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The light-time effect as the cause of period changes in β Cephei stars

III. BW Vulpeculae

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Abstract. All available photometric and radial-velocity observations of the large-amplitude β Cephei star BW Vul are analyzed in order to study the period changes in this star. We show that these changes can be fully explained in terms of an evolutionary constant-rate change equal to +2.34 s cen^{-1} and the light-time effect in a binary system. After removing the evolutionary contribution from the $O-C$ diagram, we derive the spectroscopic elements of the primary's orbit. Although no direct observational technique allows the hypothetical companion to be observed at present, precise radial-velocity observations could reveal its presence in the future. In addition, we find the changes of the phase-lag between the radial-velocity and light curves to be negligible.

Key words: stars: binaries: general – individual stars: BW Vul – stars:variable

1. Introduction

The light and radial velocity amplitudes of BW Vulpeculae (HR 8007, V = 6.55, B2 III), a monoperiodic β Cephei-type star, are the largest among all known variables of this type. Photometric amplitude increases from $0^{\rm m}_{.}2$ in visual to about $1^{\rm m}_{.}2$ at 100 nm (Barry et al. 1984), and the radial-velocity range slightly exceeds 200 km s^{-1}. The pulsation period is equal to almost five hours ($0^{\rm d}_{.}20104$). An unusual feature on the light curve of BW Vul is a short stillstand phase, preceding the time of maximum light by about $0^{\rm d}_{.}03$. Also the radial-velocity curve is not sinusoidal. Shortly after the maximum, radial velocity decreases rapidly, reaching approximately the systemic velocity and, after the stillstand phase lasting about $0^{\rm d}_{.}02$, continues to decrease.

It was Petrie (1954) who first found a considerable rate of period change (dP/dt) for BW Vul, viz. +3.7 seconds per century (s cen^{-1}). Depending on the data taken into account by subsequent investigators, the values of dP/dt from +1.8 (Valtier 1976) to +4 s cen^{-1} (Percy 1971) were reported. However, it soon became clear that a constant rate of period change does not explain the $O-C$ diagram for this star. As was proposed by Tunca (1978), the period behaviour can be better represented by intervals of constancy, interrupted by sudden changes. Chapellier (1985) maintained that this type of period changes was common among β Cephei-type stars. He and Chapellier & Garrido (1990) found that BW Vul had undergone four sudden changes since 1930 (see also Fig. 1). The weak point of this idea is that no plausible mechanism causing changes of this type is known so far.

On the other hand, Odell (1984) and Jiang (1985) showed that the parabolic fit to the $O-C$ diagram of BW Vul yields periodic residuals. Both authors attributed these residuals to the light-time effect induced by the motion of the star in a binary system, although Odell (1984) pointed out that the presence of two pulsation modes of nearly identical period may produce similar changes.

It was shown in the first two papers of this series that the light-time effect causes period changes in two other β Cephei-type stars: β Cep (Pigulski & Boratyn 1992; hereafter Paper I) and σ Sco (Pigulski 1992; hereafter Paper II). This prompted us to reinvestigate the period changes of BW Vul in order to check whether they can be still interpreted in terms of evolution and binarity, particularly that since the time of the Odell's (1984) analysis some new data have been collected. In the present paper we give an account of this investigation.

2. Observations

BW Vul was discovered as a variable in radial velocity by S.N. Hill (Plaskett & Pearce 1931). The radial-velocity data published subsequently include Burger et al. (1982), Crowe & Gillet (1989), Furenlid et al. (1987), Goldberg et al. (1976), McNamara et al. (1955), Odgers (1956), Petrie (1954), Struve (1954), Walker (1954), and Young et al. (1981). All these data were used in our analysis.

Since the discovery of the light variation by Huffer (1938), a large amount of photometric data has been collected. In our analysis we make use of all of them, namely those of Barry et al. (1984), Burger et al. (1982), Cester (1957), Chapellier (1985), Chapellier & Garrido (1990), Cherewick & Young (1975), Furenlid et al. (1987), Jiang (1985), Jung & Lee (1985), Kraft (1953), Kubiak (1972), Lynds (1954), Margrave (1980), McNamara & Gebbie (1961), Nikonov & Nikonova (1952), Odell et al. (1983), Peña et al. (1987), Percy (1971), Rios Herrera et al. (1984), Singh & Joshi (1983), Sterken (unpublished observations), Sterken et al. (1986, 1987, 1993), Tunca (1978), Valtier (1976), van der Linden & Sterken (1987), Walker (1954), and Young et al. (1981).

3. The $O - C$ diagram

The times of maximum light of BW Vul were published by many authors. However, as was argued by Sterken et al. (1987), it is better to use the times of minimum light in the determination of period changes of this star. The reason is that near the time of maximum there is a stillstand which may cause errors in determination of the time of maximum. To be consistent, we decided to use only the times of minimum in the study of the pulsation period. Because an up-to-date compilation of the photometric times of minimum was recently presented by Sterken (1993), these data have been used in our analysis.

In order to get better coverage in the $O - C$ diagram, we decided to analyze also all available radial-velocity data. Because the minimum of the radial-velocity curve is quite flat, the method which was used to get the times of minimum from photometric data (see Sterken et al. 1987) would lead to large errors, even if a higher order polynomial were fitted to the observations adjacent to the time of minimum. Therefore, we used the same method as in Paper II. Namely, we first constructed a mean radial-velocity curve. For this purpose the radial-velocity data of Kubiak (1972) were used. The data were slightly smoothed and then interpolated in the intermediate points by a cubic spline fit. This mean curve was then fitted to the observations on a given night in order to get a time of minimum radial velocity. The times of minimum radial velocity derived in this way are presented in Table 1.

As the line profiles in the spectrum of BW Vul are quite complex (Furenlid et al. 1987), the shape of the radial-velocity curve depends on the dispersion of the spectrograms, the time resolution, and the method used to derive the radial-velocity. This is especially important near the time of maximum radial-velocity where line-doubling is observed. Comparing the old radial-velocity curves (Petrie 1954) with the newest ones (Crowe & Gillet 1989) one can see that while for the latter the maximum is sharp, on the old curves the maximum is much flatter. Thus, when the $O - C$ values are derived from the times of maximum radial-velocity, large systematic errors may occur. The advantage of our method of determining the time of minimum radial-velocity is that *all* points on the radial-velocity curve are used. We believe that this considerably reduced the systematic errors mentioned above.

The $O - C$ values plotted in Fig. 1 were determined from the ephemeris:

Table 1. Heliocentric times of minimum radial-velocity of BW Vul (after HJD 2400000.0) obtained as described in the text. The abbreviations for the data papers are following: BU – Burger et al. (1982), CG – Crowe & Gillet (1989), FU – Furenlid et al. (1987), GO – Goldberg et al. (1976), MC – McNamara et al. (1955), OD – Odgers (1956), PE – Petrie (1954), ST – Struve (1954), WA – Walker (1954), and YO – Young et al. (1981)

25444.1360	PE	33896.8547	WA	34966.7568	OD
26547.9659	PE	34202.8196	PE	34975.8079	OD
27365.5557	PE	34207.8456	PE	35003.7506	ST
27988.9382	PE	34232.7776	PE,WA	35009.7775	OD
28359.8327	PE	34233.7823	PE,WA	35015.8101	OD
28392.8026	PE	34602.8834	OD	41538.8201	GO
28745.8101	PE	34879.9100	MC	44047.5962	BU
28763.7028	PE	34880.9175	MC	44065.8900	YO
29130.7826	PE	34881.9209	MC	45604.8690	FU
29138.8234	PE	34882.9268	MC	46721.8670	CG
29141.8345	PE	34883.9339	MC	46722.8732	CG
29477.7628	PE	34912.8807	MC	46724.8847	CG
29478.7612	PE	34937.8103	OD		
33504.8303	PE	34965.7542	OD		

$$\text{Min. RV} = \text{HJD}\,2425444.1360 + 0\overset{\text{d}}{.}20104\,E, \qquad (1)$$

where E is the number of elapsed cycles. This ephemeris was used for the radial-velocity as well as for the photometric times of minimum.

Before using the photometric and radial-velocity data in a single $O - C$ diagram, the question on the constancy of the phase-lag between radial-velocity and light curves should be investigated. Theory predicts small changes of the phase-lag due to the nonadiabatic effects in the star (Saio & Cox 1980), but these changes take place on the evolutionary time-scale and are certainly below the detection limit during the time interval under consideration. However, contrary to this prediction, considerable changes of the phase-lag were found for BW Vul by Chapellier (1986).

We assumed that the phase-lag is constant. The justification for this is given in Sect. 5. The value of the phase-lag, as derived in Sect. 4, is equal to $0\overset{\text{d}}{.}0533$. We would like to stress, however, that the phase-lag obtained as a difference between the times of minimum of radial-velocity and light differs from that calculated from the corresponding times of maximum. This results from different shapes of the light and radial-velocity curves. Moreover, in our case, the value of the phase-lag depends also on a subjective choice of the time of minimum on the mean radial-velocity curve. For these reasons, our phase-lag cannot be compared directly with Chappelier's (1986) phase-lags obtained from the study of the times of maximum light and radial-velocity.

After subtracting the value of $0\overset{\text{d}}{.}0533$ from the photometric $O - C$ values, a single $O - C$ diagram was constructed. It is displayed in Fig. 1. The data cover the $O - C$ diagram very well, except for the 10-year gap between 1939 and 1948. This is the only interval when some uncertainty in the cycle count occurs.

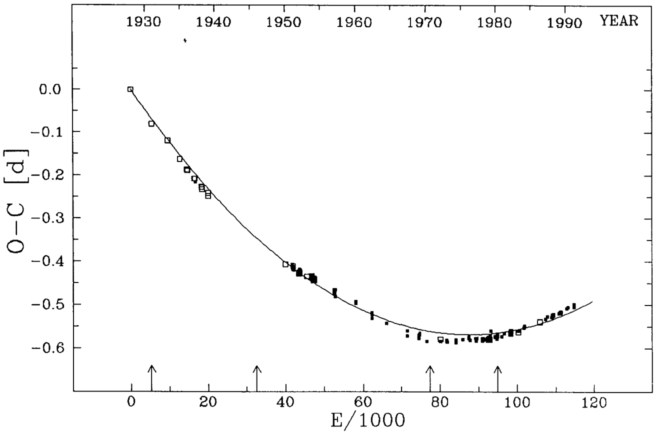

Fig. 1. The $O-C$ diagram for BW Vul. Open squares represent the values obtained from the radial-velocity times of minimum, while small filled squares, those obtained from the photometric data. Continuous line is a parabola corresponding to a change of period with a constant rate equal to +2.34 s cen^{-1}. The arrows indicate epochs of sudden changes of period suggested by Chapellier (1985) and Chapellier & Garrido (1990)

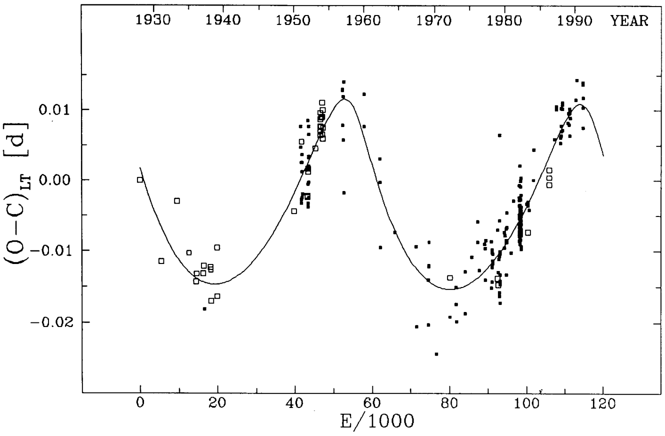

Fig. 2. The $(O-C)_{\rm LT}$ diagram for BW Vul, obtained from the $O-C$ diagram (Fig. 1) by subtracting the constant-rate increase of period (+2.34 s cen^{-1}) according to Eq. (2). The changes seen in this figure are interpreted in the present paper as due to the light-time effect only. Continuous line represents the best fit, from which spectroscopic elements given in Table 2 were obtained. The symbols are the same as in Fig. 1

The number of the cycles we adopted to bridge this gap is the same as that used by other investigators (Odell 1984, Jiang 1985, Chapellier 1985, Sterken 1993). We believe that this cycle count is correct because it yields smaller residuals from the parabolic fit to the $O-C$ diagram than any other.

4. Interpretation of the period changes

As we mentioned in the Introduction, Odell (1984) was the first to propose the interpretation of the small discrepancies from the parabolic $O-C$ diagram in terms of the light-time effect.

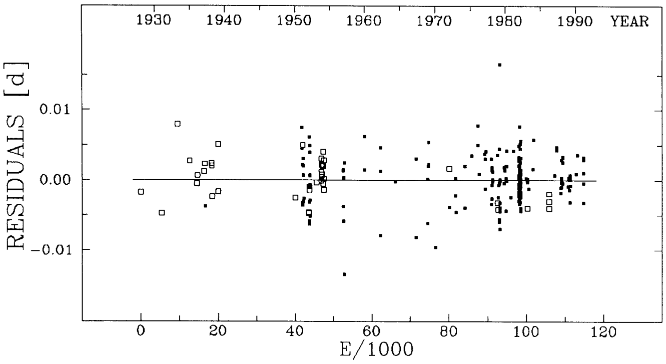

Fig. 3. The residuals from the fit shown in Fig. 2. The symbols are the same as in Fig. 1

The same interpretation was given later by Jiang (1985). Both authors found that the orbital period of the hypothetical companion is equal to about 25 yr, and that the range of the $O-C$ residuals due to this effect amounts to about 35 minutes.

If indeed the changes of the period can be explained by the superposition of a constant-rate period change and the light-time effect, the fit of a parabola to the $O-C$ diagram should yield periodic residuals. Unfortunately, for BW Vul a mechanical application of a least-squares fit cannot yet separate the two effects properly, because the data cover only about 1.5 of the orbital period. In our case, a least-squares fit of a parabola to the data shown in Fig. 1 yielded dP/dt equal to +2.40 $\pm$ 0.03 s cen^{-1}. When only photometric data are used, the fitted parabola gave dP/dt = +2.73 $\pm$ 0.03 s cen^{-1}. In order to get strictly periodic residuals we had to fix the value of dP/dt at +2.34 s cen^{-1}. However, the freedom in the selection of dP/dt is not large — when dP/dt deviating more than 0.1 s cen^{-1} from +2.34 s cen^{-1} is assumed, the residuals in Fig. 2 become non-periodic.

Figure 2 shows the diagram [hereafter referred to as an $(O-C)_{\rm LT}$ diagram], which resulted from subtracting the constant-rate change of period from the $O-C$ diagram according to the following equation:

$$(O-C)_{\rm LT} = (O-C) + 0\overset{\rm d}{.}00001302\ E - 7\overset{\rm d}{.}454\ 10^{-11}\ E^2, \quad (2)$$

where $O-C$ are the values shown in Fig. 1. The coefficient before the quadratic term in Eq. (2) corresponds to constant-rate change equal to +2.34 s cen^{-1}.

Then we analyzed the $(O-C)_{\rm LT}$ diagram in the same way as in the case of β Cep in Paper I. From the best fit to this diagram we obtained spectroscopic elements of the orbit of BW Vul as well as the value of the phase-lag. The spectroscopic elements are listed in Table 2.

The calculated range of the $O-C$ changes due to the light-time effect in the $(O-C)_{\rm LT}$ diagram is equal to about 38 minutes. The standard deviation of the residuals from the fit shown in this diagram amounts to about 4.8 minutes. This is equal to the typical uncertainty of the determination of the time of minimum light or radial-velocity for this star. In Fig. 3, where the residuals after removing both effects causing period changes are shown, no systematic deviations exceeding observational scatter can

Table 2. The parameters of the spectroscopic orbit of the pulsating primary in the BW Vul system, obtained from the fit to the $(O-C)_{\rm LT}$ diagram

$P_{\rm orb}$ = 33.5 ± 0.4 yr
K_1 = 2.4 ± 0.2 km s^{-1}
e = 0.46 ± 0.07
T_0 = 1992.5 ± 0.9
ω_1 = 116° ± 9°
$a_1 \sin i$ = 2.3 ± 0.4 AU
$f(M_1)$ = 0.012 ± 0.005 $M_\odot$

be seen. We conclude therefore that the combined effect of the increase of period with a rate of +2.34 s cen^{-1} and the light-time effect in a binary system fully accounts for the observed changes of the pulsation period of BW Vul.

5. Discussion and conclusions

The orbital period obtained in this paper is about 10 yr longer than that found in previous studies. Predicted range of the primary's radial-velocity variation, $2K \approx 5\,{\rm km\,s^{-1}}$, is much smaller than the pulsational component, which exceeds 200 km s^{-1}. This precludes the possibility of the verification of the binary hypothesis from the existing radial-velocity observations [see also Peña et al. (1987), where the radial velocities of the system are discussed]. Such the verification is, however, possible in the future, provided that good quality and homogeneous spectrographic observations, covering large part of the orbital period, will be collected.

The inclination of the orbit in the BW Vul system is not known, but if it is not very close to zero, the companion might be even 10$^{\rm m}$ fainter than the pulsating primary. Moreover, the estimated separation of the components does not exceed 0.″03. It is thus not possible to discover the companion using the interferometric methods. In fact, the star was observed by means of speckle interferometry, but no bright component was detected at separations larger than 0.″030 (Hartkopf & McAlister 1984). Thus, the light-time effect in the $(O-C)_{\rm LT}$ diagram is, for the time being, the only observational evidence for the presence of a companion to BW Vul.

From Fig. 3 another conclusion can be drawn. One can see that there is no systematic difference between the spectrographic and photometric residuals. This justifies our assumption of the constancy of the phase-lag made in Sect. 3. However, as we mentioned in that section, Chapellier (1986) found variations of the phase-lag with a range of 0.082 P, i.e., 0.$^{\rm d}$016. So large changes are clearly not seen in Fig. 3. The explanation for this discrepancy may be that Chapellier used the times of maximum light and radial-velocity. As we pointed out in Sect. 3, this may lead to systematic effects in the values of the phase-lag. Moreover, in most cases, the phase-lags have been derived by Chapellier (1986) from the data which were not simultaneous. This may have introduced additional errors in the phase-lags because the assumption was made that the period changed abruptly.

As we discussed in detail in Paper II, theory predicts different rates of period change in different evolutionary phases for a star passing through the observed β Cephei-type stars instability strip in the HR diagram. The value of dP/dt equal to +2.34 s cen^{-1}, if interpreted in terms of evolution of the star, leads to the conclusion that BW Vul is in the shell-hydrogen burning phase. In Paper II we concluded that σ Sco, the other large-amplitude β Cephei-type star, is in the same phase of evolution. Although it has been shown that most of β Cephei-type stars are in the core-hydrogen burning phase, unstable models were found for all three evolutionary phases covering the locus of the β Cephei-type stars in the HR diagram (Dziembowski & Pamyatnykh 1993). BW Vul and σ Sco are, therefore, very important objects as far as the theory of pulsation and evolution of β Cephei-type stars is concerned.

We would like to emphasize that BW Vul should still be monitored photometrically. If our interpretation of the period changes is correct, the observations of the next 10 years should cover a very steep part of the $(O-C)_{\rm LT}$ curve. The location of the 1991 data in Fig. 2 seems to indicate that the downturn in the $(O-C)_{\rm LT}$ curve really takes place. Observations of the next years will thus allow to verify the presented interpretation of the period changes and to separate unambiguously the two effects causing period changes. On the other hand, high quality and homogeneous spectrographic observations, spanning at least several years, could bring an independent verification of the binary hypothesis.

For all three stars (β Cep, σ Sco and BW Vul), which we analyzed in this series of papers, we were able to explain the observed period changes by the constant-rate change of evolutionary origin and the light-time effect in a binary or multiple system. As all these stars were supposed by Chapellier (1985) to exibit sudden period changes, his hypothesis becomes very doubtful not only because of the lack of theoretical predictions, but also from the observational point of view.

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