to night, but also shows secular brightness variations on longer timescales. In particular, the average intensity (excluding outbursts) of the 1987 I observations, and the 1988 observations is significantly higher than the average intensity in the 1985 observations, and the 1987 II observations. We will discuss this in more detail in Sect. 5.1.

### 3.1. The orbital period

From spectroscopy the orbital period of TV Col was found to be 0.228600(5) day (Hutchings et al. 1981). Recently H91 discovered the presence of an eclipse in the light curve recurring with the orbital period. In their paper H91 also determined ephemerides for the 5.2 hr and 4 day photometric periods. On the assumption that the 4 day period is the beat period between the 5.2 photometric period and the 5.5 hr orbital period they derived an orbital period of 0.2285529(2) day.

The eclipses in our Walraven data are not very conspicuous as they are partially masked by the photometric variation at the 5.2 hr period, strong  $\sim 10$ –15 % intrinsic “flickering” of the source, and the presence of “dips” of



**Fig. 1.** The intensity of TV Col in the *B* band as a function of Heliocentric Julian Date. The data is shown in four parts: a) the 1985 observations (upper right); b) the 1987 I observations (left; see Table 1); c) the 1987 II observations (lower right); d) and the 1988 observations (middle right). The intensity is in units of the intensity of the comparison star

variable strength in the light curve (see Sect. 5 and below). However, phasing our observations with the orbital period clearly shows eclipse like events recurring with this period.

Times of mid eclipse were determined from parabolic fits to the data around each eclipse in the five passbands separately. The interval over which the fit was applied was typically  $\sim 0.15$  orbital phase wide, and contained about 110 individual measurements. The error in the eclipse time was determined from the scatter around the fit. In most cases arrival times could be determined in all five passbands. In a few cases the eclipse times determined for the *W* and *U* bands showed large deviations from the arrival times in the other bands, having large formal errors, and sometimes even falling outside the interval over which the fit was performed. The reason for these deviations is most likely the occurrence of dips just before eclipse, which, relative to the eclipse, are stronger in these bands (see below), and the larger photometric error associated with

the measurements in these bands. The final eclipse times were taken to be the weighted average over the five bands, excluding the deviating measurements mentioned above. A list of the eclipse times is given in Table 2. The errors (as determined from the parabolic fits) in the last digit(s) are given in parenthesis.

Although the eclipses observed in 1985 and 1988 occur at times close to that predicted by the ephemeris determined by H91, the eclipses in 1987 are shifted by  $\sim 0.4$  in phase with respect to this ephemeris. From a linear fit to the eclipse times for 1987 alone we obtained a period of 0.228645(30) day.

On the basis of the arrival time given by H91 and the 24 arrival times obtained by us we are able to maintain cycle count over the entire data set. The corresponding orbital cycle numbers are listed in Table 2. From a linear fit to the arrival times in Table 2 we derive the following

ephemeris:

$$T_{\text{ecl}}(\text{HJD}) = 2447151.2324(11) + 0.22859884(77) \times N \quad (1)$$

$$\text{Cov}(T_0, P_0) = 1.3 \cdot 10^{-10} d^2$$

The error and covariance estimates are based on the errors in the arrival times scaled to give  $\chi_{\text{red}}^2 = 1.0$ .

**Table 2.** Times of mid-eclipse

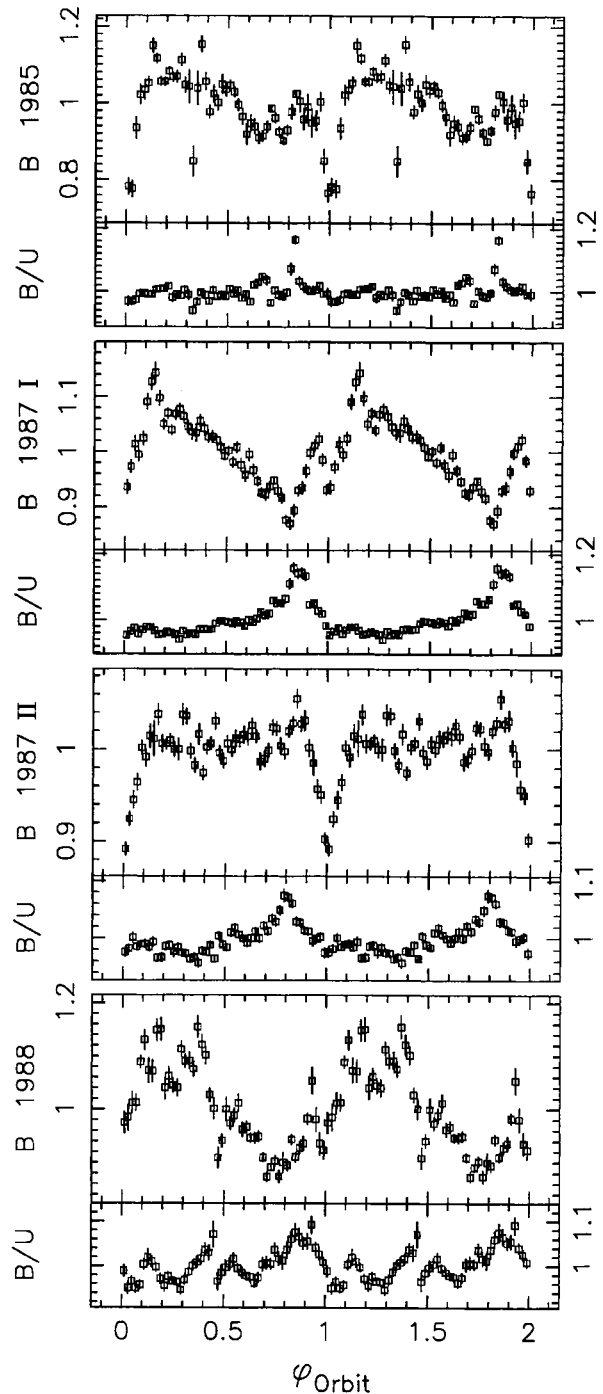
Cycle no.	$T_{\text{mid-ecl}}(\text{HJD})$ -2440000.0	Cycle no.	$T_{\text{mid-ecl}}(\text{HJD})$ -2440000.0
0	6403.7123(15)	3250	7146.6618(20)
26	6409.6609(11)	3255	7147.8046(21)
3145	7122.6472(14)	3259	7148.7230(32)
3154	7124.7126(36)	3268	7150.7778(20)
3158	7125.6270(15)	3272	7151.6916(22)
3163	7126.7674(18)	3281	7153.7422(18)
3167	7127.6953(36)	3289	7155.5815(21)
3171	7128.6077(19)	4716	7481.7853(13)
3176	7129.7344(18)	4720	7482.7017(20)
3180	7130.6556(9)	4738	7486.8157(21)
3185	7131.8089(15)	4742	7487.7361(23)
3198	7134.7805(20)	4958	7537.1114(16)*

\* Hellier et al. (1991)

The derived period is not consistent with the period derived by H91, but is consistent with the period determined from spectroscopy. The period derived by H91 is not compatible with the spectroscopic period, nor with a possible 1-year alias of this period due to the 1-year spacing in the spectroscopic observations. Furthermore, for the ephemeris derived by H91 mid eclipse occurs at  $+0.10(2)$  in phase after superior conjunction of the line emission region, whilst for the ephemeris derived above this occurs at spectroscopic phase  $+0.03(4)$ . Since, in addition we never failed to observe a predicted orbital eclipse minimum within the entire data set, we believe that the ephemeris given above is the correct one. We note here that the period reported by H91 is consistent with being the 1 cycle over three years alias of the period we derive. We would like to stress that the ephemeris given in Eq. (1) is not based on any assumption regarding a beat relation between the different periods found for TV Col.

In Fig. 2 we show the average light curve in the  $B$  band and the average  $B/U$  “colour” curve, as defined by the ratio of the intensities in the  $B$  and  $U$  band, as a function of orbital phase, for the 1985, 1987 I and II, and 1988 observations separately. To correct for the variable brightness level, the data in each individual night were first divided by the average intensity during that night before folding the data with the orbital period. The outbursts seen in the 1987 I and 1988 observations were excluded.

From Fig. 2 it can be seen that a dip of variable strength is always present around  $\phi_{\text{orb}} \sim 0.8$ , which increases in strength going from the  $B$  band to the  $U$  band (i.e. going from the red to the blue). The dip is significantly stronger in the data from the 1987 I and 1988



**Fig. 2.** In each figure we show the average orbital light curve in the  $B$  band, and the  $B/U$  “colour” curve (see text) of TV Col for, from top to bottom; the 1985, 1987 I, 1987 II and 1988 observations. The data for each night were first normalized to the average intensity of that night, before folding the data. The outbursts were excluded. The error bars indicate the error in the mean in each phase bin. Phase zero corresponds to mid-eclipse. The curves are shown twice for clarity



observations, than in the data from the 1985 and 1987 II observations. We will discuss this in more detail in Sect. 5.1.

The orbital period determined by H91 was based on the assumption that the 4 day period is the beat period between the orbital and the 5.2 hr periods. If a beat relation between the different periods indeed exists then, because we find a different value for the orbital period, one (or both) of the periods determined by H91 for the 5.2 hr and 4 day variations is also in error.

### 3.2. The 5.2 hr photometric period

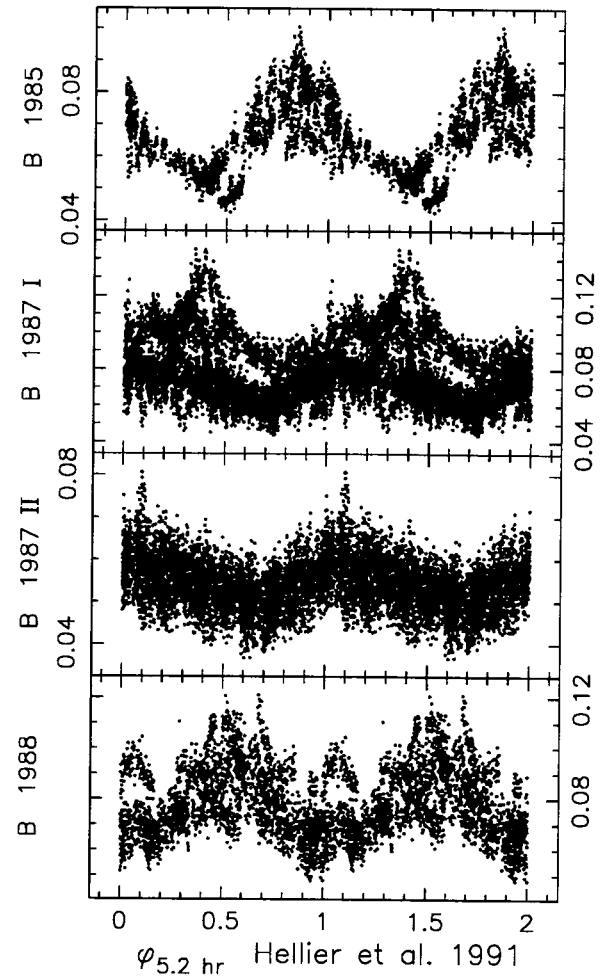
Brightness variations with the 5.2 hr photometric period were first discovered by Motch (1981) who determined a period of 0.21627(7) day. Motch also detected longer-term variations of the times of maximum light (of up to  $\sim 0.2$  in phase) in this 5.2 hr light curve as a function of the average brightness of the system, which varied with a period of  $\sim 4$  days. On the basis of times of maximum light taken from the literature and from their own data H91 determined a period of 0.2162774(14) day.

In Fig. 3 we show the folded 5.2 hr intensity variations in the  $B$  band in the different observing seasons. The phases in this figure were determined using the ephemeris as given by H91, with phase 0.0 corresponding to photometric maximum. The three outbursts seen in the 1987 I observations, and the one outburst seen in the 1988 observations (see Fig. 1) were excluded. It is clear from Fig. 3 that the ephemeris for the 5.2 hr period presented by H91 does not fit our observations. Furthermore, large variations in times of photometric maximum occur, especially evident in the 1987 I observations.

The first step in trying to derive an ephemeris is determining the arrival times and their associated uncertainties for the different observing periods. However, given the varying arrival times as functions of the 4 day brightness variations (as found by Motch 1981), and the apparently larger spread in arrival times when the source is on average brighter, this is at best a non-trivial problem.

As the data taken in 1987 present the largest self-contained data set we concentrate on these data. We have determined times of maximum light for the 5.2 hr variation from least-squares sine fits to the data for each individual night (excluding the outbursts) with data covering more than 90% of this period. In Table 3 we list the times of maximum light as determined from the sine fits for all the nights of the 1987 observations with sufficient coverage of the 5.2 hr period. The formal errors (as determined from the sine fits) in the last digit(s) are given in parenthesis.

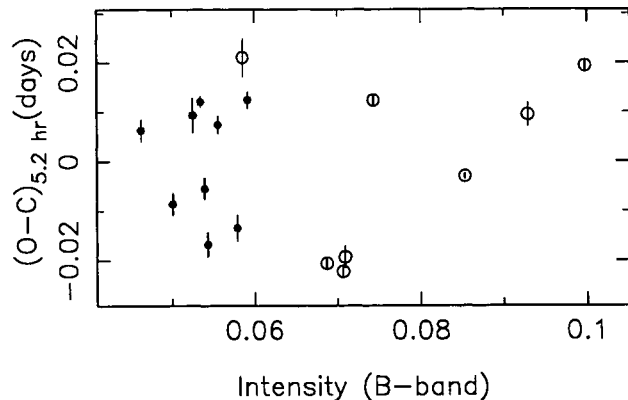
In Fig. 4 we show the differences of these times of maximum brightness with respect to the ephemeris given in Eq. (2) (see below) as a function of the average brightness in the  $B$  band. From this figure we see that the offsets of the arrival times do not show any smooth relation with the average brightness of TV Col in contrast to what was found



**Fig. 3.** The intensity in the  $B$  band as a function of phase at the 5.2 hr period as determined from the ephemeris given by H91. Phase 0.0 corresponds to the expected times of photometric maximum. From top to bottom we show; the 1985, 1987 I, 1987 II and the 1988 observations. Outbursts were excluded. The intensity is in units of the intensity of the comparison star

by Motch (1981). The spread in arrival times is similar to that found by Motch (1981). The arrival times from the 1987 I observations show a larger spread as already suggested by the data shown in Fig. 3. It is evident from Fig. 4 that an ephemeris determined on the basis of arrival times from a limited number of individual nights, depends quite strongly on the sampling of the data.

We now derive an ephemeris for the 1987 observations. In this case we can not proceed by applying a weighted linear least squares fit through the arrival times listed in Table 3 and determine the errors from the covariance matrix, as it is clear from Fig. 4 that the variations in the arrival times are significantly larger than the errors determined from the fit, and these uncertainties do not follow a simple statistical (normal) distribution.



**Fig. 4.** Difference between the observed and calculated times of maximum brightness at the 5.2 hr period as function of the average brightness in the *B* band for the 1987 observations. Formal errors in the times of maximum brightness, as determined from the sine fits, are indicated. The calculated times of maximum brightness were determined from Eq. (2). The values for the 1987 I observations are indicated open circles, and for the 1987 II observations with filled circles. The intensity is in units of the intensity of the comparison star

**Table 3.**  $T_{\max}$  5.2 hr period per night in 1987

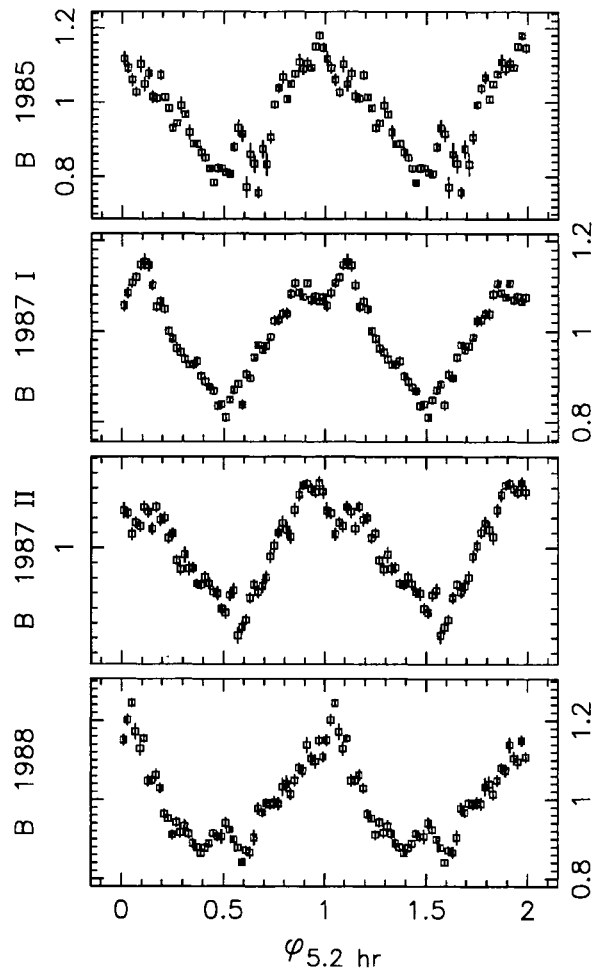
Cycle No.	$T_{\max}$ (HJD) -2440000	Cycle No.	$T_{\max}$ (HJD) -2440000
0	7120.7496(38)	111	7144.7148(21)
18	7124.5966(11)	120	7146.6394(25)
28	7126.7970(9)	125	7147.7424(34)
32	7127.6224(21)	129	7148.6093(10)
37	7128.6996(9)	134	7149.6848(17)
42	7129.7991(5)	139	7150.7408(24)
46	7130.6786(11)	143	7151.6131(22)
65	7134.7804(23)	153	7153.7945(16)
		162	7155.7209(21)

To derive the ephemeris we therefore proceeded in the following, somewhat arbitrary, way. First we determined the epoch and the period of the ephemeris by applying a linear fit to all the arrival times determined from the 1987 data, giving equal weight to each time of maximum light. From these values we determined the root-mean-squares (rms) deviation for all arrival times around this linear fit. This rms deviation was then taken to be the uncertainty in the average arrival time, with the error in the period set to the rms deviation divided by the number of cycles over which the linear fit was applied. This resulted in the following ephemeris:

$$T_{\max}(\text{HJD}) = 2447139.524(15) + 0.216036(93) \times N \quad (2)$$

The derived period is consistent with the only other period determination given in the literature ( $P=0.21627(7)$  day, Motch 1981) that is based on one long consecutive data set, in which a beat relation with other periods is not used. Although the way in which the error in that period has been derived is not given, we derive (assuming

a similar rms deviation of the arrival times around the fit) an error of 0.00005 day in that period, slightly smaller than the error quoted by Motch (1981). Similarly, separate fits to the arrival times in each of the five Walraven passbands for the 1987 observations result in ephemerides consistent with the ephemeris given in Eq. (2).



**Fig. 5.** The average light curve of TV Col in the *B* band as a function of phase at the 5.2 hr period for, from top to bottom; the 1985, 1987 I, 1987 II and the 1988 observations. The data in each night were first normalized to the average intensity of that night, before folding the data using the ephemeris given in Eq. (2). The error bars indicate the error in the mean in each phase bin. For the 1985 and 1988 observations zero phase corresponds to the time of maximum light as given in Table 4. The light curves are shown twice for clarity

In Fig. 5 we show the average normalized light curve in the *B* band as a function of phase at the 5.2 hr period for the data from the 1985, 1987 I, 1987 II, and 1988 observations, respectively. The data were first normalized to the average intensity in each night as described in Sect. 3.1. The average light curves in the other Walraven passbands are very similar to the ones presented for the *B*

band in Fig. 5. For the 1985 and 1988 observations phase zero corresponds to the times of maximum light at the 5.2 hr period given in Table 4 (see below).

It can be seen from Fig. 5 that during the 1987 I observations, when the source was relatively bright, the light curve had a slightly larger relative amplitude and a somewhat different shape of the maximum in the light curve (seemingly consisting of two maxima; see Fig. 5) than during the 1987 II observations, when the source was relatively faint. For the latter data set it seems as if the “second” maximum, i.e. the maximum just after phase 1.0, is significantly smaller than in the 1987 I observations. It might be argued that to determine the correct period for the entire set of 1987 observations we should have taken the arrival times of the first maxima, or the minima, on the basis of their similarity in the two light curves presented in Fig. 5. However, there is no a priori reason to assume that these features in the light curve are stable. The variability of the light curve over small phase intervals, and especially the change in shape and relative amplitudes between the four light curves shown in Fig. 5 indicate that any change in the light curve can not be described in a simple way (see also the average light curve at the 5.2 hr period presented by B88; their Fig. 4).

The obvious problem with trying to extend the ephemeris to other epochs is obtaining a proper determination of arrival times and their uncertainties. For the data in 1985 and 1988 we have too few arrival times to do this in a similar way as for the 1987 data. We therefore determined the arrival times from a sine fit to all the data within each year, where we first divided the data in each night by their average value. Applying this fit has the added advantage that we can also use data from nights which do not cover the 5.2 hr period completely.

To check this method we applied this method first to all the data from the 1987 I observations excluding outbursts. This added 5 more nights to the 8 nights we had already used to determine nightly arrival times (see above). Again the data in each night were first divided by the average intensity during that night. From a sine fit with a fixed period of 0.216036 day to these 13 nights we derive as the epoch of maximum light HJD 2447139.524, equal to the fiducial time in Eq. (2) determined from the linear fit to the separate arrival times of the 1987 I and II observations.

It is clear that estimating the uncertainty in an arrival time from a sine fit to data from a number of nights is not possible because applying the fit assumes that the variation consists of a strictly periodic light curve combined with some erratic brightness variation. As we already have seen, this is not the case. Lacking another estimate of the uncertainty in the arrival times we assume these uncertainties to be equal to the one determined for the 1987 ephemeris.

Table 4.  $T_{\max}$  5.2 hr period 1985–1989

year	$T_{\max}$ (HJD) -2440000	source
1985	6406.714(15)	This work
1985	6436.386(15)	Barrett et al. 1988
1987	7139.524(15)	This work
1988	7485.437(15)	This work
1989	7540.021(15)	Hellier et al. 1991

In Table 4 we list the epochs of maximum light at the 5.2 hr period determined from our own observations. We also list two times of maximum light at the 5.2 hr period from the literature determined from observations close in time to our 1985 and 1988 observations. The epochs of maximum light given by B88 and H91 were both determined from sine fits to their data. We have taken the errors in these epochs to be equal to that of the epoch in the ephemeris for the 1987 data (see Eq. (2)). This error is larger than the errors quoted by B88 and H91, and reflects the variability of the light curve. We shifted the different epochs to the approximate center of each data set (see Augusteijn et al. 1991). The assigned errors in the epochs of maximum light are listed in Table 4 in parenthesis, indicating the error in the last two digits. In the discussion below we will assume that the errors given in Table 4 can be taken as an estimate for the standard deviation ( $\sigma$ ) in the determination of each arrival time. Significance, as referred to below, is then determined at the  $3\sigma$  level.

From the period given in Eq. (2) for the 1987 data we can unambiguously determine the number of cycles between the first two (137 cycles), and the last two (253 cycles) arrival times in Table 4. However, the periods derived from these cycle counts (0.21658(15) and 0.215747(83) day respectively) differ significantly from each other.

One possible reason for our failure to find a consistent period between the different arrival times of maximum brightness at the 5.2 hr period may be that this period is not constant, e.g. it shows a constant period change. If we take as possible periods which fit between the first two and the last two arrival times listed in Table 4, the periods closest to the period determined from the 1987 data, the change in the period can be described by either a constant period decrease (on a time scale of  $|P/\dot{P}| \sim 800$  yrs), or a constant period increase (on a time scale of  $\sim 400$  yr) over the period 1985 till 1988. However, for either an increasing or decreasing period, the period calculated for the time of the observations of Motch (1981) is not compatible with the period determined for these observations, i.e. the 5.2 hr period does not have a constant period derivative. Another possibility is that the 5.2 hr period changes non-monotonically.

It might be argued that the reason for our failure is the large phase jitter in the times of maximum light. It should be noted that we used the errors listed in Table 4



as an estimate of  $\sigma$ . Taking  $3\sigma$  confidence limits then implies error intervals for individual times of maximum light of between  $+0.21$  and  $-0.21$  in phase. Our failure to find a consistent period then implies even larger jitter in the phase of maximum light than this value. However, the largest difference between the times of maximum light for the individual nights of the 1987 observations (see Table 3) and the ephemeris presented above is only  $\sim 0.10$  in phase (see Fig. 4), and we must conclude that the 5.2 hr photometric period is in fact not stable (see also Sect. 5.2).

In their Table A1 H91 list a few additional times of maximum light of the 5.2 hr light curve for earlier observations, taken from the literature. However, all these epochs are far removed in time from those listed in Table 4. As we are not able to determine a consistent period between times of maximum light much closer to each other in time, we did not include these values in our discussion.

### 3.3. The 4 day photometric period

Photometric variations with a  $\sim 4$  day period were first detected by Motch (1981) who determined a period of 3.90(15) day. On the basis of arrival times of maximum light taken from the literature and from their own data H91 determined a period of 4.0283(5) day.

Variations with a period of  $\sim 4$  days can be seen in Fig. 1, most notably in the data from the 1987 I observations. Due to the fact that the period is close to an integer number of days the observations only sample limited phase intervals of this period. The systematic errors in the times of maximum brightness at the 4 day period determined from a sine fit can therefore be significant.

As the average brightness level changes substantially between the 1987 I and the 1987 II observations, we determined times of maximum light for each half of the 1987 observations separately. The arrival time for each observing season was determined from a sine fit to the data with a fixed period of 4.0 day, and was taken to be the average over the five passbands. To get some idea of possible systematic errors we looked for each observing season at the variations of the arrival time as a function of passband, and as a function of the nights included. The latter was done by performing a series of fits with the exclusion of one night at the time.

For the fits to the 1987 I and II observations (excluding the outbursts) we found that the largest variation in times of maximum light occurred between the different passbands, with similar spread for both observations. As estimate for the error in the arrival times for the 1987 I and II observation we took the total spread in arrival times over the five passbands. For the 1985 and 1988 observations we obtained the largest variation in the times of maximum by excluding individual nights. For these observations we took the total spread of the arrival times

**Table 5.**  $T_{\max}$  4 day period 1985–1989

year of obs.	$T_{\max}$ (HJD) -2440000	Error (day)	source
1985	6406.0	0.5	This work
1985	6435.37	0.25	Barrett et al. 1988
1987 I	7130.36	0.25	This work
1987 II	7150.03	0.25	This work
1988	7484.1	1.2	This work
1989	7538.88	0.25	Hellier et al. 1991

excluding individual nights as estimate for the error in the arrival times.

As we found for the 1987 observations that the variations as a function of wavelength can be significant, and the observations of B88 and H91 cover a comparable number of observing nights to the 1987 I and II observations, we assumed the error in the arrival times for the 4 day variation determined by these authors (also from sine fits) to be equal to those determined by us for the 1987 I and II observations. All the arrival times in the period 1985–1989 (shifted to a time close to the middle of each set of observations), together with their assigned errors, are listed in Table 5.

The two arrival times determined for the 1987 I and II observations both show significant shifts (by  $\sim 0.5$  cycle) with respect to the ephemeris for the 4 day period given by H91, and we must conclude that this ephemeris is in error.

From the two arrival times of the 1987 observations we derive a period of 3.934(70) day. This period is consistent with the beat period ( $P=3.931(31)$  day) between the orbital period derived in Sect. 3.1, and the 5.2 hr period derived for the 1987 observations in Sect. 3.2. This is actually the first time that it has quantitatively been shown that the different periods in TV Col are consistent with a beat-frequency relation.

From the value of the 4 day period derived above we find that the distance between the first two arrival times listed in Table 5 corresponds to 7.5(2) cycles, i.e., only marginally consistent with the period derived for the 1987 observations. Also, given the large errors in the times of maximum light at the 4 day period and the large gaps between some of them, we are unable to determine a unique period fitting all the arrival times. If the beat relation between the different periods always holds it very well may be that this period is not constant, as is suggested by our inability to determine a constant period ephemeris for the 5.2 hr photometric variations (see Sects. 3.2 and 5.2).

### 4. The 1911 sec X-ray period

From X-ray observations Schrijver et al. (1985, 1987) detected a 1911(4) sec (frequency 45.21(10) cy/day) periodic signal in the X-ray intensity (see also B88). This period is thought to represent the rotation period of the (magnetic)

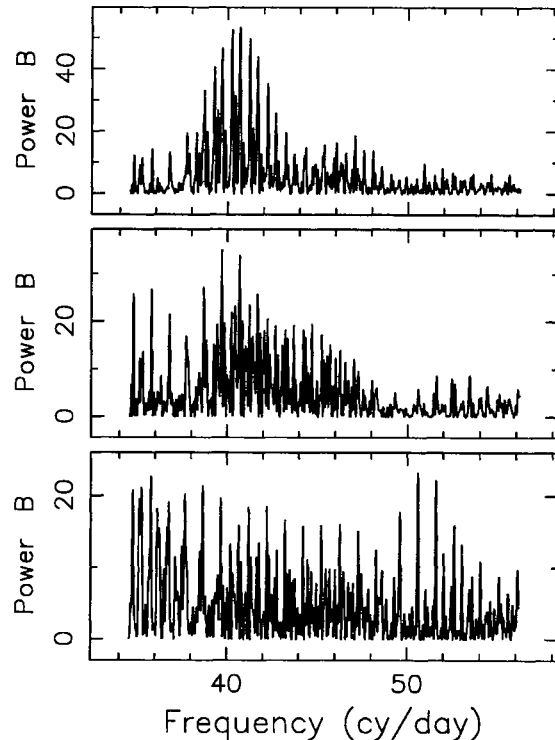
white dwarf, placing TV Col among the intermediate polar (IP) sub-class of cataclysmic variables. An interesting feature of TV Col is that no photometric variation at the 1911 sec period, or its orbital side bands, has been detected (B88). This is rather surprising as in most IP's strong optical variation of tens of percents are found at the X-ray period, and/or its orbital sidebands.

One possible reason for the failure to detect this period in the optical is the complicated light curve of TV Col due to the variations at the other three periods. Furthermore, it might be argued that during orbital eclipse and/or the dip seen at  $\phi_{\text{orb}} \sim 0.8$  (which is probably the result of a partial eclipse of the inner disk by the hot spot, see Sect. 5.1) any photometric variation at the X-ray period (or its orbital sidebands) is strongly reduced in amplitude, and/or the shape of its light curve changed. As both the eclipse and the dip have a duration which is comparable to the X-ray period this could further complicate the detection of any photometric variation at this period.

As the average orbital light curve for the data from the 1987 II observations shows a relatively weak dip at  $\phi_{\text{orb}} \sim 0.8$ , and these data are also less affected by large brightness changes, we will look at these data in some detail.

In Fig. 6 we present power spectra of the intensity in the *B* band for the 1987 II observations around the X-ray frequency using the Lomb-Scargle method (see Press & Rybicki 1989 and references therein). In each case the data from the different nights separately were first divided by the average of the data that were included for that night. In the top part of Fig. 6 we show the power spectrum of all the data. No peak is found near the expected position of the 1911 sec period, but we do find a number of peaks in the region of the negative orbital (at 40.84(10) cy/day) and 5.2 hr period (at 40.58(10) cy/day) sidebands to the 1911 sec period. The relative strength of the different peaks in this region varies between the different Walraven passbands (not shown here). In the middle part of Fig. 6 we present the power spectrum for the data after correcting for the photometric variations at the 5.2 hr period (see Sect. 5.2 for a description of the correction method used). In this figure it can be seen that all these peaks have been reduced in power. If we now limit the data to the orbital phase interval  $\phi_{\text{orb}}=0.15-0.85$  (i.e. excluding the eclipse; lower part of .6) all these peaks have disappeared. We also looked at the power spectra of the data limited to the orbital phase intervals  $\phi_{\text{orb}}=0.15-0.50$  (i.e. also excluding the dip at  $\phi_{\text{orb}} \sim 0.8$ ) and  $\phi_{\text{orb}}=0.50-0.85$ . Again no significant peaks were found.

We conclude that, also considering potential effects of the occultation of part of the disk by the secondary and the hot spot, the detection of optical variations at the X-ray pulse period (or its orbital or 5.2 hr period sidebands) remains elusive. We derived upper limits to the fractional amplitude of any signal with a period close to



**Fig. 6.** Power spectra of the intensity in the *B* band for the 1987 II observations in the region of the X-ray period, and its orbital and 5.2 hr period sidebands. Shown are the power spectra of: all data (top); all data after correction for the 5.2 hr period (middle; see text); the same but for the orbital phase interval  $\phi_{\text{orb}}=0.15-0.85$  (lower). In each case the data from the different nights separately were first normalized to the average of the data that were included for that night. The ordinate gives the power, normalized on the total variance of the data, as a function of frequency

the X-ray period in the five Walraven passbands. This was done by adding sinusoidal light curves with varying amplitude and fixed period (of 1911 s) to the data of the 1987 II observations and determine for which fractional amplitude the peak at this period in the power spectrum reached the same height as any other peak in the period range 1850-1960 sec. In this way we derived upper limits of 1.4% (for the *V* passband), 0.8% (*B*), 1.3% (*L*), 0.9% (*U*) and 1.3% (*W*).

## 5. Discussion

### 5.1. Long term brightness changes

It is clear from Fig. 1 that long-term brightness changes occur in TV Col. To get some measure of these brightness changes we took the average of all the observations in each observing period, dividing the 1987 observations in two parts and excluding the outbursts. Of course, the

average brightness depends on the sampling of the different periodicities, which, given their complexity (see Sect. 3), is difficult to quantify in any unbiased manner. However, given the large number, and the distribution in time of the observations in both observing periods in 1987, we expect any systematic effect in the average brightness for these observations to be small.

In Table 6 we list the average brightness in the five Walraven passbands (in mJy) for the different observations. Also listed in Table 6 is the average magnitude in the  $B$ -Johnson filter as determined from the transformation equation by Pel (1987). From this table one can see that also the colours of the system change with time. In particular the source is bluer in  $(V-B)_W$  during the 1987 I observations when the source was bright, than during the 1987 II when the source was faint. During the 1987 I observations the Balmer decrement, as measured by  $(B-U)_W$ , is much less pronounced than during the 1987 II observations. A similar difference in Balmer decrement is seen between the 1988 observations when the source was at a similar bright level as during the 1987 I observations, and the 1985 observations when the source was fainter. However, for the 1985 and 1988 observations systematic effects due to incomplete sampling of the different periodicities might still be present.

The question arises if these average brightness changes in TV Col are a common feature, and if there is a preferred brightness level. For the 10 nights of observations presented by Motch (1981) we estimate (from his Fig. 1) an average brightness level of  $B_J \sim 13.9$  and for the 5 nights of observations presented by Mateo et al. (1985) we estimate (from their Fig. 2, excluding the two outbursts detected during these observations) an average brightness level of  $B_J \sim 13.8$ , i.e. during both these sets of observations the source was at a similar (high) brightness level as during the 1987 I and 1988 observations. Unfortunately, the exact calibration for the extensive data sets presented by B88 and H91 is not known. However, the shape of the average orbital light curve presented by B88 (their Fig. 4) and H91 are remarkably similar to the  $B$  light curve of our 1987 I and 1987 II observations, respectively (see Fig. 2). This might indicate that the source was relatively bright (similar to our 1987 I observations) during the observations of B88, and relatively faint (similar to our 1987 II observations) during the observations of H91. However, the observations performed by B88 were made using a blue-sensitive S-11 photomultiplier without filter, and those by H91 were made using a (red-sensitive) RCA CCD without filter. As the strength of the dip increases towards shorter wavelength the shape of the average orbital light curve presented by these authors might also be the result of the particular wavelength region at which their observations were made.

The available data are not sufficient to determine if the source has a preferred brightness level. The observed range

**Table 6.** Average brightness per observing period

year	Flux in mJy					$B_J$ (mag.)
	$V_W$	$B_W$	$L_W$	$U_W$	$W_W$	
1985	10.31	10.27	10.62	11.02	10.20	14.05
1987 I	11.78	11.99	11.96	12.11	11.55	13.87
1987 II	8.45	8.24	8.40	8.80	8.23	14.28
1988	12.37	12.11	12.06	12.30	11.59	13.87

of the average brightness of TV Col is between  $B_J \sim 13.9$  and  $B_J \sim 14.3$ . Within this range faint and bright states occur approximately equally often.

The shape of the average orbital light curve shows long-term variations (see Fig. 2). The main difference between the average orbital light curves for the 1987 I observations, when the source was bright, and for the 1987 II observations, when the source was faint (see Table 6), is in the strength of the dip near  $\phi_{\text{orb}} \sim 0.8$ . During the 1987 I observations the dip is strong, somewhat deeper than the eclipse in the  $B$  band and substantially deeper than the eclipse in the  $U$  band. During the 1987 II observations the dip is weak, being invisible in the  $B$  band and being somewhat shallower than the eclipse in the  $U$  band.

By analogy to the dip in orbital X-ray intensity of low-mass X-ray binaries (see e.g. Mason 1986), the orbital phase of this dip suggests a connection with a “hot spot”, i.e. the point where the accretion stream from the secondary hits the outside of the disk: the dips are then understood as the result of occultation of part of the accretion disk by an extended optically thick hot spot. The relative depth of dips and eclipse in the  $U$  band compared to the  $B$  band would indicate that the vertical angular extent of the hot spot as seen from the white dwarf primary, is larger than that of the secondary. An alternative explanation for the dips might be that the accretion stream skims over the rim of the accretion disk, and hits the magnetosphere of the magnetic white dwarf directly (a similar geometry has been proposed to explain the optical and X-ray observation of BG CMi; see Norton et al. 1992). The dip might in that case be the result of occultation of the region close to the white dwarf by the area where the stream hits the magnetosphere. In both models an increase in the depth of the dip (as seen in the 1987 I observation) is most easily explained by an increase in size of the occulting area, which in turn would be a natural result of an increase in the mass transfer rate from the secondary. The average orbital light curves (see Fig. 2) and the average brightness of the 1985 and 1988 observations (see Table 6) are consistent with this picture. Unfortunately, it is not possible to accurately infer the change in mass transfer rate from the change in brightness. Following Warner (1988; his Eq. (18)) we estimate, for the change in brightness between the 1987 I and II observations a corresponding change in the mass transfer rate by a factor  $\sim 1.5$ .



We have entertained the idea that the long term brightness variations are due to changes in the rate at which matter is transported through the disk, with a constant rate of inflow from the secondary, as envisioned in disk-instability models for dwarf novae outbursts (see, e.g., Cannizzo 1993). This idea has the problem that it does not explain the changes in the strength of the dip (which are correlated with the average brightness). This model also would not easily explain why outbursts occur when the source is bright (see Sect. 5.3), and we conclude that this model is not suitable.

## 5.2. Variations at the 4 day period

A possible model to explain the different photometric variations in TV Col is the presence of a tilted accretion disk which is retrogradely precessing with the 4 day period (e.g. Bonnet-Bidaud et al. 1985). Similar models have been proposed to explain long-term variations in the X-ray binaries Her X-1 (Gerend & Boynton 1976), SS433 (Leibowitz 1984), LMC X-4 (Ilovaisky et al. 1984; Heemskerk & Van Paradijs 1989), and LMC X-3 (Cowley et al. 1991). An alternative model is the precession of an eccentric accretion disk similar to what has recently been proposed to explain the superhumps seen in SU UMa type dwarf novae during “superoutbursts” (Whitehurst 1988). In both models the 5.2 hr period is the recurrence time between the same relative position of the secondary with respect to the accretion disk. An obvious problem with the latter model is that the accretion disk is supposed to precess progradely, and not retrogradely as implied by the photometric periods observed in TV Col.

In this section we will investigate the changes in the optical light curve as function of the 4 day cycle and discuss their cause. As the 1987 I and II observations cover the 4 day period best we will only discuss these observations.

In Fig. 7 we present the average  $B$  light curve and the  $B/U$  colour curve as function of orbital phase for four different phase intervals of the 4 day cycle for the 1987 I and 1987 II observations, respectively. The data of each night were first normalized to the average intensity for that night. Phase 0.0 of the 4 day period coincides with maximum light (see Table 5). The average phase at the 4 day period for each phase interval was calculated using the period determined for the whole 1987 observations (see Sect. 3.3), and is indicated in the figure. The error in the average phase is determined by the uncertainty in the time of maximum light, which is the same for the 1987 I and the 1987 II observations (see Table 5), and corresponds to 0.06 in phase. The main difference between the sets of orbital light curves is the larger depth of the dip at  $\phi_{\text{orb}} \sim 0.8$  in the 1987 I observations compared to the 1987 II observations.

Figure 7 shows the changing phase difference between the time of the eclipse and the time of maximum light throughout the 4 day period. From Eqs. (1) and (2) we

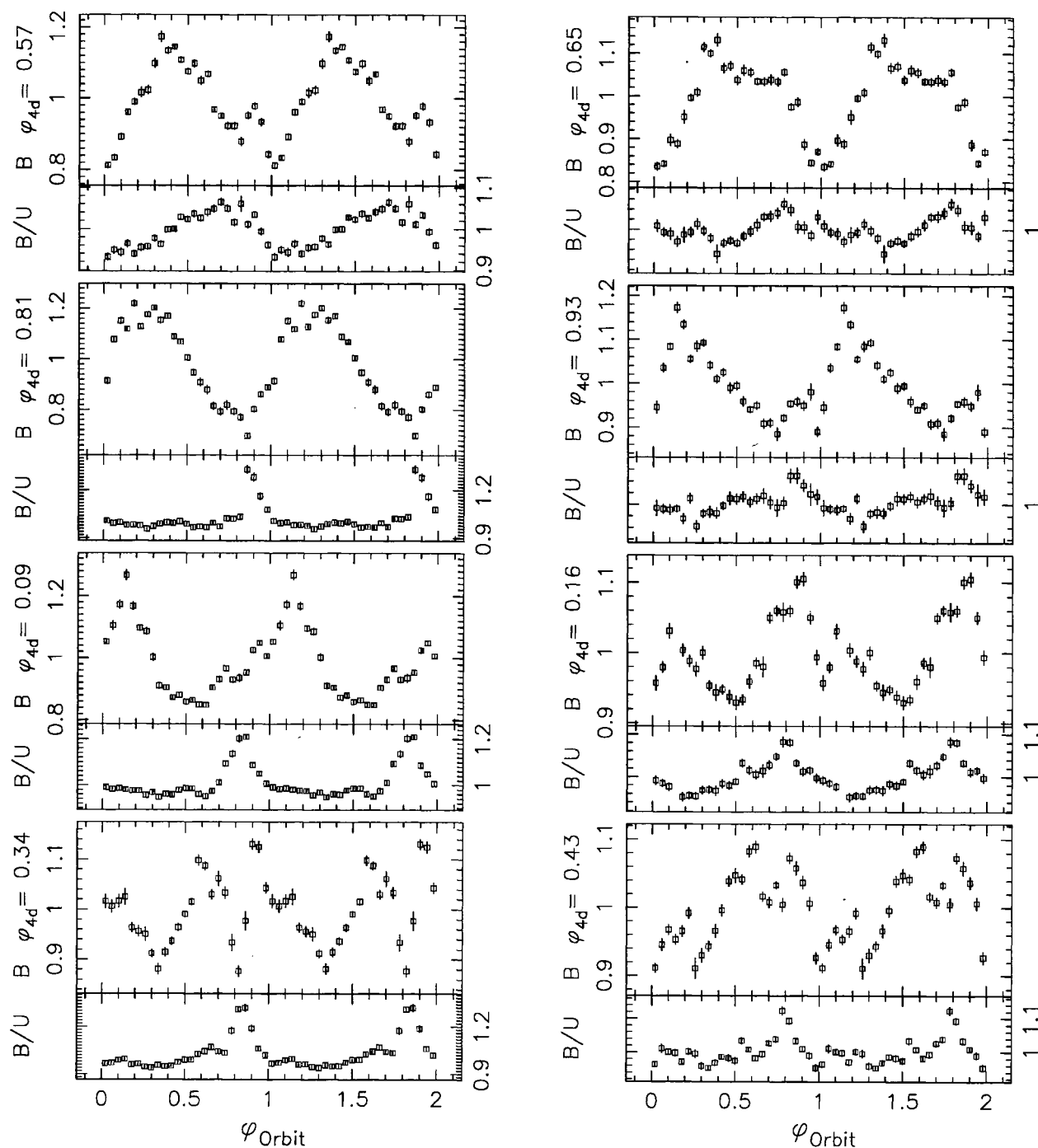
find that the orbital eclipse and the maximum of the 5.2 hr light curve are in phase near the time of maximum light of the 4 day period. This phase relation was already noted by H91, and can be seen by “interpolating” between the average orbital light for  $\phi_{4d}=0.93$  and  $\phi_{4d}=0.16$  for the 1987 II observations shown on the right side in Fig. 7. This phase relation is less clear in the data for the 1987 I observations (left side of Fig. 7) as the data for  $\phi_{4d}=0.09$  are affected by a flare in one of the nights included in that phase interval, which reached maximum shortly after eclipse.

One simple prediction which can be made about the expected photometric variations is that if any precessing accretion disk is present in TV Col, this should result in a variable depth and shape of the orbital eclipse and possibly of the dip at  $\phi_{\text{orb}} \sim 0.8$ . However, as can be seen in Fig. 7 the photometric variations at the 5.2 hr period and the orbital period interfere strongly with each other, making any decomposition of the brightness variations very difficult.

From Fig. 5 we have seen that the average light curve at the 5.2 hr period for the 1987 II observations has a fairly regular triangular shape. These observations are also least affected by long-term brightness variations and/or outbursts (see Fig. 1). A close look at the light curves presented on the right side in Fig. 7 suggest that the different light curves for the 1987 II observations can be understood as a simple super-position of the orbital light curve and the 5.2 hr period light curve with a varying phase difference ( $\sim$ equal to the phase at the 4 day period). If we assume that the light curve at the 5.2 hr period has a fixed shape and amplitude independent of the phase of the 4 day cycle, this would allow us to decompose the light curve and look more closely at any possible change in the orbital light curve as function of the 4 day period. This idea is supported by the fact that the amplitude of the different light curves presented on the right side in Fig. 7 is practically constant as a function of the 4 day cycle, with the increased amplitude at  $\phi_{4d}=0.65$  the result of the orbital eclipse being in phase with photometric minimum of the 5.2 hr period.

The average light curve at the 5.2 hr period for the 1987 II observations (see Fig. 5) is not very smooth. As correcting the data with this observed average light curve may introduce complex systematic errors we chose to fit a simple geometric shape to the average 5.2 hr light curve. We decided to divide the light curve in two phase intervals, 0.60–0.92 and 0.92–1.60 respectively, and fit a straight line to each part. The two lines cross at phase 0.591 and 0.914 supporting our election of phase intervals. The individual data points of the 1987 II observations were corrected for the variations at the 5.2 hr period using this fit.

The average orbital light curves for the 1987 II observations corrected for the variation at the 5.2 hr period are presented in Fig. 8 for four different phase intervals of the



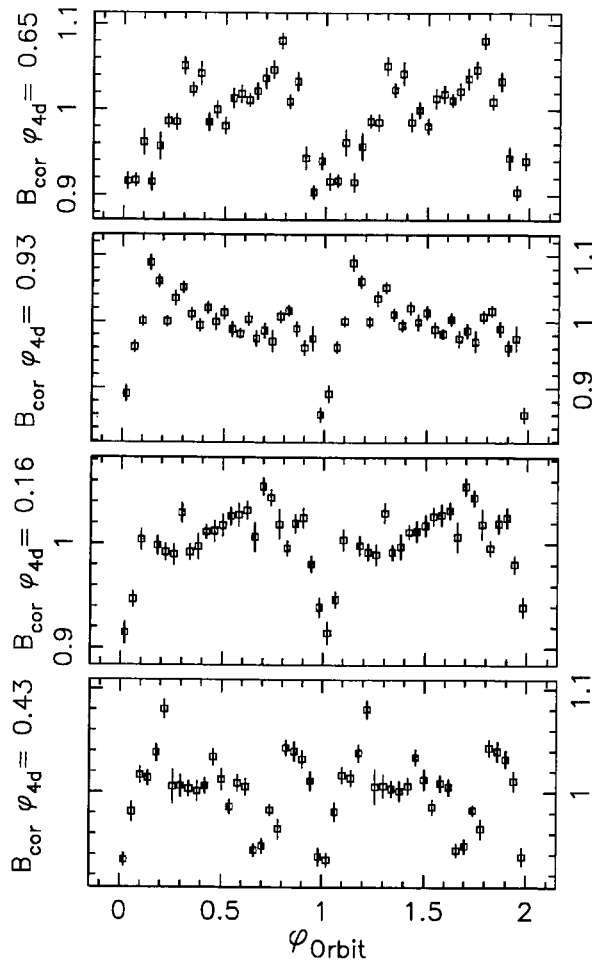
**Fig. 7.** The four plots on the left show the average orbital  $B$  light curve and the  $B/U$  colour curve for the 1987 I observations for four different phase intervals of the 4 day period, and the four plots on the right show the same for the 1987 II observations. The data of each night were first normalized to the average intensity for that night. The average phase at the 4 day period is indicated along the ordinate. Phase zero at the 4 day period corresponds to maximum brightness

4 day period. Although the light curves show some residual variations at the 5.2 hr period and also look rather erratic a number of interesting features can be noted. The eclipse in the light curve at  $\phi_{4d}=0.65$  is wider than the eclipse in the overall average orbital light curve (see Fig. 2), in particular the egress is at a later phase. Furthermore, the dip at  $\phi_{orb} \sim 0.8$  is only seen at  $\phi_{4d}=0.43$ . These same

features are also seen in the data of the other Walraven passbands, with the dip at  $\phi_{orb} \sim 0.8$  in the light curve at  $\phi_{4d}=0.43$  extending below the eclipse in the  $U$  and  $W$  bands.

The strongest dip at  $\phi_{orb} \sim 0.8$  in the 1987 I observations (at  $\phi_{4d}=0.34$ ; see left side of Fig. 7) occurs at practically the same phase in the 4 day cycle as the strongest





**Fig. 8.** The average orbital light curve in the  $B$  band for the 1987 II observations corrected for the variations at the 5.2 hr period (see text) for four different phase intervals of the 4 day period. The average phase at the 4 day period is indicated along the ordinate

dip at  $\phi_{orb} \sim 0.8$  seen in the 1987 II observations. If we interpret the brightness variations at the 4 day period as a result of the varying aspect of a precessing tilted accretion disk,  $\phi_{4d}=0.0$  would then coincide with the axis perpendicular to the accretion disk pointing towards us. At this phase in the 4 day cycle the hot spot is expected to block only a small part of the inner disk from our view, whilst blocking a relatively large part at  $\phi_{4d} \sim 0.5$ . This might explain the observed increase in the dip at  $\phi_{orb} \sim 0.8$  close to phase 0.5 in the 4 day cycle. This interpretation assumes that the hot spot is somehow “fixed” to the disk rim, which moves up and down as function of phase at the 4 day period relative to the secondary where the mass transfer stream originates.

A similar extended eclipse like the one seen at  $\phi_{4d}=0.65$  in Fig. 8, including an egress at later phase, also seems to be present in the average orbital light curve at

$\phi_{4d}=0.57$  for the (uncorrected) 1987 I observation shown on the left side in Fig. 7. However, if we assume the same precessing tilted accretion disk interpretation for the brightness variations at the 4 day period one would expect the widest eclipse to occur at  $\phi_{4d}=0.0$ , i.e. photometric maximum at this period.

Of course, the light curves presented on the left side in Fig. 7 are difficult to interpret, and the specific shape of the eclipse light curve at  $\phi_{4d}=0.65$  presented in Fig. 8 might be the result of variations in the 5.2 hr period light curve which we have assumed to be constant. We, therefore, cannot exclude the presence of a precessing tilted accretion disk, but Fig. 8 shows that a decomposition of the light curve on the basis of the above simple assumptions does not describe the observations well. Yet, the variations in the shape and depth of the eclipse and the dip at  $\phi_{orb} \sim 0.8$  make it seem likely that geometric changes related to the accretion disk occur on the 4 day period. However, a discussion of more complicated geometric models (e.g., twisted accretion disks; Petterson 1975, 1977) would require better observational constraints on TV Col than currently available.

Some information on the mechanism that governs the variation at 4 day period might be obtained from looking at the shape of the light curve at the 5.2 hr period. The photometric variation at the equivalent period for sources which are thought to contain a tilted precessing disk is assumed to arise from the variable X-ray heating of the secondary. There are a number of problems with a similar explanation for the origin of these photometric variations in TV Col. For the observed X-ray luminosity of  $(0.6\text{--}6.2) 10^{32} \text{ erg s}^{-1}$  (Norton & Watson 1989) one would expect to see full amplitude photometric variations in TV Col of at most 0.1 mag, i.e. substantially smaller than the observed  $\sim 0.2\text{--}0.3$  mag full amplitude variations seen in Fig. 3. Furthermore, given the relatively high inclination of TV Col one would expect, except for very particular configurations of the disk, to see two maxima in the 5.2 hr photometric light curve due to the variable X-ray heating of the upper and lower part of the secondary.

If we assume an eccentric precessing disk model we can compare the 5.2 hr light curve directly with the equivalent photometric variations seen in systems which are thought to contain such a disk, i.e. the so-called superhumps seen in SU UMa type dwarf novae during outburst. The triangular shape and amplitude of the average light curve for the 1985 and 1987 II observations are remarkably similar to the superhump light curves in SU UMa stars (see Fig. 3 and, e.g., La Dous 1993, and references therein). However, the average light curve for the 1988 observations looks significantly different.

Another aspect that can be compared is the stability of the equivalents of the 5.2 hr and 4 day periods. The prototype of a system which is thought to contain a tilted precessing disk is Her X-1. Boynton et al. (1980) found that

the cycle length of the  $\sim 35$  day period in X-ray brightness, identified with the precession period of the disk, can vary by as much as  $\sim 5\%$  over intervals of order 10 cycles. Ögelman (1987) performed a statistical study of an extensive set of X-ray observations and found that the data were consistent with either a  $\sim 35$  day period which is intrinsically unstable, or with a period that is intrinsically stable but shows large phase jitter.

The superhump period of SU UMa systems, the equivalent of the 5.2 hr variation in TV Col, often show a period change during the decline from a superoutburst (see e.g. La Dous 1993). In the precessing-disk model this would imply that the precession period also changes (it is unclear whether the moderate changes in the brightness of TV Col would give rise to substantial corresponding period changes).

In view of the above, we conclude that if TV Col contains either a tilted or eccentric precessing disk, the period and/or phasing of the precession of the disk need not be stable. This might explain our inability to determine a constant period ephemeris for the 5.2 hr variations, and we argue that this period in fact changes non-monotonically with time.

### 5.3. The outbursts

During our observations we detected four outbursts. Previously, two outbursts from TV Col have been reported, one strong outburst, which was also detected with IUE (Szkody & Mateo 1984) and a second outburst, occurring only two days earlier (Mateo et al. 1985). The latter outburst had a lower amplitude, although it is possible that the rise to maximum had not finished by the end of the observations.

All six outbursts occurred when TV Col was relatively bright ( $B_J \sim 13.9$ , see Sect. 5.1). For the disk instability model Cannizzo & Mattei (1992; see also Ichikawa & Osaki 1993) found from model calculations that the recurrence time between normal outbursts in dwarf novae is approximately inversely proportional to the square of the mass transfer rate from the secondary, i.e. proportional to  $\sim \dot{M}^{-2}$ . The detection of outbursts in the high state can then simply be understood as the result of a higher outburst frequency due to an increase in the mass transfer rate, i.e. the brightness increase reflects an increase in  $\dot{M}$  (see Sect. 5.1).

The two large-amplitude outbursts in our 1987 observations (see Schwarz et al. 1988, their Fig. 1) both show large brightness decreases near maximum (to avoid confusion we do not call them “dips”). A similar decrease is also present during the large amplitude outburst presented by Szkody & Mateo (1984, their Fig. 3). The two decreases in our data occur at orbital phase 0.65 and 0.0, respectively, so it is unlikely that they reflect occultation by a hot spot, or an eclipse by the secondary. It is, of course, possible that all minima observed near the peak

of outbursts of TV Col have a common origin, but this is unlikely to be an occultation by the same object.

The outbursts in TV Col have a very short duration and low amplitude when compared to outbursts in dwarf novae (see e.g. La Dous 1993). This might be explained by the absence of the inner part of the accretion disk which is truncated by the strong magnetic field of the white dwarf (Schwarz et al. 1988; Angelini & Verbunt 1989). The observed spread in outburst amplitudes is comparable to that of dwarf novae, although it might be argued that the small amplitude outbursts in TV Col are in fact observations of only a part of a larger amplitude outburst. However, the observations of the first outburst in 1987 observations (see Fig. 1) seems to cover nearly an entire outburst, showing both a rise and decline in brightness.

The two large-amplitude outbursts presented here, and the one observed by Szkody & Mateo (1984) all occur at about the same phase (just before maximum light) of the 4 day cycle. The small amplitude outburst observed in our 1987 I observation and the small amplitude outburst observed by Mateo et al. (1985) occur elsewhere in the 4 day cycle. This might indicate that the difference in the observed amplitude of the outbursts is related to the changing aspect of the disk with respect to the observer as a function of the 4 day cycle (the time of maximum light at the 4 day cycle of the 1988 observations is too uncertain, see Table 5, to determine the phase of the outburst in the 1988 observations).

## 6. Summary

In summary, our results are the following.

- i) We determined a new ephemeris for the orbital period;
- ii) Additional times of maximum light at the 5.2 hr and 4 day period were presented which are inconsistent with the ephemerides presented in the literature;
- iii) We are unable to find a constant period which connects all the times of maximum light at the 5.2 hr period. We suggest that this period is not stable and can change non-monotonically with time;
- iv) We did not detect any photometric variations at the X-ray pulse period, nor at its orbital or 5.2 hr period sidebands;
- v) Changes in the orbital eclipse and the dip at  $\phi_{\text{orb}} \sim 0.8$  occur as a function of phase at the 4 day cycle, indicating geometrical changes related to the accretion disk. These changes seem to be a persistent feature of the 4 day cycle;
- vi) Apart from the photometric variations at the three previously known periods long-term brightness changes occur. The average brightness of the system ranges from  $B_J \sim 14.3$  to  $B_J \sim 13.9$ , and we argue that these brightness changes are the result of variations in the mass transfer rate from the secondary;
- vii) The source exhibits 1–2 mag outbursts when it is in the bright state.

From our discussion in Sect. 5 it is clear that many of the variations seen in TV Col are not well understood. In particular the variations in the light curve as a function of the 4 day cycle cannot easily be modelled by assuming either a tilted or an eccentric disk precessing at that period. Simultaneous multiwavelength photometric and spectroscopic observations (ranging from X-ray to the [near] infra-red) covering the entire 4 day cycle seems to be the only way to properly disentangle the contributions from a (precessing) disk and the (X-ray heated) secondary at the different periods. In this way one might hope to constrain possible models for TV Col, and other similar systems.

A copy of the reduced Walraven data set of TV Col in the form of an ASCII file can be obtained from the authors. Your request should be send by electronic mail to thomas@astro.uva.nl (internet).

*Acknowledgements.* We thank an anonymous referee for valuable comments which especially improved the discussion presented in this article. We thank Vik Dhillon for supplying the 'PERIOD' analysis package, which we used for part of our data analysis. TA acknowledges support by the Netherlands Foundation for Research in Astronomy (NFRA) with financial aid from the Netherlands Organisation for Scientific Research (NWO) under contract number 782-371-038.

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