Journal of The Korean Astronomical Society
44: 97 ∼ 108, 2011 June

doi:10.5303/JKAS.2011.44.3.97
ISSN:1225-4614
http://jkas.kas.org

ORBITAL PERIOD VARIATION AND MORPHOLOGICAL LIGHT CURVE STUDIES FOR THE W UMa BINARY BB PEGASI

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(Received December 20, 2010; Revised March 03, 2011; Accepted May 16, 2011)

ABSTRACT

The photometric light curves of the W–type W UMa eclipsing contact binary system BB Pegasi have been found to be extremely asymmetric over all the observed 63 years in all wavelengths UBVR. The light curves have been characterized by occultation primary minima. Hence, the morphology of these light curves has been studied in view of these different asymmetric degrees. The system shows a distinct O'Connell effect, as well as depth variation. A 22.96 years of stellar dark spots cycle has been determined for the system. Almost the same cycle (22.78 yr) has been found for the depth variation of MinI and MinII. We also present an analysis of mid–eclipse time measurements of BB Peg. The analysis indicates a period decrement of 5.62$\times$ 10^{-8} day/yr, which can be interpreted in terms of mass transfer at a rate of -4.38 $\times$ 10^{-8}M$_\odot$/yr, from the more to the less massive component. The $O-C$ diagram shows a damping sine wave covering two different cycles of 17.0 yr and 12.87 yr with amplitudes equal to 0.0071 and 0.0013 day, respectively. These unequal durations show a non-periodicity which may be explained as a result of magnetic activity cycling variations due to star spots. The obtained characteristics are consistent with similar chromospherically active stars, when applying the Applegate's (1992) mechanism.

Key words : binaries: close — binaries: eclipsing — stars: individual (BB Peg) — stars: W–subtype W UMa — period variation: magnetic activity.

1. INTRODUCTION

The low temperature W UMa contact binary (LTCB) system BB Peg (M_v = 11.6, spectral type F8V, $P = 0^d.361501$) was first classified as a binary by Hoffmeister (1931). Its period was revised by Whitney (1959) to be 0.3615015 day.

The BV observations of Cerruti–Sola et al. (1980) revealed a variable degree of asymmetry from the yellow to the blue light curve, and a phase shift of the secondary minimum. They classified the system as a contact of the W–subtype, with the fill–out parameter of 37%.

Leung et al. (1985) have found the light curves of BB Peg to be very complex, with large asymmetry and significant discrepancy in the differential eclipse depth (Min I and Min II) between the V– and B– light curves. The system has been also found to be in over contact with small degree of 12%. The UBV observations of Awadalla (1988) have shown a variable depth of the primary eclipse that is a total occultation, and an increase of the orbital period.

Zola et al. (2005) have found that the configuration of BB Peg is contact with intermediate (21%) fill out factor, using BVR observations at the Mt. Suhora observatory in 2004. They have stated that the O'Connell effect is noticeable for the system. Kalomeni et al. (2007) have confirmed the claim and determined the rate of mass transfer from the less massive to the more massive component. Snyder (2008) has shown that the light curve of the system is asymmetric (O'Connell effect) and displays total annular eclipses in the primary. He has found two small cool stellar spots on the secondary star.

The first radial velocity study of the system has been done by Hrivnak (1990) which gives the spectroscopic value of the mass ratio $q_{sp} = 0.34$. Later, it has been redetermined to be $q_{sp} = 0.36$ by Lu and Rucinski (1999). D'Angelo et al. (2006) have suggested from their spectroscopic study the existence of an M-type dwarf star of minimum mass $M_3 = 0.18\,\mathrm{M}_\odot$ orbiting around the binary.

Several photometric solutions of the light curves for the BB Peg system have been determined by various authors; among them Cerruti–Sola et al. (1981), Zola et al. (2005) and Snyder (2008). Kalomeni et al. (2007) have observed the system in V and R during 8 nights between Aug–Dec 2004, and during two nights in 2006. They have determined the absolute parameters for the system, and analyzed the light curves obtained by themselves as well as those obtained by Cerruit–Sola & Scaltriti (1980), Zhai & Zhang (1979) and Awadalla (1988). The analysis and fitting light curves for the four sets of the observations have different and poor results. Both sets of light curves for BB Peg obtained by Cerruti–Sola & Scaltriti (1980) and

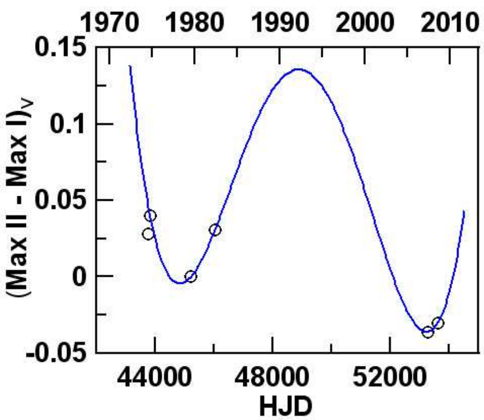

Fig. 1.— Relation between the O'Connell effect (MaxII−MaxI) and the corresponding HJD and years for all the published light curves in the V–filter.

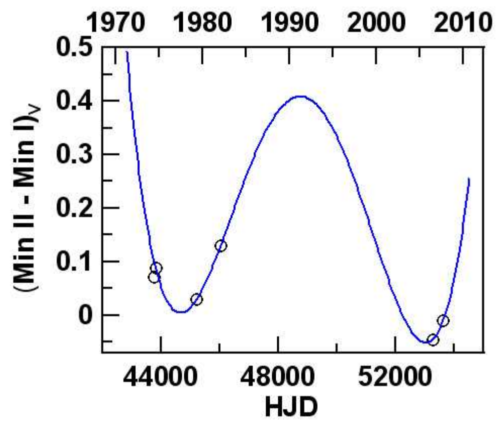

Fig. 2.— Relation between the depth differences (MinII−MinI) and the corresponding HJD and years for all the published light curves in the V–filter.

Zhai & Zhang (1979) show distinct asymmetry at maximum light, even though the two sets were observed in a two–month interval. This means that the light curves for the system BB Peg are undergoing relatively rapid changes. Hence, all the analysis of the light curves for the present system have been poorly determined, and in particular the fill out ratio, the O'Connell effect and the depth differences of minima.

Since most of the adopted solutions for the system BB Peg are poor due to the asymmetry of the light curves, their morphology has to be studied again, especially its asymmetry and the depth difference over all the time interval that the system has been observed. Moreover, the $(O-C)$ diagram has been examined to explain the orbital period behaviour, in view of any possible relation with magnetic activity cycling for the system.

2. STUDY OF LIGHT CURVE MORPHOLOGIES

All the light curves observed from HJD 2449564.0 to HJD 2454359.0 have asymmetric shapes in both maxima and minima in all $UBVR$ filters, except those observed by Cerruti–Sola and Scaltriti (1980) which are in equal depths but slightly differ in maxima –i.e. likely to be symmetric. From the compilation of all published light curves, we can investigate the short time light variation.

Most of the light curves of BB Peg have been analysed by various authors with different methods, such as the Wood method (1972), the Russel & Merrill method (1952) and the Wilson & Devinney (W–D) method (1971). Most of the solutions that have been obtained show poor agreements with data, due to either a variable degree of asymmetry from yellow to blue light curve or a phase shift of the second minimum (Cerruti–Sola et al. 1981).

Kalomeni et al. (2007) have analyzed (using the W–D code) the light curves observed by Cerruti–Sola and Scaltriti (1980), Zhai and Zhang (1979), Awadalla (1988), as well as their observations simultaneously with Lu and Rucinski's (1999) radial velocities. They have determined different parameters and various fill–out factors for the system.

Tables 1 and 2 summarize the maximum difference (O'Connell effect, MaxII−MaxI) and the depth difference (MinII−MinI) in UBVR for all the published light curves with the corresponding observed date (HJD), respectively. Figs. 1 and 2 show the changes in the O'Connell effect and the depth difference for BB Peg with the corresponding mean HJD, respectively. The solid lines represent 4^{th} degree polynomial fits, for both the O'Connell effect and the depth difference. The two figures show nearly periodical cyclic changes with the same behavior. The correlation coefficient and the standard deviation for both polynomials have been determined: $r = 0.985$, $SD = 0.012$, and $r = 0.989$, $SD = 0.021$, respectively. The O'Connell effect shows a periodicity of 22.96 years from HJD 2444903 to 2453290; approximately the same periodicity has been found for the depth differences from HJD 2444645 to 2452968, i.e. 22.78 years.

The light curve observed by Zola et al. (2005) shows a flat bottom for the primary minimum, and a little shallower secondary minimum. It also shows an inclination equal to 88°.5 and a 21% fill out–ratio. Kalomeni et al. (2007) have found that the system is over–

Table 1.
O'Connell effect

Observation Date	HJD.† 2400000+	O'Connell Effect (MaxII−MaxI) U	B	V	R	Ref.
Aug 08/1978– Sep 12/1978	43747	0.000	0.043	0.028	-	[1]
Oct 01/1978– Nov 30/1978	43811	-	0.050	0.040	-	[2]
Aug 26/1982– Aug 27/1982	45208	0.045	0.055	0.000	-	[3]
Nov 18/1984– Nov 22/1984	46026	−0.010	0.039	0.031	-	[3]
Aug 10/11/2004 Oct 05–07/2004	53256	-	−0.055	−0.036	−0.027	[4]
Aug–Dec/2004– Oct 2006	53613	-	-	−0.030	−0.015	[5]

Ref.: [1] Cerruti–Sola and Scaltriti (1980), [2] Leung et al. (1985), [3] Awadalla (1988), [4] Zola et al. (2005), [5] Kalomeni et al. (2007). † mean value.

Table 2.
Depth difference and fill–out ratio

Observation Date	HJD.† 2400000+	Depth difference (MinII−MinI) U	B	V	R	F–ratio%	Ref.
Aug 08/1978 – Sep 12/1978	43747	0.112	0.057	0.071	-	35–37	[1]
Oct 01/1978 – Nov 30/1978	43811	-	0.081	0.088	-	12–38	[2]
Aug 26/1982 – Aug 27/1982	45208	0.090	0.050	0.030	-	-	[3]
Nov 18/1984 – Nov 22/1984	46026	0.240	0.150	0.130	-	33	[3]
Aug 10/11/2004 Oct 05-07/2004	53256	-	−0.045	−0.045	−0.036	21	[4]
Aug–Dec/2004– Oct 2006	53613	-	-	−0.010	0.000	34	[5]

Ref.: Same as Table 1. † mean value.

Table 3.
Ephemerids of BB Peg by various authors

JD.+240000	Period	Quadratic term	Reference
30285.75400	0.36150720		Whitney (1943)
30285.75500	0.36150150		Whitney (1959)
30285.76300	0.36150100		Zhai & Zhang (1979)
30285.76180	0.36150027	2.35×10^{-11}	Qian (2001)
43764.33340	0.36150210	2.30×10^{-11}	Cirruti Sola & Scatriti (1980)
43764.33340	0.36105150		Cirruti Sola & Scatriti (1980)
50657.45990	0.36150150		Kalomeni et al. (2007)
43764.34160	0.36150147		Kreiner (2004)
52500.03730	0.36150256	1.49×10^{-11}	Snyder (2008)
53228.45740	0.36150100		Zola (2005)
43764.34160	0.36150147		Present work †
43764.33810	0.36150099	1.08×10^{-11}	Present work †
43764.33319	0.36150213		Present work ‡
43764.33083	0.36150295	-2.78×10^{-11}	Present work ‡

† All v, pg, pe and CCD minima times. ‡ Only pe and CCD minima times.

Table 4.
Comparison between number of data used in previous and present studies

	Visual	Photog.	Pe	CCD	Total
Cerruti–Sola and Scaltriti (1980)	5*	25	5	-	35
Awadalla (1988)	9	25	9	-	43
Qian (2001)	33		23	4	60
Kalomeni et al. (2007)	7**	14	33	19	73
Present work	25†	127†	45	45	90

* The authors have used only 5 minima out of 9, due to the data large internal errors; ** The authors have used only 7 out of 9 minima. † The visual and photographic minima times are listed in Table 10 of the Appendix; these have been used only in Fig. 4 and in eq.(3).

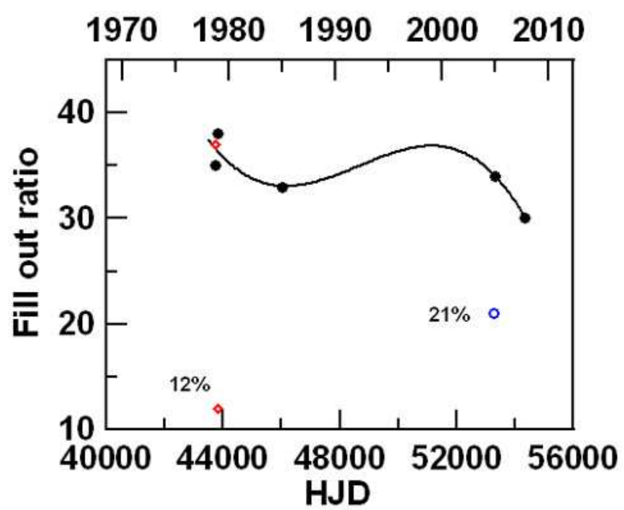

Fig. 3.— Variation of the fill–out ratio, by various authors.

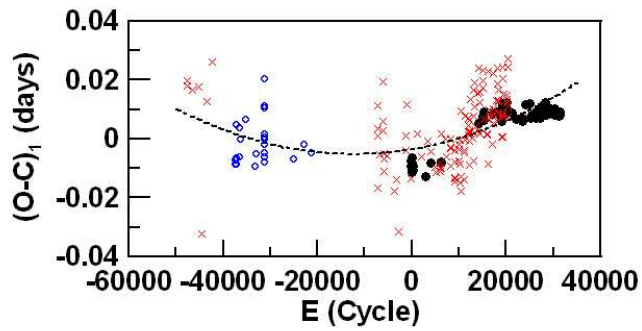

Fig. 4.— The $(O - C)$ diagram of BB Peg constructed with the line elements of Kreiner (2004). The dashed line is the description by a quadratic fit with $SD = 0.008$ and $r = 0.562$. The open circles, x signs, and dots, correspond to visual, photographic, and pe & CCD minima, respectively.

luminous and oversized, like the other W–subtype of W UMa binaries.

Awadalla's (1988) light curves show that the primary minima are deeper than the secondary ones in both sets of his observations (1982 and 1984), which is in agreement with Whitney (1943). Whitney (1943) found that the primary minimum is 0.11 mag deeper than the secondary. The asymmetry noted by Prager (1941) was also confirmed by Whitney's observations (1943). Awadalla (1988) has stated that the depth varies from colour to colour as well, as from time to time. The light curves analyzed by Leung et al. (1985) show large asymmetry in minima and significant discrepancy in the differential eclipse depths.

In spite that the two sets of observations of Cerruti–Sola & Scaltriti (1980) and Zhai & Zhung (1979) are only about two months apart, both sets of light curves show distinct asymmetry at maximum light, an indication that BB Peg has undergone relatively rapid changes (Leung et al. 1985). Giuricin et al. (1981) confirmed that the eclipses are partial, and that the primary minima are occultations.

The asymmetry in the light curves for BB Peg has been modelled with cold spots on the secondary component, the cooler with higher mass and radius (Kalomeni et al. 2007).

In Table 2 we provide the fill out factors, and we show them in Fig. 3. The figure indicates that the size of the envelope varies with the asymmetry of the light curves, and shows an alternative change from HJD 2443750 to 2454359, i.e. within 29 years. This means that the system has undergone a very rapid variation in this short time.

3. DATA AND LINE ELEMENTS

3.1 Data set

In order to study the period variation of BB Peg, the times of the minima (v, pg, pe and CCD) have been carefully collected from the literature (listed in Tables 9 and 10 of the Appendix). Table 9 provides the pe and CCD times of the primary and secondary minima, while Table 10 gives the visual (v) and photographic (pg) minima.

3.2 Line Elements

Whitney (1943) has determined the 1^{st} true orbital period value of the system BB Peg, after several approximate trials by various authors. However, he has obtained the line elements:

$$JDHel.\ (MinI) = 2430285.754 + 0.3615072 \cdot E. \quad (1)$$

Later on, several authors have obtained different line elements. In the present study we construct the $O-C$ diagram (Fig. 4) using all the available times of minima data (Tables 9 & 10), with Kreiner's (2004) line elements:

$$JDHel.\ (MinI) = 2443764.3416 + 0.36150147 \cdot E. \quad (2)$$

A quadratic least–square fitting of the $O-C$ values has been performed; it yields the following ephemeris:

$$JDHel.\ (MinI) = 2443764.3381 + 0.361501737 \cdot E + 1.08 \times 10^{-11} \cdot E^2, \quad (3)$$

with standard deviation SD=0.0085, regression r = 0.5616, and a rate of increment in the period dP/dt = 2.16×10^{-11} d/cycle (=2.19×10^{-8} d/yr) associated with the mass–loss from the secondary to the primary component.

By studying the $O-C$ values from Fig. 4, one should question the accuracy of the results obtained in the previous paragraph. The scatter is very big, especially for visual and photographic observations. If we only consider the pe and CCD minima times (Table 9), which are quite unscattered, we obtain the following new linear and quadratic ephemerides, respectively (Fig. 5):

$$JDHel.\ (MinI) = 2443764.33319 + 0.361502127 \cdot E, \quad (4)$$

with SD=0.003 and r=0.915;

$$JDHel.\ (MinI) = 2443764.3383 + 0.361502946 \cdot E - 2.78 \times 10^{-11} \cdot E^2, \quad (5)$$

with SD = 0.002 and r = 0.963.

All the line elements of the system given by previous authors, together with the line elements obtained in this work, are listed in Table 3.

4. PERIOD VARIATION STUDIES

An essential method to study the period variation in eclipsing binary systems is the analysis of the $O-C$ diagram, by the use of minima times determined throughout all the observational history of the binary.

The orbital period variations of BB Peg have been studied by Cirruti–Sola & Scaltrity (1980), Zhai & Zhang (1977), Awadalla (1988), Qian (2001), Kalomeni et al. (2007) and Snyder (2008). Table 4 provides the comparison between the numbers of data used in previous and present studies.

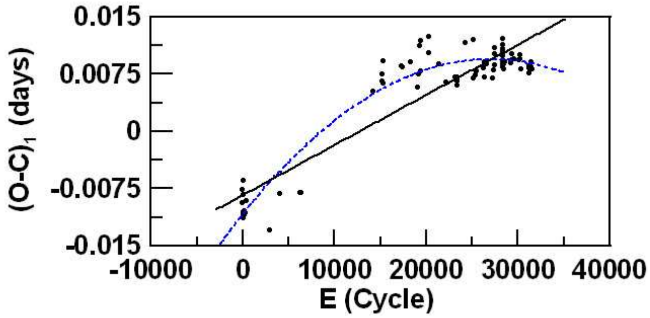

Fig. 5.— Linear and quadratic fits of the $O-C$ residuals for the pe and CCD minima times alone.

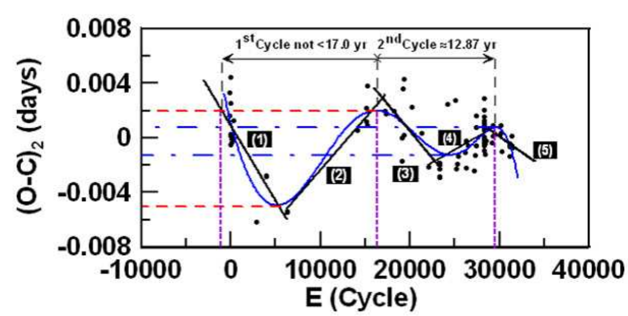

Fig. 6.— Residuals of BB Peg obtained from the quadratic ephemeris, and their description by several linear ephemerides. The solid curve represents the 7^{th} order polynomial fit with SD=0.0014 and r = 0.72. The vertical and horizontal dashed lines represent the duration and amplitude of each cycle, respectively. (A colour version of this figure is available in the online journal)

The general trend of the previous studies suggests: (i) to calculate the changing rate of the orbital period and to refer such change to the mass transfer from the less to the more massive component, (ii) to consider either a hypothetical 3^{rd} companion orbiting the close pair, or the presence of a magnetic activity cycling effect.

4.1 Mass Transfer

Awadalla (1988) has collected 43 minimum light times, and pointed out an increase in the orbital period by $\triangle P \simeq 1.5 \times 10^{-7}$ d/yr. However, a redetermination of this value gives instead 3.5×10^{-8} d/yr.

Qian (2001) has used only the pe and CCD minima times in his orbital period study of BB Peg, and reported that the general $O-C$ trend may be increasing continuously. However, he has constructed the $O-C$

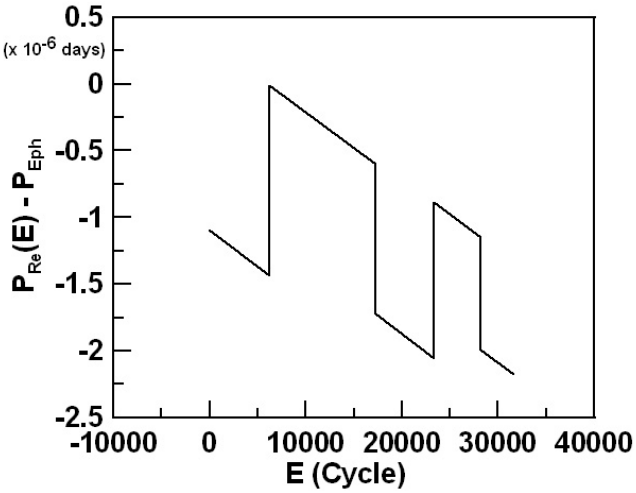

Fig. 7.— Variations in the orbital period of BB Peg. Several jumps in the period are clearly visible.

diagram using 33 (v & pg) minima with weight 1, and 27 (pe & CCD) minima times with weight 8. Hence, he deduced a continuous period increment rate of 4.75 $\times\ 10^{-8}$ day/yr.

In the same study, Qian (2001) has found that systems of W–subtype contact binaries showing a period increment usually have higher mass ratios ($q > 0.4$), while periods of low–mass ratio systems ($q < 0.4$) vary in secular decrements. Eq. (5), obtained from the analysis of the $O-C$ diagram of pe and CCD minima times alone, shows a period decrement for BB Peg. Considering the mass ratio q=0.364 of Lu and Rucinski (1999), the obtained secular period decrement agrees with Qian's (2001) result. However, in all the previous studies and in the present analysis of the $O-C$ diagram of BB Peg, one can notice that, when using all the data with high–scattered values (obtained mainly from visual and spectroscopic minima times), the fit produces an orbital period increment rate (see Table 5). This increment may be considered a spurious effect.

Kalomeni et al. (2007) have reported a rate of period increment of 3.0 $\times\ 10^{-8}$ day/yr. They have also reported that this increment can be interpreted in terms of a mass transfer rate of 2.4 $\times\ 10^{-8}$ $M_\odot$/yr from the less to the more massive component. Snyder (2008) has deduced a period increase of 2.98 $\times\ 10^{-8}$ day/yr instead.

In the present analysis, Eq. 5 shows a decrement rate in the period, $dP/dt = -5.56 \times 10^{-11}$ day/cycle ($= -5.62\times10^{-8}$ day/yr), associated with mass transfer (ΔM) from the more to the less massive component.

If the period decrement is caused by conservative mass transfer, one can calculate the mass transfer between the binary components. To estimate the mass transfer rate, the following equation given by Kreiner & Ziolkowski (1978) has been used:

$$\frac{1}{M_t} \cdot \frac{dM}{dt} = \frac{q}{3\,P\,(q^2-1)} \cdot \frac{dP}{dt}, \qquad (6)$$

where, $M_t = M_1 + M_2$ and $q = M_2/M_1$.

Adopting the values 0.53 $M_\odot$ and 1.42 $M_\odot$ for M_1 and M_2, respectively (Kalomeni et al. 2007), the mass transfer rate is -4.38×10^{-8} $M_\odot$/yr, from the more massive secondary star to the less massive primary one. This result shows mass transfer from the cooler secondary massive star to the primary less massive one. However, the obtained result is in contradiction with other previous results (see Table 5).

4.2 Third Body Hypothesis

D'Angelo et al. (2006) searched for spectroscopic signature of a tertiary by fitting the spectrum of the contact binary BB Peg, and checked if adding a spectrum of a fainter tertiary improves the fit significantly. They motivated their technique in the same study, and detected M dwarf signatures in the spectra. In principle, a direct detection of the third component via spectroscopic observations is preferable in detecting the tertiary, but it comes with some difficulties. These difficulties arise from the complex nature of the W UMa type binaries due to the high rotational velocity of the binary components, the mass transfer and/or loss, and the chromospheric activity which causes high noise in the spectra.

Pribulla and Rusinski (2006) have studied the $O-C$ diagram and reported that the light time effect (LITE) for BB Peg is a marginal detection. However, they have given orbital parameters for a hypothetical third body with $P_3 = 20.4$ yr (Table 6).

Irwin's (1959) LITE technique has several advantages over many other approaches. The advantages and disadvantages of the LITE approach have been summarized by Pribulla and Rucinski (2006). However, these authors have reported that: (1) the detection of

Table 5.
Previous studies and this work

	dP/dt (d/yr) ($\times\ 10^{-8}$)	ΔM_2($M_\odot$/yr) ($\times\ 10^{-8}$)
Cerruti–Sola& Scaltriti(1980)	+4.65	-
Awadalla (1988)	+3.5†	-
Qian (2001)	+4.75	-
Kalomeni (2007)	+3.00	2.4
Snyder (2008)	+3.00	-
Present work	−5.62	−4.38

†The new corrected value, instead of the one in the original paper (+15.0 $\times\ 10^{-8}$ d/yr).

Table 6.
Orbital parameters of the hypothetical 3^{rd} body by various authors

	Pribulla & Rucinski (2006)	D'Angelo et al. (2006)	Kalomeni (2007)	Snyder (2008)
P_3 (period in yrs.)	20.4(4)	-	27.9(2)	35.5(1.1)
a (full amplitude., in days)	0.0092	-	-	-
e_3 (eccentricity)	0.32(21)	-	0.56(0.3)	-
ω_3 long. preias. pass.	-	-	69(18)	-
$f(M_3)(M_\odot)$	0.0014(5)	-	0.0010(5)	-
M_3 $(M_\odot)$	-	0.51	-	-
M_3 $(M_\odot)_{i=90}$	0.19	-	0.16	-
M_3 $(M_\odot)_{i=30}$	-	-	1.23	-
$a_{12} \sin i$ (projection of semi-major axis, AU)	0.83(9)	-	0.96(15)	-
no. of 3^{rd} body cycles	3.59	-	-	-

Table 7.
Four jumps in the orbital period of BB Pegasi

Interval in cycles	ΔT (days)	$\Delta P (10^{-7}$ days)
-96.5 to 6257	+0.0009	−0.1100
6257 to 17253	−0.0033	+3.3085
17253 to 23345	+0.0163	−7.9116
23345 to 28293	−0.0103	+3.7620
28293 to 31486	+0.0140	−4.6550

short-period orbits may be negatively influenced by the enhanced surface activity; migrating spots can cause wavelike behaviour of the $(O-C)$ diagrams, and only increase the scatter of observed minima times; (2) another possible interpretation of the cyclic period variation is a periodic transfer of orbital angular momentum to magnetic momentum in active systems (Applegate 1992).

A recent study of the $(O-C)$ diagram has been carried out by Snyder (2008), who has determined a third body orbital period value (P_3=35.522 yr) which is higher than the values obtained by previous authors (see Table 6). However, he has not confirmed nor supported the triplicity of the system by determining any other orbital parameter for the third body. He has considered such high deviation between his and other results given by Kalomeni et al. (2007) or D'Angelo (2006), and argued that the discrepancy is due to the method of analysis. In fact, this is not acceptable for the following reasons: (1) he has used scattered unweighted data in constructing the $O-C$ diagram, while Kalomeni et al. (2007) have given a suitable weight for each type of the observed data; (2) in spite that D'Angelo (2006) and Kalomeni (2007) have determined P_3 via two different methods, they obtained two comparable values of P_3 (29.7 and 27.9 years, respectively), which are off from Snyder's (2008) value of 35.522 years.

From the above investigations and because of: (1) the conflict between results obtained from the previous studies for determining M_3 and P_3, (2) the observed high scatter in the (v and pg) collected data, (3) the chromospheric activity nature of BB Peg, and, (4) the light curve morphology variation, we have aimed in the present $O-C$ study to illustrate the non-continuous variation superimposed on a secular decrement due to mass transfer and/or loss from the system.

Subtracting off the effect of mass transfer or mass loss from the system, we obtain the $(O-C)_2$ residual plot in Fig. 6, which shows a significant quasi-sinusoidal variation. A 7^{th} order polynomial fit with standard deviation SD=0.0014 and correlation coefficient r=0.7241 is the solid curve in the figure. In spite of using such a high degree polynomial, the data are not well–fitted. Hence, more details in studying such behavior have to be considered.

The $(O-C)_2$ values in Fig. 6 clearly suggest a non–continuous variation. Four clear jumps have taken place in the period of BB Peg within a time interval of 31.18 years which covers two complete cycles. The first cycle is not less than 17.0 years, and the second cycle is of about 12.87 years. Between these jumps, the period is assumed to have undergone a steady decrement. Similar systems, such as TZ Boo and Y Sex, have been studied by Awadalla et al. (2006) and Qian & Liu (2000). Using the least squares method, a linear function in each portion is used to obtain the best fit to the $(O-C)_2$ values:

$$(O-C)_2 = \Delta T + \Delta P \times E; \quad (7)$$

the values of ΔT and ΔP in each portion are listed in Table 7. The period at any cycle E has been computed with the following equation:

$$P_{Re}(E) = P_{Eph} + \Delta P + \frac{dP}{dE} \times E; \quad (8)$$

results are shown in Fig. 7, where we have plotted the difference between the real $P_{Re.}(E)$ and the ephemeris $P_{Eph.}$ ($0^d.36150147$) – in units of 10^{-6} day – as a function of time.

An alternative method has been suggested by Hanna (2010). He has divided the variations of the $O-C$ diagram of the system V839 Oph into cycles, in order to highlight its cyclic behaviour. BB Peg may be considered as a similar case to V839 Oph. The 7^{th} order polynomial fit of Fig. 6 shows two cycles, with different durations and different amplitudes.

5. MAGNETIC ACTIVITY VARIATION

Applegate (1992) has shown that variations of the subsurface magnetic field which may be compared to the solar activity cycles can lead to a difference between the rotational velocity of the core and that of the outer layer of the convective star. Consequently, the distribution of the angular momentum of this star will vary, and the binary will respond by changing the orbital period. This theory provides a plausible explanation of the observed cyclic period variations of such chromospherically active stars.

As far as magnetic activity, star–spots are expected to be on the cooler, rather than on the hotter star. Hence, the secondary (cool) more massive star has been considered as the active component, when applying the Applegate's (1992) mechanism. In addition, it is the donor component, as clearly suggested by the quadratic term of Eq. 5.

Adopting the Applegate's formalism, we consider the two unequal duration cycles found in the $(O-C)_2$ diagram to be the modulation periods P_{mod}: these are $P_{mod1} = 17.0$ and $P_{mod2} = 12.87$ years, with amplitudes equal to 0.0071 and 0.0013 day, respectively. Moreover, using the parameters given by Kalomeni et al. (2007) ($M_2 = 1.42\,\mathrm{M}_\odot$, $R_2 = 1.29\,\mathrm{R}_\odot$, $L_2 = 1.86\,\mathrm{L}_\odot$, and their obtained mean value for the orbital semi–major axes $a = 2.667\,\mathrm{R}_\odot$), and assuming that there is no energy storage in the outer layers of the active cool star, we apply the Applegate's (1992) procedure.

The required value for the angular momentum transfer ΔJ which produces the observed orbital period variations, the energy required to transfer this ΔJ, the RMS luminosity variations ΔL_{RMS}, and the magnetic field strength that sustains the whole mechanism, have been computed for both cycles; that are given in Table 8.

The quantities obtained in Table 8 are consistent with and close to those derived by the Applegate's (1992) model, for similar chromospherically active stars.

Table 8.
Magnetic circulation elements from the Applegate mechanism

	1^{st}Cycle	2^{nd}Cycle
$\Delta P/P$	3.550×10^{-6}	0.880×10^{-6}
ΔP (Sec.)	0.1107	0.0276
ΔJ ($\mathrm{g\,cm^2\,s^{-1}}$)	1.490×10^{47}	0.370×10^{47}
$\Delta\Omega/\Omega$	3.250×10^{-4}	0.810×10^{-4}
ΔE (ergs)	2.927×10^{40}	1.815×10^{40}
ΔL_{RMS}($\mathrm{ergs\,s^{-1}}$)	1.720×10^{32}	0.140×10^{32}
$\Delta L_{RMS}/L$	0.024	0.002
B (kG) (the mean sub-surface field)	8.50	4.88

6. DISCUSSION AND CONCLUSIONS

We summarize the asymmetry of the light curves obtained from morphology studies of the binary system BB Peg, as well as its evolutionary status in view of all collected published light curves and the $(O-C)$ diagram, as follows. (1) The photoelectric observations for the system show an occultation primary (Giuricin et al. 1981) or a flat bottom primary (Zola et al. 2005). The occulted duration varies with time over all the light curves of the system. This can be interpreted as a swilling of the bigger star radius, which is due to mass exchange between the binary components. (2) All the light curves of the system show a distinct O'Connell effect, which means that the system has magnetic activity due to a group of cool spots. These spots may be found on one or on both components with cycling of about 23 years (see Table 1 and Fig. 1). (3) The change in depths refers to the luminosity variations of the components, that may confirm the presence of the cool spots on the system. (4) The different fill–out ratio values (Table 2 & Fig. 3) obtained by previous authors may be due to changes in the asymmetric structure; these changes are usually caused by surface brightness anomalies due to mass exchange between the binary components. The short–time variation of the light curves for the system could be explained by active envelope and/or mass exchange, as well as by magnetic activity cycling. However, the chromospheric and coronal activities on W UMa binaries are common and have been taken into consideration in the literature. (5) A careful study of the $(O-C)$ diagram shows that the cause of the quasi–periodic variation is not due to the LITE as a result of the presence of a third body; however, some authors have determined the elements of third body and have tried to prove its presence spectroscopically (D'Angelo et al. 2006) by various techniques.

A possible explanation is magnetic activity due to the presence of star spots, which affects the period variation cyclically– as it is common in chromospheric active late type stars. Such cyclic magnetic activity variation (not strictly periodic) is superimposed to the mass exchange between the binary components with jumps of its orbital period behaviour (Fig. 7).

The present study shows mass transfer from the more to the less massive component, which contradicts previous studies. The difference between our result and previous studies may be due to the use of all the available high quality data, represented in terms of the pe and CCD minima times.

Notice also that when we used pg and v data together with pe and CCD minima (as previous authors), we obtained an increment in orbital period rate which is similar to their results.

The analysis of the $(O-C)$ diagram shows variations in the period, which can be explained either by stellar magnetic activity cycles on the cool secondary more massive component (with subsurface magnetic fields equal to 8.5 kG and 4.88 kG for the two cycles), or by a third companion orbiting the close pair. These magnetic activity cycling may be superimposed on a long term orbital period modulation decrement of rate $dP/dt = -5.62 \times 10^{-8}$ d/yr, corresponding to a time–scale of 6.43×10^{6} years.

Further accurate photoelectric and CCD observations are required to determine any asymmetry for the binary system BB Peg, as well as to confirm the magnetic activity cycling to be the cause of such quasi–sinusoidal variation in the $O-C$ diagram.

ACKNOWLEDGMENTS

The authors would like to thank the anonymous referee for his comments and efforts in modifying the text. This paper has made use of the variable star observations from the AAVSO and the BBSAG International Database contributed by observers worldwide. Many thanks to the NASA Astrophysics Data Service and to the Cracow Eclipsing Binaries Minima Database.

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APPENDIX A. TIMES OF MINIMA

Table 9.
Photoelectric and CCD minima times

HJD. (+2400000)	E	$(O-C)$	Type	Ref.
43729.4491	-96.5	-0.00761	pe	[1]
43730.3512	-94	-0.00926	pe	[1]
43750.5940	-38	-0.01054	pe	[2]
43754.3890	-27.5	-0.01131	pe	[2]
43754.3896	-27.5	-0.01071	pe	[1]
43757.4667	-19	-0.00637	pe	[1]
43764.3334	00.0	-0.00820	pe	[1]
43806.0845	115.5	-0.01049	pe	[3]
43806.9884	118	-0.01039	pe	[3]
43813.1337	135	-0.01065	pe	[3]
43814.0371	137.5	-0.01095	pe	[3]
43842.0537	215	-0.01069	pe	[3]
43866.9989	284	-0.00909	pe	[3]
44812.5022	2899.5	-0.01291	pe	[4]
45208.3511	3994.5	-0.00812	pe	[5]
45208.5319	3995	-0.00807	pe	[5]
46024.2600	6251.5	-0.00804	pe	[5]
46026.2483	6257	-0.00800	pe	[5]
48887.3650	14171.5	0.00532	ccd	[6]
49243.4462	15156.5	0.00757	pe	[7]
49244.3490	15159	0.00662	pe	[7]
49273.2689	15239	0.00640	pe	[7]
49275.2600	15244.5	0.00924	pe	[7]
50001.3351	17253	0.00864	pe	[8]
50026.2785	17322	0.00844	pe	[8]
50359.4028	18243.5	0.00913	ccd	[9]
50657.4575	19068	0.00587	pe	[10]
50671.3770	19106.5	0.00756	pe	[10]
50702.4698	19192.5	0.01124	ccd	[11]
50739.7052	19295.5	0.01199	ccd	[12]
50769.5250	19378	0.00791	ccd	[12]
51078.4304	20232.5	0.01031	ccd	[13]
51471.3810	21319.5	0.00881	ccd	[14]
51770.5212	22147	0.00654	pe	[15]
52131.8425	23146.5	0.00712	ccd	[16]
52201.2508	23338.5	0.00714	pe	[17]
52201.4305	23339	0.00609	pe	[17]
52203.2386	23344	0.00668	pe	[17]
52203.4188	23344.5	0.00613	pe	[17]
52207.3962	23355.5	0.00702	pe	[17]
52513.4118	24202	0.01162	ccd	[18]
52838.4020	25101	0.01200	ccd	[19]
52852.4956	25140	0.00704	pe	[20]
52903.4676	25281	0.00738	ccd	[21]
52956.2474	25427	0.00795	ccd	[21]
53243.4607	26221.5	0.00830	ccd	[22]
53266.4149	26285	0.00717	ccd	[21]
53284.3112	26334.5	0.00914	pe	[17]
53285.3957	26337.5	0.00913	pe	[17]
53353.3577	26525.5	0.00886	ccd	[22]
53591.4046	27184	0.00703	ccd	[21]
53638.4009	27314	0.00814	ccd	[21]
53661.3569	27377.5	0.00881	pe	[23]
53661.5390	27378	0.01015	pe	[23]
53675.2769	27416	0.01100	pe	[23]
53684.3136	27441	0.01020	ccd	[21]
53984.3589	28271	0.00924	ccd	[22]
53984.3591	28271	0.00944	ccd	[22]
53984.5409	28271.5	0.01049	ccd	[22]
53984.5411	28271.5	0.01069	ccd	[22]
53986.3485	28276.5	0.01058	pe	[24]
53986.5271	28277	0.00843	ccd	[22]
53986.5276	28277	0.00893	ccd	[22]
53987.4330	28279.5	0.01058	pe	[24]
53988.3352	28282	0.00903	pe	[25]
53988.5175	28282.5	0.01057	pe	[26]
53990.3248	28287.5	0.01037	pe	[27]
53990.5040	28288	0.00882	pe	[28]
53991.4089	28290.5	0.00996	ccd	[29]
53992.4949	28293.5	0.01146	ccd	[22]
53992.4957	28293.5	0.01226	ccd	[22]
54008.5804	28338	0.01014	ccd	[30]
54009.3042	28340	0.01091	ccd	[21]
54037.3178	28417.5	0.00818	pe	[24]
54039.3068	28423	0.00892	ccd	[31]
54086.3022	28553	0.00913	ccd	[32]
54298.5034	29140	0.00896	ccd	[33]
54360.3206	29311	0.00941	pe	[34]
54366.6477	29328.5	0.01024	ccd	[35]
54444.5506	29544	0.00957	ccd	[36]
54631.8082	30062	0.00941	ccd	[37]
54658.7402	30136.5	0.00955	ccd	[37]
54678.8041	30192	0.01012	ccd	[37]
54710.6143	30280	0.00819	ccd	[37]
55022.7710	31143.5	0.00837	ccd	[38]
55033.4355	31173	0.00858	ccd	[33]
55044.8219	31204.5	0.00768	ccd	[36]
55089.4688	31328	0.00915	ccd	[36]
55096.6981	31348	0.00842	ccd	[36]
55146.5851	31486	0.00822	ccd	[36]

Ref: [1] A&AS, 40, 85., [2] IBVS 2023., [3] Zhai&Zhang, 1979 (cf., AJ. 143, 647), [4] IBVS 2159., [5] Awadalla, 1988, Ap&SS, 140,137. [6] BBSAG Bull., 102., [7] IBVS 4380., [8] IBVS 4382., [9] IBVS 4562., [10] IBVS 4534., [11] IBVS 4606., [12] AAVSO 5., [13] IBVS 4712., [14] IBVS 5017., [15] IBVS 5296., [16] IBVS 5224., [17] IBVS 5623., [18] IBVS 5364., [19] IBVS 5464., [20] IBVS 5643., [21] B.R.N.O. Contrib. 34, 2007. [22] Kalomeni et al., 2007, AJ, 143, 647., [23] IBVS 5731., [24] IBVS 5736., [25] IBVS 5737., [26] IBVS 5738., [27] IBVS 5739., [28] IBVS 5740., [29] IBVS 5746., [30] IBVS 5843., [31] IBVS 5777., [32] IBVS 5897., [33] IBVS 5898., [34] IBVS 8530., [35] JAAVSO, 2008, 36, 171., [36] IBVS 5814., [37] JAAVSO, 2008, 36, 186., [38] JAAVSO, 2010, 38, 1.

Table 10.
Visual and photographic minima times

HJD (+2400000)	E	$(O-C)_1$	Type	Ref.
26559.241	-47593.5	0.01961	v	[1]
26582.014	-47530.5	0.01802	v	[2]
26965.204	-46470.5	0.01646	v	[2]
27393.223	-45286.5	0.01772	v	[2]
27675.144	-44506.5	-0.03243	v	[3]
28058.561	-43446	0.01267	v	[4]
28498.522	-42229	0.02598	v	[5]
30226.826	-37448	-0.00855	pg	[6]
30235.865	-37423	-0.00709	pg	[7]
30258.638	-37360	-0.00868	pg	[7]
30264.797	-37343	0.00479	pg	[7]
30281.776	-37296	-0.00677	pg	[7]
30285.753	-37285	-0.00629	pg	[7]
30530.861	-36607	0.00371	pg	[7]
30552.903	-36546	-0.00588	pg	[7]
30584.721	-36458	-0.00001	pg	[7]
30994.128	-35325.5	0.00658	pg	[2]
31731.756	-33285	-0.00917	pg	[8]
31783.455	-33142	-0.00488	pg	[8]
32433.631	-31343.5	0.01072	pg	[8]
32433.801	-31343	-0.00003	pg	[8]
32436.866	-31334.5	-0.00779	pg	[8]
32436.687	-31335	-0.00604	pg	[8]
32451.697	-31293.5	0.00165	pg	[8]
32455.683	-31282.5	0.01114	pg	[8]
32473.567	-31233	0.00081	pg	[8]
32477.538	-31222	-0.00470	pg	[8]
32477.744	-31221.5	0.02055	pg	[8]
32479.710	-31216	-0.00171	pg	[8]
34711.615	-25042	-0.00679	pg	[8]
35468.604	-22948	-0.00187	pg	[8]
36056.764	-21321	-0.00476	pg	[8]
41148.518	-7236	0.00104	-	†
41176.356	-7159	0.00342	-	†
41178.352	-7153.5	0.01117	-	†
41181.397	-7145	-0.01660	v	[9]
41335.227	-6719.5	-0.00547	v	[1]
41561.371	-6094	0.01936	v	[11]
41562.439	-6091	0.00285	v	[11]
41563.346	-6088.5	0.00610	v	[11]
41616.289	-5942	-0.01087	v	[12]
41618.283	-5936.5	-0.00512	v	[12]
41622.258	-5925.5	-0.00664	v	[12]
41624.248	-5920	-0.00490	v	[12]
41863.561	-5258	-0.00587	v	[13]
42405.259	-3759.5	-0.01782	v	[14]
42607.523	-3200	-0.01390	v	[15]
42748.310	-2810.5	-0.03172	v	[16]
43337.766	-1180	-0.00387	v	[17]
43337.771	-1180	0.00113	v	[17]
43346.819	-1155	0.01160	v	[17]
43705.765	-162	-0.01336	v	[17]
44191.638	1182	0.00166	v	[17]
44474.686	1965	-0.00599	v	[17]
44944.643	3265	-0.00090	v	[17]
45193.714	3954	-0.00441	v	[17]
45578.708	5019	-0.00948	v	[17]
45591.720	5055	-0.01153	v	[17]
45959.730	6073	-0.01003	v	[17]

Table 10. — continued

HJD (+2400000)	E	$(O-C)$	Type	Ref.
45959.732	6073	-0.00803	v	[17]
45962.621	6081	-0.01104	v	[17]
46017.582	6233	0.00174	v	[17]
46026.608	6258	-0.00980	v	[17]
46321.603	7074	0.00000	v	[17]
46413.599	7328.5	-0.00612	v	[17]
46706.418	8138.5	-0.00331	v	[18]
46713.642	8158.5	-0.00934	v	[17]
46731.365	8207.5	0.00008	v	[19]
46759.559	8285.5	-0.00303	v	[17]
47027.420	9026.5	-0.01462	v	[20]
47052.365	9095.5	-0.01322	v	[20]
47054.353	9101	-0.01348	v	[20]
47055.443	9104	-0.00798	v	[20]
47062.677	9124	-0.00401	v	[17]
47391.463	10033.5	-0.00360	v	[21]
47407.365	10077.5	-0.00766	v	[21]
47412.432	10091.5	-0.00168	v	[21]
47439.357	10166	-0.00854	v	[22]
47466.297	10240.5	-0.00040	v	[22]
47470.259	10251.5	-0.01492	v	[22]
47524.328	10401	0.00961	v	[22]
47526.294	10406.5	-0.01265	v	[22]
47528.277	10412	-0.01791	v	[23]
47742.480	11004.5	-0.00453	v	[24]
47778.450	11104	-0.00392	v	[24]
47804.468	11176	-0.01403	v	[25]
47857.261	11322	-0.00024	v	[25]
47861.607	11334	0.00774	v	[17]
47862.330	11336	0.00774	v	[25]
48092.425	11972.5	0.00705	v	[26]
48114.471	12033.5	0.00146	v	[26]
48115.378	12036	0.00471	v	[26]
48162.371	12166	0.00252	v	[26]
48170.328	12188	0.00648	v	[26]
48176.639	12205.5	-0.00879	v	[17]
48187.314	12235	0.00191	v	[26]
48205.390	12285	0.00284	v	[27]
48210.628	12299.5	-0.00093	v	[17]
48219.680	12324.5	0.01353	v	[17]
48441.448	12938	0.00038	v	[28]
48479.422	13043	0.01673	v	[28]
48500.365	13101	-0.00736	v	[28]
48519.359	13153.5	0.00781	v	[28]
48537.609	13204	0.00199	v	[17]
48546.302	13228	0.01895	v	[29]
48564.369	13278	0.01088	v	[29]
48623.287	13441	0.00414	v	[30]
48837.488	14033.5	0.01552	v	[31]
48843.440	14050	0.00275	v	[31]
48885.757	14167	0.02407	v	[17]
48936.345	14307	0.00187	v	[31]
48954.615	14357.5	0.01604	v	[17]
49001.245	14486.5	0.01235	v	[32]
49198.449	15032	0.01730	v	[33]
49219.422	15090	0.02322	v	[34]
49241.651	15151.5	0.01988	v	[17]
49264.593	15215	0.00653	v	[17]
49549.451	16003	0.00138	v	[35]

Table 10. — continued

HJD (+2400000)	E	$(O-C)$	Type	Ref.
49561.381	16036	0.00183	v	[35]
49602.597	16150	0.00666	v	[17]
49605.474	16158	-0.00835	v	[38]
49633.341	16235	0.02303	v	[36]
49679.598	16363	0.00785	v	[17]
49713.581	16457	0.00971	v	[17]
49917.466	17021	0.00788	v	[37]
49934.447	17068	-0.00169	v	[37]
49983.623	17204	0.01011	v	[38]
49989.600	17220.5	0.02234	v	[38]
50002.597	17256.5	0.00528	v	[38]
50014.349	17289	0.00849	v	[37]
50276.442	18014	0.01292	v	[39]
50331.396	18166	0.01870	v	[40]
50357.610	18238.5	0.02384	v	[38]
50370.613	18274.5	0.01279	v	[38]
50376.752	18291.5	0.00626	v	[38]
50390.315	18329	0.01296	v	[41]
50391.584	18332.5	0.01670	v	[38]
50425.557	18426.5	0.00856	v	[38]
50455.562	18509.5	0.00894	v	[38]
50682.215	19136.5	0.00052	v	[42]
50692.705	19165.5	0.00698	v	[38]
50698.671	19182	0.00820	v	[38]
50703.363	19195	0.00068	v	[43]
50726.688	19259.5	0.00884	v	[38]
50731.580	19273	0.02057	v	[38]
50753.274	19333	0.02448	v	[43]
50799.537	19461	0.01529	v	[38]
51012.821	20051	0.01343	v	[38]
51020.773	20073	0.01239	v	[38]

Table 10. — continued

HJD (+2400000)	E	$(O-C)$	Type	Ref.
51069.759	20208.5	0.01494	v	[38]
51084.590	20249.5	0.02438	v	[38]
51097.607	20285.5	0.02733	v	[38]
51099.579	20291	0.01107	v	[38]
51129.580	20374	0.00745	v	[38]

†Visual minima times listed in the Crakow Eclipsing Binaries Minima Database, but not presented in their source (BBSAG Bull. 31).

Ref.: [1] Zessewitsch, 1939, Quoted in Princeton Contributions No. 19,.[2] Tsessevich, V. P., 1954, Odessa Izv., 4, 271., [3] Dobronravin, 1935, N.N.V.S., 4, 415., [4] Piotrowski, S., 1936, ibid, 2, 157 [cf., AcA, 1977, 27,151]., [5] Dworak, T.Z., 1977, AcA, 27,151., [6] Whitney, B. S., 1943, AJ, 50, 131., [7] Whitney, B.S., 1959, AJ, 64, 258., [8] Diethelm, R., 1973, Rocznik Astron. Obser. Krakowskiego, 44, 102., [9] BBSAG Bull. 1., [10] BBSAG Bull. 5., [11] BBSAG Bull. 6., [12] BBSAG Bull. 10., [13] BBSAG Bull. 19., [14] BBSAG Bull. 23. [15] BBSAG Bull. 25., [16] AAVSO 2., [17] BBSAG Bull. 81., [18] BBSAG Bull. 83., [19] BBSAG Bull. 86., [20] BBSAG Bull. 89., [21] BBSAG Bull. 90., [22] BBSAG Bull. 91, [23] BBSAG Bull. 92. [24] BBSAG Bull. 93., [25] BBSAG Bull. 96., [26] BBSAG Bull. 97., [27] BBSAG Bull. 98., [28] BBSAG Bull. 99., [29] BBSAG Bull. 100., [30] BBSAG Bull. 102., [31] BBSAG Bull. 103., [32] BBSAG Bull. 104., [33] BBSAG Bull. 105., [34] BBSAG Bull. 107., [35] BBSAG Bull. 108., [36] BBSAG Bull. 110., [37] AAVSO 5., [38] BBSAG Bull. 112. [39] BBSAG Bull. 114. [40] BBSAG Bull. 115., [41] BBSAG Bull. 116., [42] BBSAG Bull. 116.