# *uvbyβ* PHOTOMETRY OF ACTIVE-CHROMOSPHERE BINARIES. I. THE SYSTEM TZ CORONAE BOREALIS

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## ABSTRACT

We present simultaneous *uvby* and H$\beta$ photometry of the non-eclipsing double-lined spectroscopic binary TZ CrB, an active binary system with almost unevolved components. A small amplitude distortion wave (0.012 mag in $y$) has been found with maximum light at phase $\sim 0.75$. No variations in color or the $\beta$ index during the orbital cycle have been detected within the precision of the observations. The resulting color indices in the standard *uvby* system allow the estimation of some basic stellar parameters, such as the average effective temperature $\sim 6000$ K and the stellar radii of the component stars $\sim 1.1\ R_\odot$. These results, together with available spectroscopic data, permit us to obtain a consistent picture for this interesting binary.

## I. INTRODUCTION

$\sigma$ CrB is a visual binary (ADS 9979, HR 6063/4) with an eccentric orbit ($e = 0.78$) and an orbital period of $10^3$ yr, whose components are separated by 6 arcsec. The brighter member is a double-lined spectroscopic binary (TZ CrB $= \sigma^2$ CrB = HD 146361, $V = 5.64$ mag, G0 Ve) with an orbital period of 1.14 days that presents important chromospheric and coronal activity (Bopp 1984), as deduced from ultraviolet and x-ray observations (Agrawal *et al.* 1981; Tarafdar and Agrawal 1984), as well as radio flares (Spangler *et al.* 1977). The fainter visual companion ($\sigma^1$ CrB = HD 146362, $V = 6.59$ mag, G1 V) does not present any indication of chromospheric activity from high-resolution spectra in the region of the Ca II H and K lines (Fernández-Figueroa *et al.* 1986).

TZ CrB was cataloged as a non-eclipsing RS CVn type binary according to the emission features observed by Young and Koniges (1977); thus the likely existence of a migrating wave in its light curve was expected. The first photometric search for such variability was carried out by Skillman and Hall (1978). They found indications of a sinusoidal light variation with an amplitude of 0.05 mag and a superposed $\delta$ Scuti type cyclical variation with a period of $\sim 0.1$ days and a total amplitude of $\sim 0.05$ mag. None of these light changes was confirmed by later observations carried out by Vivekananda Rao *et al.* (1985) though they only covered a small fraction (0.25) of the orbital period. A larger coverage, as well as a better quality of the photometric observations, was thus clearly required if any light variation in the binary system was to be definitely detected.

Throughout this paper, we have adopted the linear ephemeris given by Bakos (1984),

$$T = \text{J.D. hel. } 242\ 3869.390 + 1^{\text{d}}1397912\ E, \qquad (1)$$

but have slightly corrected the zero epoch so that it coincides with conjunction instead of periastron passage.

## II. THE OBSERVATIONS

All the observations were carried out during eight nights in July 1985. We used the 75 cm reflecting telescope at the Observatory of Sierra Nevada (Granada, Spain), which is equipped with a 4 + 2 channel spectrograph photometer and a photon-counting system that measured simultaneously the four *uvby* bands and, respectively, the $n$ and $w$ bands centered on the H$\beta$ line. A detailed description of this instrument is given by Florentin-Nielsen (1983). A circular diaphragm of 45″ was used, which means that the close visual companion $\sigma^1$ was also included in the measurements as well as the fainter star ADS 9979 C (13.0 mag at a distance of 9″) but not ADS 9979 D (10.8 mag at a distance of 71″).

Extinction corrections were based on the nightly coefficients derived from the comparison star and other constant stars. The bright star HR 5968 ($V = 5.41$ mag, G2 V), which is one of the standards for the Strömgren four-color system given by Crawford and Barnes (1970), was used as comparison, and its constancy was checked every night. The observation log is presented in Table I, which includes the number of measurements for each date and the phase coverage according to the adopted ephemeris. In total, 138 individual magnitude differences have been obtained in each of

TABLE I. Observation log.

| Dates | $N_{\text{obs}}$ | | Phases | |
|---|---|---|---|---|
| | *uvby* | $\beta$ | initial | final |
| 6/7 July 1985 | 18 | 20 | 0.700 | 0.760 |
| 7/8 July 1985 | 30 | 30 | 0.559 | 0.645 |
| 8/9 July 1985 | 17 | 29 | 0.439 | 0.521 |
| 9/10 July 1985 | 26 | 26 | 0.322 | 0.404 |
| 11/12 July 1985 | 14 | 14 | 0.071 | 0.120 |
| 12/13 July 1985 | 5 | 7 | 0.975 | 0.000 |
| 13/14 July 1985 | 9 | 19 | 0.825 | 0.908 |
| 14/15 July 1985 | 19 | 21 | 0.693 | 0.773 |

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the *uvby* bands and 166 for H$\beta$. The error of one measure is found to be $\pm 0.005$ mag (in $v$, $b$, and $y$) and $\pm 0.007$ mag (in $u$ and $\beta$). This represents a considerable improvement with respect to previous observations by Skillman and Hall (1978) and Vivekananda Rao *et al.* (1985), which attained $\pm 0.02$ mag in $V$.

The original observational data have been deposited in the IAU Commission 27 Archive for Unpublished Photometry of Variable Stars (Breger 1982) as File No. 189. Given there are individual magnitude differences of the variable with respect to the comparison star HR 5968, measured before and after the variable, in the sense variable minus comparison. All the magnitude differences are given in the instrumental system.

## III. THE LIGHT CURVES

The *uvby* observations described above are plotted in Fig. 1 with orbital phases $\phi$ computed from Eq. (1). It is immediately apparent that a cyclical variation of small, but detectable, amplitude ($\sim 0.01$ mag) is displayed by the $y$ band. Nevertheless, the color light curves do not show any indication of variability. This should not be unexpected due to the very low amplitude of the variations in $\Delta y$, but prevents us from studying the temperature differences between spotted regions and the surrounding photosphere. Only the $c_1$ index seems to present some marginal variation, in phase with respect to the $y$ band but with the opposite sign, though the scatter is too large and conclusions can only be tentative.

From Fig. 1(a), it is clear that the light variations in $\Delta y$ are a function of cos $\phi$ and not cos $2\phi$ as would be expected for proximity effects due to tidal and rotational distortion of the component stars. Using estimated values for the absolute dimensions of the components and the orbital inclination (see Sec. IV), we have computed the effect of binarity on the observed light variations, including those coming from reflection, by means of the synthetic light-curve model WINK for close binaries developed by Wood (1972). The results show that no cos $\phi$ term is significant and the amplitude of the cos $2\phi$ term amounts to just 0.001 mag when third light due to the simultaneous measurement of $\sigma^1$ CrB is taken into account (a value of $L_3/L_{\rm TOT} = 0.29$ was used according to the individual magnitudes given in Sec. IV). This amplitude is in perfect agreement with the distortion coefficients given by Morris (1985) for ellipsoidal variables and remains well below the error range of our observations.

A sinusoidal least-squares fitting of the $\Delta y$ measurements provided a value of 0.25 for the phase of minimum light and a semiamplitude of $0.006 \pm 0.001$ mag, but the quality of the fit indicates that the light variations correspond to a dark-spot pattern somewhat more complicated than a simple sinusoidal curve. This could be due to the fact that both components present a similar degree of activity (as indicated by the observed emission lines which can be measured separately for each of the stars) and to the inclination of the orbital plane. Unfortunately, nothing more can be deduced at this level about the presence of multiple groups of dark spots and their distribution along the surfaces of the stars. The low amplitude of the light variations is nevertheless in good agreement with the almost constant fluxes observed in the Mg II and Ca II emission lines (Fernández-Figueroa *et al.* 1986).

Using the ephemeris given by Tanner (1949), adopted by Skillman and Hall (1978) as well as Vivekananda Rao *et al.* (1985), the phase of minimum light corresponds to 0.53. The latter authors did not observe orbital phases around this value and were not able to detect any variation. On the other hand, it is clear that the total amplitude of 0.05 mag proposed by Skillman and Hall (1978) is not confirmed by our observations but, contrary to the case of the suggested $\delta$ Scuti type variability already dismissed by Giménez *et al.* (1985), it may be possible that the amplitude of the migrating wave actually decreased during the 7 years since the observations by Skillman and Hall. This could be due to a redistribution of the group of spots, changing the average cross section in the line of sight.

In Fig. 2, we have represented the differential measurements of the $\beta$ index. An average value of $\Delta\beta = 0.003 \pm 0.005$ mag is found in the instrumental system that after transformation to the $\beta$ standard provided $\beta = 2.602 \pm 0.006$ mag. Considering the observational scatter, no cyclical variation can be deduced from these measurements. Nevertheless, some indications of a systematic effect can be seen showing the same behavior of $\Delta c_1$ mentioned above, i.e., in phase with the $\Delta y$ variations but with opposite sign. This result is very marginal since a least-squares fitting to a sinusoidal curve gave a very small, though internally significant, amplitude of 0.004 mag. If real, this would reflect the existence of a maximum emission in H$\beta$ at phases when the dark-spotted surface is maximum. A weak emission in H$\beta$ has been observed in several RS CVn-like binaries (e.g., Naftilan and Drake 1980) and it would be interesting to test other systems for $\beta$ variations with larger photometric amplitudes than TZ CrB.

## IV. ASTROPHYSICAL PARAMETERS

The astrophysical information contained in the Strömgren *uvby* photometric indices has been found to be very rewarding in the study of late-type stars, particularly those showing indications of chromospheric and coronal activity (Rucinski 1983; Eggen 1984). A careful and systematic study of the astrophysical information provided for G, K, and M type stars has been recently carried out by Olsen (1984).

Standard indices for $\sigma$ CrB were already given by Giménez *et al.* (1985) on the basis of limited coverage of the orbital cycle. Improved values of the average magnitude differences using all phases are given in Table II together with their mean errors and the corresponding four-color indices after transformation to the standard system for the visual binary. If, as expected, there is no reddening, the $b-y$ value is in perfect agreement with the observed $\beta$ index according to the calibration by Crawford (1975) for main-sequence stars as well as the mean values for MK types given by Olsen (1984, Table V). This indicates that core emission in H$\beta$ should be very small, if there exists any at all.

In order to isolate the contribution of TZ CrB from the combined values given in column (3) of Table II, both stars were observed separately during a night of perfect seeing, and the magnitude differences given by Giménez *et al.* (1985) were thus obtained. Separated standard colors for each of the visual components of ADS 9979 are given in columns (4) and (5).

The color indices of the fainter member $\sigma^1$ CrB indicate that it is a normal G1 V star close to the zero-age main sequence with an effective temperature of 5970 K (from $b-y$), normal abundance of metals (intermediate between that of the Hyades and the Sun) according to the calibration by Nissen (1981), and an absolute visual magnitude

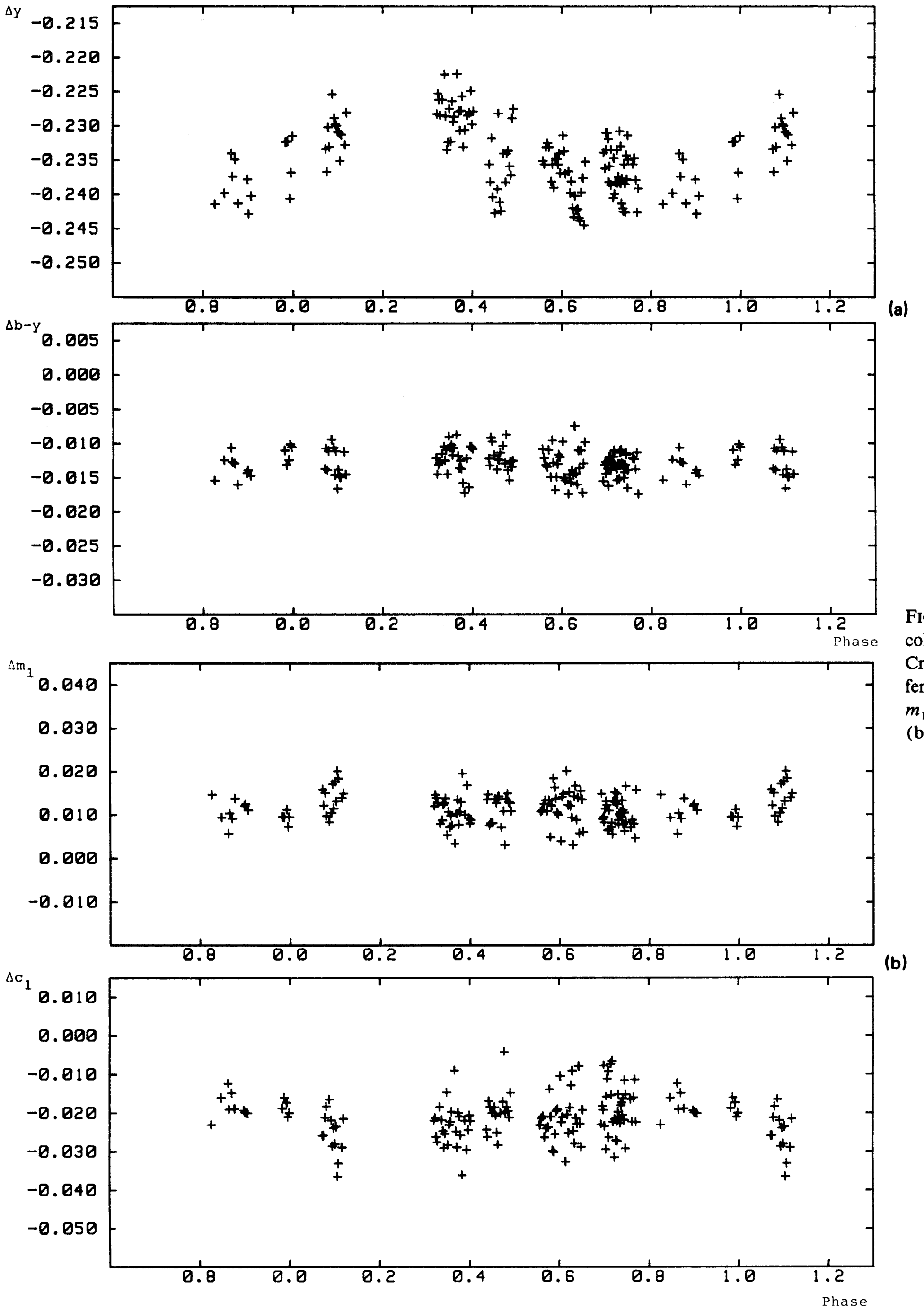


FIG. 1. $y$ magnitude differences and color-index differences between $\sigma$ CrB and HR 5968. $y$ and $b-y$ differences are given in (a), while the $m_1$ and $c_1$ differences are included in (b).

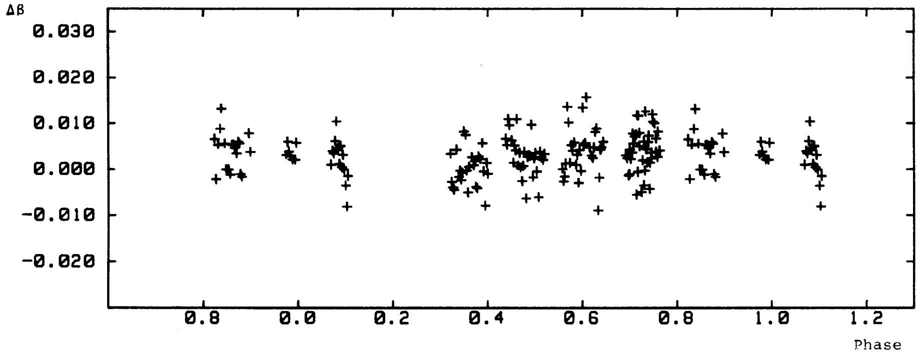


FIG. 2. $\beta$ magnitude differences between $\sigma$ CrB and HR 5968.

TABLE II. *uvby* photometry of $\sigma$ CrB.

| | Instrumental (mag) | | Standard (mag) | | |
|---|---|---|---|---|---|
| | $\Delta$ (1) | $\sigma$ (2) | $\sigma$ CrB (3) | $\sigma^1$ CrB (4) | TZ CrB (5) |
| $V$ | −0.235 | 0.005 | 5.17 | 6.52 | 5.54 |
| $b-y$ | −0.013 | 0.002 | 0.382 | 0.390 | 0.379 |
| $u-b$ | −0.032 | 0.009 | 1.451 | 1.485 | 1.437 |
| $m_1$ | +0.011 | 0.004 | 0.190 | 0.206 | 0.184 |
| $c_1$ | −0.021 | 0.006 | 0.307 | 0.294 | 0.312 |

$M_v = 4.7$ mag, using Crawford's (1975) calibration. Moreover, an approximate stellar radius of 1.06 $R_\odot$ can be estimated from the surface flux in $V$, corresponding to the observed $b-y$ (Popper 1980b, Table 1).

With respect to the spectroscopic binary TZ CrB, since all evidence indicates that any differences between the components in spectral type, color, and luminosity are quite small (Bakos 1984; Bopp 1984), we take the combined indices to represent a single average component. The system is, then, very well represented by two normal, unreddened and almost unevolved G0 V stars, in perfect agreement with the spectral classification. The effective temperature derived from the $b-y$ index is 6030 K, while the same procedure and calibrations mentioned above indicate $M_v = 4.5$ mag and stellar radii $R$ (average) $= 1.12\ R_\odot$. For zero reddening, the distances to $\sigma^1$ CrB and TZ CrB are immediately found to be 22.9 and 22.6 pc, respectively, which agree very well with each other and the observed trigonometric parallax.

Nevertheless, there is an excess $\delta m_1 = 0.03$ mag in the binary system that is not observed in the nonactive visual companion $\sigma^1$ CrB. In general, this is interpreted as an indication of metal weakness and expressed, in terms of the logarithm of the [Fe/H] ratio with respect to the Sun, as −0.18 (Nissen 1981). Since the average $\delta m_1$ value is not affected by duplicity, and interstellar reddening is completely negligible, this color excess should be real. A quite different matter is the interpretation of this photometric anomaly as an actual metal weakness of the star, particularly when the same effect is not seen in the close visual companion. It may well also be caused by the presence of an active chromosphere. A similar effect was noticed by Eggen (1984) in a study of very active-chromosphere stars.

To complete the picture of the system $\sigma$ CrB, we can adopt the masses of the component stars from the tabulation by Straizys and Kuriliene (1981), which uses an initial chemical composition $(X,Z) = (0.70,0.03)$. Assuming thus 1.05 $M_\odot$ for each of the G0 V members of the close pair, the separation between them should be $a = 5.9\ R_\odot$ and the average relative radius $r = R/a \sim 0.19$ (this indicates that the binary system is well detached). An orbital inclination around 29° is furthermore derived from the minimum masses given by Bakos (1984). The corresponding average value of the surface gravity is then $\log g = 4.36$, while for the G1 V visual component a value $\log g = 4.40$ is deduced, assuming $\log m/m_\odot = 0.01$ from the abovementioned tabulation. Introducing all these parameters in the evolutionary tracks computed by Hejlesen (1980), a strong agreement is found for a common age of both the spectroscopic system and its visual companion with a value $\log t$ (years) $= 9.5$.

## V. CONCLUSIONS

It has been shown, by means of accurate differential photometry, that TZ CrB presents a distortion wave, though with a very small amplitude. If one removes the light of the fainter companion of $\sigma$ CrB, the amplitude of the light variations in the close pair is found to be 0.016 mag, instead of the observed value 0.012 mag. From *uvby* color indices we have found that the system resembles a slightly metal-deficient dwarf star in its photometric properties. Apart from these two effects, TZ CrB behaves as a completely normal, almost unevolved, main-sequence system.

Nevertheless, it is well known that this binary is one of the most active main-sequence objects yet observed (Bopp 1984). The question may thus arise as to whether or not TZ CrB is actually a member of the RS CVn group of active binaries (Popper 1980a). A class of systems should in principle have common evolutionary status, but TZ CrB fails the condition of having at least one subgiant component. We therefore prefer to classify it as an active-chromosphere star showing RS CVn phenomena. The younger evolutionary status of TZ CrB with respect to the main group of the RS CVn binaries places the system in an intermediate position with the BY Dra variables.

On the other hand, it is very interesting to note that the slightly later-type visual component $\sigma^1$ CrB does not present any indication of activity either, from the photometric indices of the chromospheric emission lines. Given the same evolutionary status and expected initial chemical composition of both, the only significant difference is the effect of binarity.

The time scales for synchronization in later-type close binaries can be estimated with the equations given by DeCampli and Baliunas (1979), adopting a convective mean viscosity of $10^{12}$ g cm$^{-1}$ s$^{-1}$. The synchronization time scale for the components of TZ CrB is thus found to be $\log t_s$ (years) $= 6.1$, much smaller than the estimated evolutionary age of the system. Both components should therefore rotate with synchronized velocities $v_{\rm rot} \simeq 50$ km s$^{-1}$, which are much larger than the expected values for an early G type star like $\sigma^1$ CrB. The corresponding time scale for circularization of TZ CrB, $\log t_c = 8.4$, agrees with the marginal eccentricity detected by Bakos (1984).

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