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ASTRONOMY AND ASTROPHYSICS

On the nature of the Be phenomenon

I. The case of ω Canis Majoris

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Abstract. The main purpose of this paper is to demonstrate the extreme complexity of the observed variations of Be stars on the example of a well-observed bright Be star ω CMa. A detailed analysis of all published radial velocities and a representative set of photometric and spectral observations of this star led to the following firm conclusions:

- At least three and possibly four different time scales of variability of ω CMa, ranging from $1^{\mathrm{d}}.37$ to more than 40 years, could be identified.
- The correct *mean* period of the RV and line-profile changes is $1^{\mathrm{d}}.371906$, not $1^{\mathrm{d}}.3667$ as derived earlier.
- The brightness of the object and the strength of the Balmer emission vary in an apparent cycle of several thousands of days. The long-term brightness and emission-line changes can be understood as consequences of the formation and gradual dispersal of a gaseous envelope which is flattened and seen more face-on than equator-on. During each episode, the envelope grows from an optically thick pseudophotosphere to a more extended and optically thin envelope.
- Existence of much smaller episodes of light brightening which can have the same cause (though on a more limited scale) has clearly been demonstrated.
- The amplitude of the $1^{\mathrm{d}}.37$ RV curve varies on a time scale somewhere between 10 and 300 d.

The following conclusions are less certain and represent possible alternatives to be tested by future, systematic and homogeneous observations:

- Some evidence is presented that the amplitude of the $1^{\mathrm{d}}.372$ RV variations, local mean RV and brightness of the object, prewhitened for the long-term changes, all vary on a time scale of about 35 d, possibly with a period of $34^{\mathrm{d}}.675$.
- The O-C deviations of the local epochs of RV maxima from a linear ephemeris for the $1^{\mathrm{d}}.372$ period seem to be undergoing a slow and probably cyclic variation in time, being shortest at times when the star is brightest and when a new Be envelope begins to grow. However, the same O-C deviations can also be reconciled with the $34^{\mathrm{d}}.675$ period. Whatever the true timescale of the O-C deviations is, their behaviour can also be simulated as an interference of several periods, the second most significant period being close to $1^{\mathrm{d}}.35$. Several reasons are given why the explanation in terms of one variable period appears more probable.
- With the help of both, real and artificial data it is demonstrated that the slow variation of the $1^{\mathrm{d}}.3719$ period — if unrecognized — may be misinterpreted for a multiperiodic variation with several close periods between $1^{\mathrm{d}}.3$ and $1^{\mathrm{d}}.45$. This constitutes a methodological warning for the period analyses of data on some β Cep, Be and "slowly pulsating" B stars.
- The cause(s) of the variations with the $1^{\mathrm{d}}.37$ (and $1^{\mathrm{d}}.345$) period(s) and/or the 35 d cycle remain unexplained. It is obvious, however, that these three periods are not mutually independent. The $34^{\mathrm{d}}.675$ period may be either a real physical period or a beat period between the $1^{\mathrm{d}}.372$ and $1^{\mathrm{d}}.345$ periods. In the former case, ω CMa could be a $34^{\mathrm{d}}.7$ binary in an eccentric orbit and the periods twice longer than the two periods near $1^{\mathrm{d}}.4$ would represent the sidereal and synodic rotational periods of the Be primary.
- Finally, some speculations are offered in terms of a hierarchical multiple system of three or even four stars.

Key words: stars: emission-line, Be – binaries: eclipsing – stars: individual: ω CMa, HR 2733

1. Introduction

The B2e star ω CMa (28 CMa, HR 2749, HD 56139, CD$-26^{\circ}4073$) has long been known to be a light and radial-velocity (RV hereafter) variable (cf., e.g., Frost, Barrett & Struve 1926, Campbell & Moore 1928, Stoy 1959, Cousins & Warren 1963, van Hoof 1975). However, it has only become well-known after Baade's (1979a, b, 1982 a, b) discovery of its remarkable RV, V/R and line-profile variation with a period of $1^{\mathrm{d}}.365$. Baade (1982a) also found that the RV of the Balmer emission lines varied in antiphase to that of the absorption lines. Baade (1984) demonstrated that the outer wings of the absorption lines showed only little or no RV changes. He used all his RV observations to improve the value of the period to $1^{\mathrm{d}}.36673 \pm 0^{\mathrm{d}}.00005$ and noted that the RV curves from various seasons looked different.

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Baade (1982b) obtained $uvby$ photometry of the star and concluded that the light variations cannot be reconciled with the spectroscopic period but rather with a shorter period of $0\overset{\mathrm{d}}{.}435$. However, Stagg (1987) obtained UBV photometry of the star which could be reconciled with the $1\overset{\mathrm{d}}{.}365$ period and noted that the period $0\overset{\mathrm{d}}{.}435$ is an alias of the spectroscopic 1.37-d period. Balona et al. (1987) obtained a long series of b observations of the star from Sutherland and La Silla Observatories. They found a monotonic decrease of the brightness over one year. Moreover, they found a low-amplitude periodic variation with a period of $1\overset{\mathrm{d}}{.}471$ from the 1986/87 data when the star was secularly rather stable, and about $0\overset{\mathrm{m}}{.}3$ fainter than at the beginning of the 1985/86 season. Clarke (1990) analyzed polarimetry and Hβ scans and suggested that the true period of variations is twice the value found by Baade, $2\overset{\mathrm{d}}{.}7335$. Mennickent, Vogt & Sterken (1994) reported large long-term brightness variations and the presence of quasiperiodic light changes with a cycle of about 25 d at the phases of increased brightness. Balona, Štefl & Aerts (1998) analyzed a series of high-resolution electronic spectra from January 1996 and confirmed the presence of $1\overset{\mathrm{d}}{.}37$ period in the line moments of He I 6678. They were unable to model the varying shape of the line profile with either spot or NRP model and had to assume a patch with intrinsic line width differing from that outside it. Finally, Štefl et al. (1998) analyzed long series of Heros spectra of ω CMa and reported the presence of two periods: a stable one of $1\overset{\mathrm{d}}{.}37$, and a transient one of $1\overset{\mathrm{d}}{.}49$ seen only in the lines affected by the circumstellar emission.

Given these contradictory results, I decided to check whether an independent analysis of available data which would also include the older RV data could resolve the question of the true period(s) of the star. Results of this analysis led me far beyond my original plan. They demonstrate an extreme complexity of the variations observed and may have some important implications for the understanding of the variability of Be stars in general.

Table 1. Journal of RV data sets of ω CMa

I	Dispersion (Å mm^{-1})	Weight	Epoch (HJD-2400000)	No. of RVs	S
1	30	0.333	16450.8–18301.8	6	A
2	37.4	0.267	16481.8–17612.7	9	B
3	20.3	0.493	17957.7–18996.9	6	B
4	12.3	0.813	40607.5–40608.8	6	C
5	16.9	0.592	42033.0–42887.6	16	D
4	12.3	0.813	43091.8–43096.9	12	E
6	42	0.238	43499.6–43510.6	15	E
4	12.3	0.813	43884.5–43895.8	44	E
4	12.3	0.813	44951.7–44955.9	17	F
7	1.3	1.000	45245.9–45247.9	3	G
7	1.3	1.000	45351.8–45357.7	17	G

Instruments in column "I": 1... Yerkes 1.02-m refractor, Bruce prism spg.; 2... Chile Lick 0.929-m reflector, one-prism spg.; 3... Chile Lick 0.929-m reflector, two-prism spg.; 4... ESO La Silla 1.52-m reflector, coudé grating spg.; 5... KPNO coudé feed 1.0-m, coudé grating spg.; 6... Calar Alto 1.23-m, Nasmyth grating spg.; 7... ESO 1.4-m coudé auxiliary telescope, coudé echelle spectrometer with a Reticon 1872 detector.
Sources in column "S": A... Frost et al. (1926); B... Campbell & Moore (1928); C... van Hoof (1975) remeasured by Baade (1982a); D... Abt & Levy (1978); E... Baade (1982a); F... Baade (1982b); G... Baade (1984);

Table 2. Periodic signals with largest amplitude found in the Hipparcos $H_{\rm P}$ photometry of the four stars used as comparisons for ω CMa. Errors of the last decimal digit of the period and semi-amplitude (in brackets) and the rms error of a single observation calculated from a sinusoidal fit for the respective period are given

Star	Period	Semi-amplitude	rms
GY CMa	$1\overset{\mathrm{d}}{.}6682(4)$	$0\overset{\mathrm{m}}{.}0028(9)$	$0\overset{\mathrm{m}}{.}0066$
HR 2733	$1\overset{\mathrm{d}}{.}0247(1)$	$0\overset{\mathrm{m}}{.}0054(6)$	$0\overset{\mathrm{m}}{.}0112$
HR 2774	$1\overset{\mathrm{d}}{.}8035(4)$	$0\overset{\mathrm{m}}{.}0034(7)$	$0\overset{\mathrm{m}}{.}0071$
HR 2756	$1\overset{\mathrm{d}}{.}3789(2)$	$0\overset{\mathrm{m}}{.}0033(6)$	$0\overset{\mathrm{m}}{.}0058$

2. Observational data used

Since I have had no chance to observe ω CMa myself, this study is based solely on the observational data either published or kindly provided in advance of publication by several colleagues.

2.1. RV data

Basic information about the data is summarized in Table 1. I used either the mean RV or the mean He I triplet RV to be able to employ all available observations. It is necessary to warn, however, that the Lick velocities from Chile are based on the Hγ *emission*. Yerkes early RVs are based on absorption lines but the emission RV is also given for the first two spectra. In all cases I derived heliocentric Julian Dates (HJDs hereafter) if they were not given in the original source. Since neither the exact number of lines measured for RV nor the S/N ratio are known for some of the data sets, I only assigned all RVs by weights inversely proportional to the dispersion of the original spectra (cf., e.g., Horn et al. 1996). The only exception is the last data set, based on high-dispersion Reticon spectra, for which I somewhat arbitrarily adopted weight 1 (instead of 7.7 which would come out from a straightforward calculation) since these RVs rest on a single line and since putting such a large weight on two localized data sets could overweight them in the combined fits. Note that the weights only played a role in least-square fits to the data. They are given explicitly in Table 1.

2.2. Photometry

Stoy (1959) reported that ω CMa is a light variable. Since then, a large number of photometric observations of ω CMa has been accumulated. I collected and homogenized a representative set of photometric observations which were — or could be — calibrated to the standard UBV or $uvby$ systems. An interested reader can find the details on the individual data sets and their homogenization in the Appendix.

Table 3. Equivalent widths and peak intensities of the Hα and Hβ emission lines compiled from various sources

JD−2400000	$EW_{H\alpha}$	$I_{H\alpha}$	$EW_{H\beta}$	$I_{H\beta}$	S
43540± 30	−14.2	3.96	−1.55	1.34	1
43813± 30	−12.9	4.03	−1.65	1.38	1
45245.9	–	–	–	1.286	2
45246.9	–	–	–	1.289	2
45247.9	–	–	–	1.308	2
45352.8	–	–	–	1.271	2
45356.7	–	–	–	1.286	2
44924± 5	−7.17	2.52	−0.79	1.06	3
44951± 1	−10.6	3.12	−1.14	1.14	3
45029± 30	−11.8	3.44	–	–	3
45394± 30	−9.98	3.37	−1.26	1.18	3
45226.9	−10.7	3.745	–	–	4
46835.7	−19.2	5.54	–	–	5
47532	–	5.93	–	1.37	6
47808	–	5.13	–	–	6
48633	–	3.38	–	1.01	6
48705	–	2.96	–	–	6
49095	–	3.29	–	–	6
48995.7	–	–	–	1.08	7

Notes: Data sources are identified in column "S" as follows: 1... Dachs et al. (1981); 2... Baade (1984); 3... Dachs et al. (1986); 4... Hanuschik et al. (1988); 5... Dachs et al. (1992); 6... Hanuschik et al. (1996); 7... Zboril et al. (1997). In cases when the equivalent widths and peak intensities were not tabulated in the original papers, I measured the peak intensities in the published line profiles

It is useful to consider the true noise level of the existing photometric data. To this end I extracted the observations of all four comparison stars used by various observers from the Hipparcos catalogue. A time plot of these observations immediately shows that HR 2733 varies with a cycle of (353±6) d and a full amplitude of $0\overset{m}{.}029$. Individual observations of the remaining three comparisons scatter within $0\overset{m}{.}03$. I calculated Fourier periodograms for all four comparisons for periods from $0\overset{d}{.}4$ to $2\overset{d}{.}0$ and the results for the highest peaks found are summarized in Table 2. For HR 2733, I analyzed the O-C deviations from the 353-d cycle. They define the amplitude limits of the periodic signals over that range of possible periods.

2.3. Balmer line profiles

I also compiled the equivalent widths and peak intensities of the Hα and Hβ emission lines of ω CMa from more recent spectral observations. These are listed in Table 3. Additionally, Dr. T. Rivinius very kindly put at my disposal the Hα peak intensities derived from the unpublished measurements in the Heros spectra. These measurements will later be published in detail by their authors.

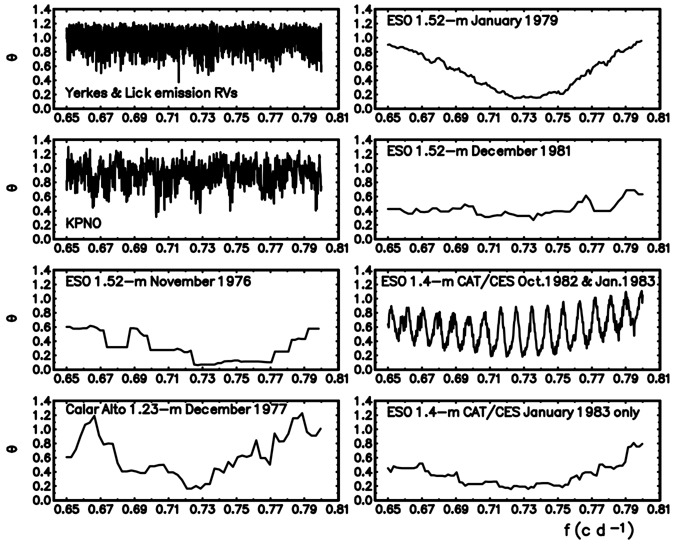

Fig. 1. Stellingwerf's PDM periodograms of ω CMa for various RV data subsets

3. Periodic changes with the $1\overset{d}{.}37$ period

3.1. Is there a secularly stable $1\overset{d}{.}37$ period?

First, I analyzed the available RVs. For all least-square fits discussed below, I formally used the program FOTEL (Hadrava 1990, 1995a) which is designed for orbital (and light-curve) solutions of spectroscopic (eclipsing) binaries, uses the simplex method and calculates realistic errors based on the covariance matrix. I verified that Baade's RVs can indeed be best reconciled with periods close to $1\overset{d}{.}37$. Other periods, including both 1-d aliases, seem to give much worse phase diagrams. On the other hand, the scatter is not significantly reduced for the double-wave periods near $2\overset{d}{.}74$, advocated by Clarke (1990). I, therefore, restricted my initial data analyses to the neighbourhood of the $1\overset{d}{.}37$ period.

Fig. 1 shows Stellingwerf's (1978) PDM periodograms (structured into 5 bins with 2 'covers') for the individual RV data sets for periods between $1\overset{d}{.}25$ and $1\overset{d}{.}54$. It is seen that the resolution in frequency is inevitably low for the short data strings while the longer strings of data suffer from aliasing problems. Yet, it seems clear that the only period common to all periodograms is a period close to $1\overset{d}{.}372$ (frequency 0.7289 c d^{-1}), i.e. a one-year alias of the $1\overset{d}{.}36673$ period derived by Baade (1984). It is a bit curious that the RVs which best show the $1\overset{d}{.}372$ periodicity – without too much aliasing - are the Kitt Peak RVs published by Abt & Levy (1978) who concluded from them that the RV of ω CMa is constant. (During preliminary analyses, I was obtaining a different period from the Reticon RVs published by Baade 1984. Upon a closer examination, I came to the conclusion that the correct HJDs of the three October 1982 Reticon spectra must be higher by 1 day than what is given in Table 1a of Baade 1984. Upon my request, Dr. Baade very kindly checked his original records and confirmed that it is indeed so. After this correction of dates (already applied in Table 1 and Fig. 1), also

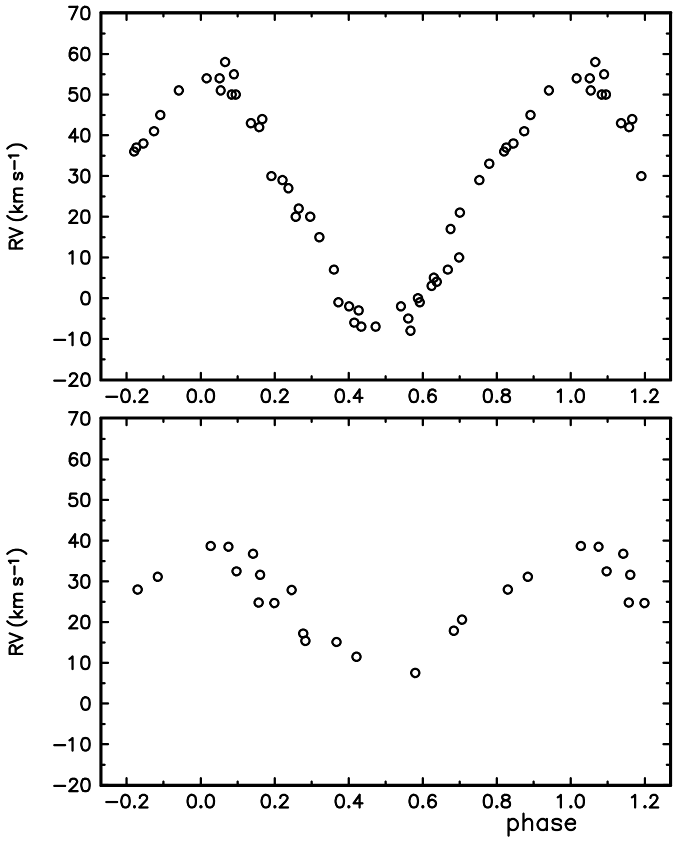

Fig. 2. Radial-velocity curves of the He I triplet lines of ω CMa (P = $1\overset{\mathrm{d}}{.}372$) from two consecutive observing runs by Baade with the same instrument. The upper one is based on data secured between HJD 2443884 and ...895, the lower one on data taken between HJD 2444951 and ...955. A large difference in the amplitudes of the two curves is clearly seen

the RVs from Baade's 1982-83 Reticon observations seem to be best reconciled with a period of $1\overset{\mathrm{d}}{.}372$.)

The problem of the determination of an accurate value of the $1\overset{\mathrm{d}}{.}37$ period is not trivial, however. This is not only because of the heterogeneity of the data but also due to the fact that the amplitude and mean RV of the apparent RV changes varies not only with the dispersion and resolution of the spectrograms (as already pointed out by Baade) but probably also from physical reasons. This is best illustrated by Fig. 2 where the RV curves, based on two consecutive observing runs by Baade with *the same instrument*, are compared. The semi-amplitudes of the two curves are (30.61 ± 0.34) km s^{-1} and (14.5 ± 1.3) km s^{-1}, respectively, the rms of the fit per 1 observation being 3.1 km s^{-1} in both cases. As Baade remarked, the Balmer emission has decreased between these two epochs. Therefore, the change of the amplitude of the $1\overset{\mathrm{d}}{.}37$ RV curve can indicate either that the variation of the line cores is affected by the strength of the circumstellar matter or that it is controlled by more than one period close to $1\overset{\mathrm{d}}{.}4$.

Putting aside the early RVs I therefore adopted a period of $1\overset{\mathrm{d}}{.}3718$ which resulted from trial period searches over all more recent RVs, and calculated local sinusoidal fits to individual subsets of data covering no more than 400 d (for Abt and Levy's data) and much less for all other data sets obtained since HJD 2440607.[1] This way, the particularly chosen exact value of the $1\overset{\mathrm{d}}{.}37$ period played a negligibly small role in the determination of locally derived semi-amplitudes and systemic velocities of individual RV subsets. Using these locally derived values, I then transformed all RV data (HJD$>$2440607) into an interval $< -1, 1 >$ and subjected this homogenized data set to a period analysis. Clearly the best period was indicated in the neighbourhood of $1\overset{\mathrm{d}}{.}3719$. A sinusoidal fit led to the following linear ephemeris:

$$\begin{aligned} T_{\rm max.RV} &= (\mathrm{HJD}\ 42805.884 \pm 0.016) \\ &+ (1\overset{\mathrm{d}}{.}371906 \pm 0\overset{\mathrm{d}}{.}000013) \times E. \end{aligned} \tag{1}$$

(The best fit period in the neighbourhood of the period derived by Baade (1984) is $1\overset{\mathrm{d}}{.}366791$. It gives a much worse phase curve than the period of $1\overset{\mathrm{d}}{.}371906$.)

3.2. *Cyclic changes of a single period or an interference of several short periods?*

A phase diagram of the transformed RVs for ephemeris (1) is shown in the upper panel of Fig. 3 where the individual data subsets are denoted by different symbols. Comparing this plot to Fig. 2, one can see an increased scatter in the phase diagram based on all RVs. (Note, however, that the scatter in the transformed RVs is a bit confusing since, say, a deviation of 0.1 from the mean curve represents 1.5 km s^{-1} for a subset with a semi-amplitude of 15 km s^{-1} but 3.5 km s^{-1} for another one, with a semi-amplitude of 35 km s^{-1}.) On a closer inspection, one clearly sees that the individual subsets are slightly shifted in phase with respect to each other. This indicates that *the period is changing with time*.

To check on this suspicion, I used the best-fit period $1\overset{\mathrm{d}}{.}371906$ to re-calculate local epochs for the individual data subsets. Then I derived the O-C deviations of these epochs from the linear ephemeris (1). Their plot vs. time (see the upper panel of Fig. 6a–d) shows that the change is smooth and indicative of a slow and possibly periodic change of the $1\overset{\mathrm{d}}{.}372$ period. Note that if one assumes a strictly sinusoidal variation of the O-C changes, the best-fit period is (5650 ± 400) d, the semi-amplitude of the variation is $0\overset{\mathrm{d}}{.}174 \pm 0\overset{\mathrm{d}}{.}017$ and the mean O-C amounts to $0\overset{\mathrm{P}}{.}940$. This latter value implies that the epoch of maximum RV of ephemeris (1) for the mean period should be corrected to HJD 2442805.802. One should adopt this result as a tentative one, however, since the O-C variations – even if they vary strictly periodically – need not follow either an exact sinusoid or the period found from a few data points only.

As a test of internal consistency of the procedure, I analyzed three subsets of more recent RVs, each of them spanning more than 400 d, namely (in HJD-240000): 40607 – 42452, 42724 –

[1] Trial non-sinusoidal fits were first carried out only to find that the deviations of any of the available local RV curves from sinusoidal shape are negligible

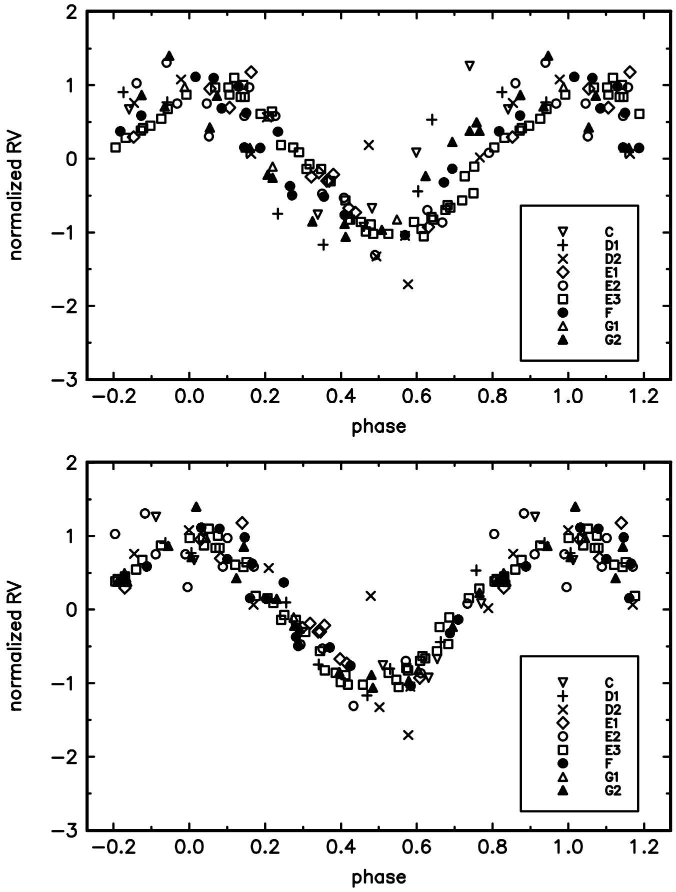

Fig. 3. A RV curve of the KPNO, La Silla and Calar Alto observations, transformed locally into an interval $< -1, 1 >$. *Upper panel:* RVs plotted vs. phase of the linear ephemeris (1). *Bottom panel:* RVs re-plotted vs. phase of a periodically varying $1\overset{\mathrm{d}}{.}372$ period (see the text for details). Individual data subsets localized in time and denoted by various symbols in both plots refer to the following epochs (in HJD−2400000): C: 40607.5–40608.8; D1: 42033.0–42452.8; D2: 42724.9–42887.6; E1: 43091.8–43096.9; E2: 43499.6–43510.6; E3: 43884.5–43895.8; F: 44951.7–44955.9; G1: 45245.9–45247.9; G2: 45351.8–45357.7

43895, and 44951 – 45357. The resulting local periods of their sinusoidal fits were $1\overset{\mathrm{d}}{.}37196 \pm 0\overset{\mathrm{d}}{.}00004$, $1\overset{\mathrm{d}}{.}37192 \pm 0\overset{\mathrm{d}}{.}00003$ and $1\overset{\mathrm{d}}{.}37162 \pm 0\overset{\mathrm{d}}{.}00006$, respectively. It is possible to compare them to those from the sinusoidal model used: If one assumes that the O-C varies sinusoidally, then

$$T(E) - T_0 - P_0 \times E = A\cos\left(2\pi P_1^{-1}(T(E) - T_1)\right), \qquad (2)$$

where T is the time of observation, P_0, T_0 and P_1, T_1 are the period and time of maximum of the short and long variation, respectively, A is the semi-amplitude of the long variation and E is a generalized epoch, i.e. cycle and phase of the observation. Since $P_1 >> P_0$, one can substitute, with a high accuracy $T = T_0 + P_0 \times E$ into the cosine term in eq.(2). For the instantaneous period one then obtains

$$P(T) = dT(E)/dE = \qquad (3)$$
$$P_0 - 2\pi A P_0 P_1^{-1} \sin\left(2\pi P_1^{-1}(T(E) - T_1)\right).$$

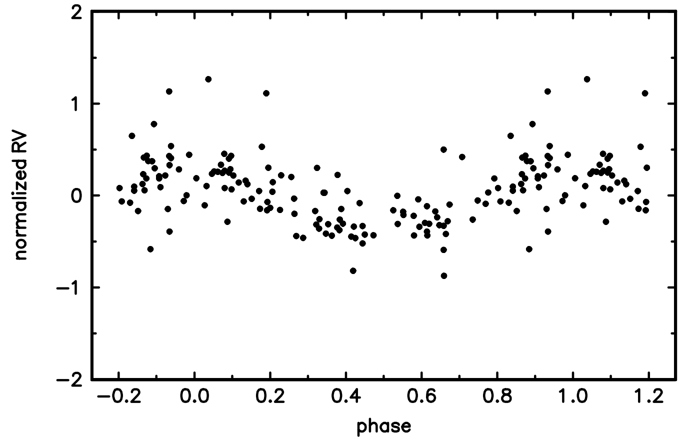

Fig. 4. The O-C from the 1.372-d RV curve (normalized RVs) plotted vs. phase of the $1\overset{\mathrm{d}}{.}348548$ period. A calculated epoch of the maximum residual RV, HJD 2442805.817, is used as phase zero

Table 4. Results of a multiperiodic fit to the *original* more recent RVs of ω CMa (the rms errors of the last 2 digits of the periods are given in brackets; the rms per 1 observation of the fit is 4.28 km s^{-1})

Period (days)	Frequency (c d^{-1})	Amplitude (km s^{-1})	$T_{\rm max.RV}$ (HJD-2400000)
1.371925(15)	0.7289027	21.14	42981.449
1.346368(18)	0.7427389	11.27	42982.363
1.353607(26)	0.7387668	6.81	42981.817
38.047(25)	0.0262834	5.63	42980.071
0.6178363(55)	1.6185518	4.85	42982.238
0.6239372(62)	1.6027253	3.84	42982.346

With the numerical values derived above, formula (3) predicts $1\overset{\mathrm{d}}{.}3720$, $1\overset{\mathrm{d}}{.}3721$ and $1\overset{\mathrm{d}}{.}3716$, in a reasonable agreement with the above results of the local fits if one realizes inevitable inaccuracies of the tentative model function used.

Finally, I derived the phases of the $1\overset{\mathrm{d}}{.}372$ variation, assuming its slow sinusoidal change, from eq. (2) and re-plotted all normalized RVs in the bottom panel of Fig. 3. Note that the remaining larger deviations all come from photographic spectra of moderate dispersions.

Next, I considered the possibility of multiperiodic changes. I first searched for periodicity the O-C residuals from the normalized RV curve for a *constant* period of ephemeris (1). I used Breger's program PERIOD (Breger 1990), searching over the whole range of frequencies up to 20 c d^{-1}. I indeed found a periodic variation with a period close to the $1\overset{\mathrm{d}}{.}3719$ period, namely $1\overset{\mathrm{d}}{.}348548 \pm 0\overset{\mathrm{d}}{.}000026$. The phase curve for this period is shown in Fig. 4. However, the fit of normalized RVs with these two periods gives a larger rms error per 1 observation than the fit with one periodically variable period.

I also analyzed *the original RVs* for multiperiodicity to see whether the amplitude change could be due to interference of several frequencies. In every step, I fitted the original data with all the frequencies found and analyzed the new residuals from the fit again. The results of this analysis are summarized in Table 4. The rms errors of individual original RVs range from 3 to 6 km s^{-1} which is comparable to the rms from the multiperiodic fit. I repeated this analysis for two data subsets, covering the first, and the last about 3000 d, respectively. The first two periods with largest amplitudes (in brackets) were $1\stackrel{\rm d}{.}37196$ (22.6) and $1\stackrel{\rm d}{.}36933$ (7.7) in the former, and $1\stackrel{\rm d}{.}37189$ (24.0) and $1\stackrel{\rm d}{.}34631$ (12.7) in the latter subset. Further frequencies with smaller amplitudes, found in each subset, differ totally from each other and from those of Table 4. The rms error of the fit for the second subset (containing solely Baade's data) was only slowly decreasing with more frequencies added. I verified, however, that the first two periods of Table 4 also fit the first data subset quite well. Since these two frequencies are clearly essential to modelling of the amplitude changes, this may in turn indicate that *there is some regularity* in the amplitude changes of the RV curves. At the same time, it is obvious that the instrumental effects of the very different spectral resolutions used also affects the actually measured amplitude of each RV curve from heterogeneous sources. I calculated RV amplitudes for about 1-d long subsets of the longest set of homogeneous RV observations (HJDs 2443884-895) to find that any variation of the RV amplitude must occur on a time scale much longer than 10 d. On the other hand, Fig. 6a–d shows that a significant amplitude change took part within 300 d. Note that the beat period between the first two periods of Table 4, $72\stackrel{\rm d}{.}274$, is indeed within these limits. I also created artificial data using the first two periods of Table 4 and calculated local RV fits exactly as for the real data, for the $1\stackrel{\rm d}{.}371906$ period fixed. This gave an approximate (far from ideal) reproduction of the run of the O-C deviations for the local epochs, a rather fair reproduction of all local amplitudes, and a poor reproduction of local mean velocities. Moreover, the artificial local RV curves showed significant systematic variations over the intervals covered by real data subsets as well as significant deviations from the sinusoidal shape – in contrast to real observations.

At this stage I decided to carry out a numerical test. Using the sinusoidal fit to the O-C changes (cf. the upper panel of Fig. 6a–d), I constructed a model function describing a sinusoidal variation with the mean period of $1\stackrel{\rm d}{.}371906$ which periodically varies with a period of 5644 d and generated an artificial data set for HJDs identical to those of real RV observations. Then I subjected the model function to a Fourier analysis over the range of frequencies from 0.0001 to 2 c d^{-1}. This analysis indeed led to the detection of several periods in the neighbourhood of the $1\stackrel{\rm d}{.}3719$ period, the second largest amplitude being detected for a period of $1\stackrel{\rm d}{.}354$, reminiscent of what I obtained from the Fourier analysis of the real RVs - both normalized and original ones (note that my model is close to, but not identical to the real data since it is based on pure sinusoids with no scatter added). I also verified that if the normalized RVs were pre-whitened for the periodically variable period, no other periods close to $1\stackrel{\rm d}{.}3$ – $1\stackrel{\rm d}{.}4$ were detected in the residuals. Some remaining power was found in the frequency range of about 0.01 to 0.1 c d^{-1} but I was unable to find any clear periodicity in these residuals.

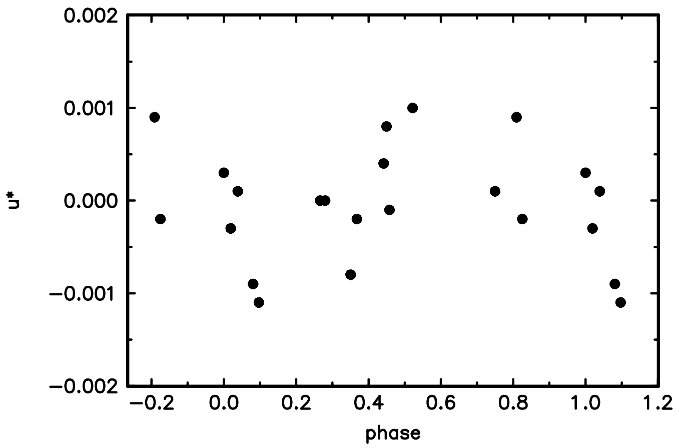

Fig. 5. A phase plot of the Stokes parameter u with respect to intrinsic stellar axes (from Clarke 1990) for the $1\stackrel{\rm d}{.}37$ period. Phases were calculated using ephemeris (1)

My tentative conclusion is that one observes a combination of a slow and probably cyclic small variation of the $1\stackrel{\rm d}{.}372$ period and of an amplitude variation on a time scale of 10^0–10^1 d which may be related to changes in the Be envelope, as already suggested by Baade and as may be suspected from Fig. 6a–d below. New systematic spectral observations are clearly needed to check on the possible true periodicity of the amplitude changes.

3.3. Polarimetric and light changes with the $1\stackrel{\rm d}{.}372$ period

Fig. 5 shows the polarimetric observations by Clarke (1990) plotted vs. phase of the mean $1\stackrel{\rm d}{.}372$ period from ephemeris (1). Some mild variability may be suspected.

A firm detection of photometric variations with the $1\stackrel{\rm d}{.}372$ period is seriously hampered by the presence of light variations on at least two different longer time scales which are discussed below. I carried out various trials only to find out that the $1\stackrel{\rm d}{.}372$ period *is not* convincingly present in accurate photometric data sets after their proper prewhitening for changes on longer time scales (see below).

4. An overview of photometric and emission-line variations of ω CMa

Given the evidence of the slow cyclic change of the $1\stackrel{\rm d}{.}372$ period, it was deemed important to identify the timescales of spectral and light changes of ω CMa and investigate their possible relations.

4.1. Photometry

The V-magnitude time variations are compared with variations seen in some other quantities in Fig. 6 while Fig. 7 is a plot of the B observations vs. time. Using some overlapping B and b observations, I decreased all b magnitudes for $0\stackrel{\rm m}{.}1$ to bring them on the scale of B magnitudes. It is seen that the long-term variations of ω CMa are characterized by rather regular major brightenings, with an amplitude as large as $0\stackrel{\rm m}{.}4$, and by

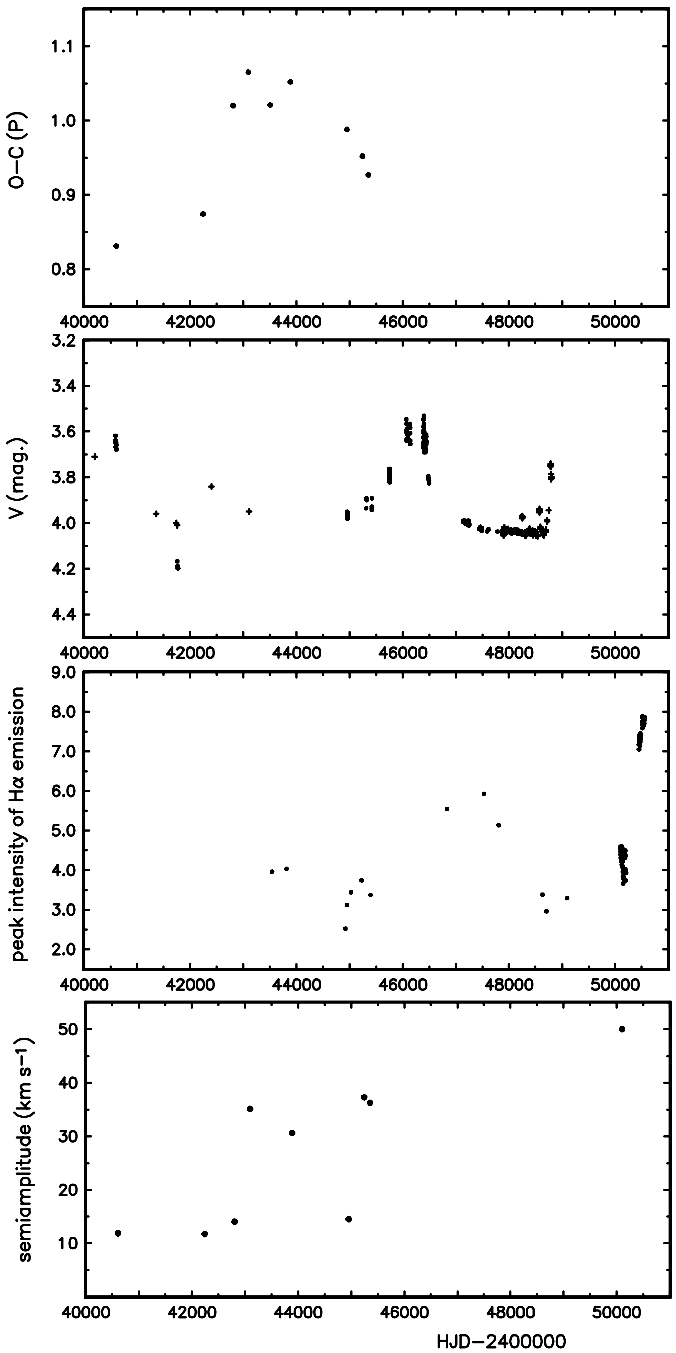

Fig. 6a–d. Several measured or deduced quantities plotted vs. time. From top to bottom: **a** The O-C of locally derived epochs calculated for a constant period of P = $1\overset{\mathrm{d}}{.}371906$: The O-C deviations are expressed in fractions of the period, i.e. as phases of the local RV maxima with respect to ephemeris (1); **b** The V magnitude: Differential observations are shown by dots, all-sky measurements by crosses; **c** Peak intensity of Hα emission line; **d** The semi-amplitude of the locally fitted $1\overset{\mathrm{d}}{.}3719$ RV curves (only data from spectrograms with a dispersion better than 20 Å mm^{-1} are shown); The last data point at JD 2450100 comes from a preliminary report by Balona et al. (1998) who give $2K \ = \approx 100$ km s^{-1}

occasional smaller brightenings. It is important to stress that these smaller brightenings, taking place within less than a few

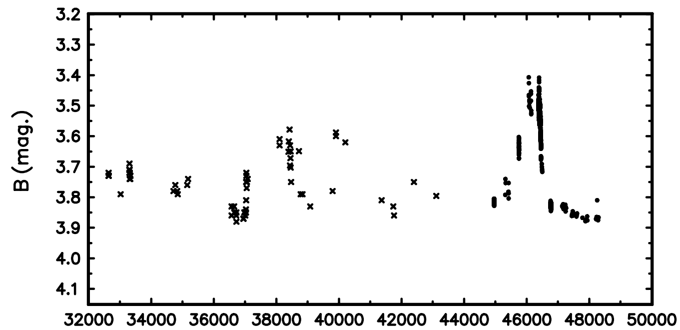

Fig. 7. Plots of the B magnitude of ω CMa vs. time. Differential observations are shown by dots, all-sky measurements by crosses. Strömgren b magnitudes were decreased by $0\overset{\mathrm{m}}{.}1$ to get them on a scale comparable to Johnson B magnitudes.

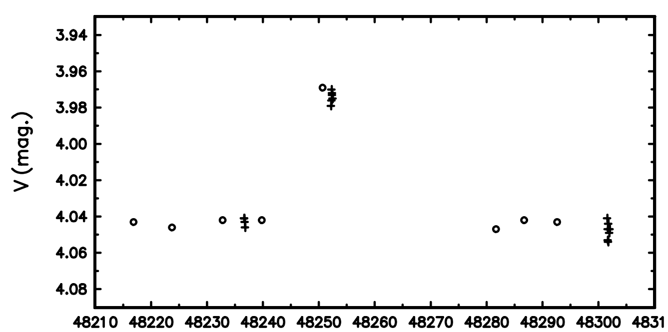

Fig. 8. An example of a smaller temporal brightnening of ω CMa recorded by two independent instruments. The ESO y observations and the Hipparcos H_{p} observations are denoted by circles and crosses, respectively. See the Appendix for details

weeks, are no doubt real. This is clearly documented by Fig. 8 where the independent ESO and Hipparcos observations of one such episode are compared. This very fact shows how difficult the search for the periodic components of the light changes of Be stars can be.

There is some indication that the luminosity of the object in the periods outside the brightenings is secularly decreasing in time over the whole period of about 44 years covered by observations. Besides all that, there are also lower-amplitude cyclic brightness variations of the star, first explicitly noted by Mennickent, Vogt & Sterken (1994).

4.2. Balmer line profiles

The most numerous peak-intensity measurements of Hα are also plotted vs. time in Fig. 6. One can see that the intensity of the Balmer lines seems to vary on a time scale similar to the cyclic variations of the $1\overset{\mathrm{d}}{.}3719$ period and brightness of the object. A series of Hβ profiles obtained by Baade (1984) indicates (as pointed out by the author and as seen in Table 3) that the emission strength is fairly constant on shorter time scales. This is not quite true for the recent Heros Hα data.

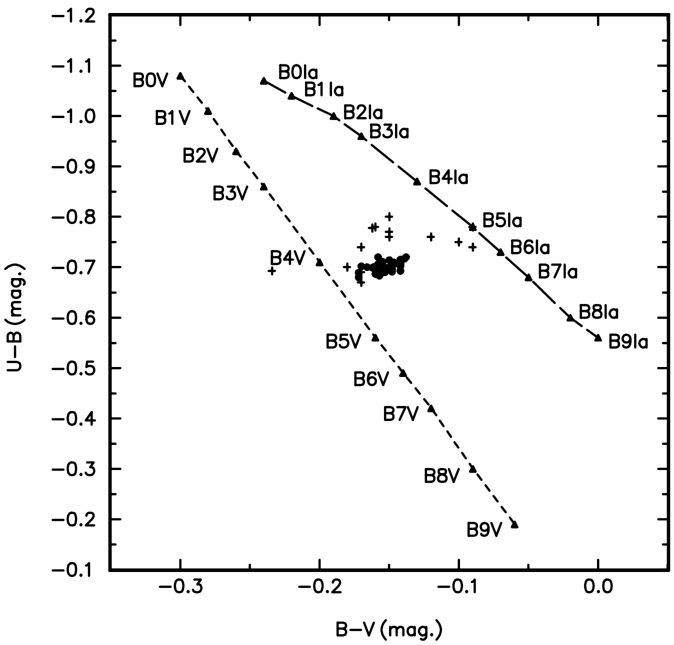

Fig. 9. The $U-B$ vs. $B-V$ diagram for ω CMa. Individual all-sky observations are shown by crosses, differential ones by black dots. The standard main and supergiant sequences are also shown. It is seen that ω CMa moves from the main to supergiant sequence. The same trend can also be seen for the existing $uvby$ observations (not shown here).

5. The long-term changes

5.1. Their character and phenomenological interpretation

As already noted, the secular light changes of ω CMa are characterized by occasional larger or smaller brightenings from a certain more or less undisturbed level. There may also be a correlation between the major brightenings and the strength of the Balmer emission (found for several other well-observed Be stars). Note, however, that the maximum brightness corresponds in both so far recorded cases to rather early stages of the new emission-line episode, i.e. that the maximum strength of the emission lags behind the maximum brightness.

This behaviour can be qualitatively well understood if one adopts Harmanec's (1983) concept of an optically thick pseudophotosphere, as recently developed semi-quantitatively by Koubský et al. (1997): The process of the formation of a new envelope starts close to the stellar photosphere. It means that the envelope begins to grow first as an equatorially flattened and optically thick region which mimics the stellar photosphere. Clearly, ω CMa is a typical example of the positive correlation between the brightness and emission strength as defined by Harmanec (1983): the object indeed moves from the main towards the giant sequence in the colour-colour diagram when it brightens (see Fig. 9) and this agrees with the view that ω CMa ($v \sin i \approx 80$ km s^{-1}) is a rapidly rotating star seen under a relatively small angle between the line of sight and the rotational axis of the star. Thanks to this geometry, the formation of an extended pseudophotosphere near the equatorial regions effectively increases the apparent radius of the star for an observer on the Earth and the object brightens. Later, as the envelope gets larger and more rarified, it becomes optically thin so that the brightness gradually decreases again while the Balmer emission gets stronger.

I tentatively suggest that also the smaller brightenings (such as the one shown in Fig. 8) are caused by the same process occuring on a smaller and shorter time scale since - for a given star - the character of all such episodes is the same (either brightenings or fadings from a certain light level) which seems to point towards the geometrical interpretation in terms of either more pole-on or equator-on orientation of each particular star (see Harmanec 1983 for details).

A new and exciting result of this study is that also the value of the $1\overset{d}{.}37$ RV period changes cyclically and quite possibly in phase with the major light brightenings, being shortest at the light maxima.

Little can be concluded from Fig. 6 about the changes of the amplitude and mean velocity of the $1\overset{d}{.}37$ RV curve besides the fact that they occur on a much shorter time scale. For instance the mean velocity based on Baade's (1984) Reticon observations secured with the same instrumentation and for the same He I line some 100 d apart (JD 2445245-7 vs. JD 2445352-8) differ by as much as 14 km s^{-1}.

5.2. Are the long-term changes cyclic or periodic?

In spite of the amount of data presented in Fig. 6 it is impossible at present to make any firm conclusion whether the long-term changes observed are cyclic or truly periodic ones. I verified that the existing data ($1\overset{d}{.}37$ period variation, brightness and emission strength) can indeed be reconciled with several long periods, e.g. about 2700 d, 3500 d, 5600 d or 8100 d, but the decision if this is indeed a regular clock can only come from future observations or from an independent piece of evidence.

6. Variations on a time scale of a few weeks

Mennickent et al. (1994) called attention to the fact that the star exhibits cyclic brightness variations with a pseudoperiod of about 25 d in the epoch when it brightens. My analysis of the semiaplitude and mean RV of the local $1\overset{d}{.}372$ RV curves also indicated that these variations occur on a time scale of weeks. I attempted to find a consistent periodicity in the range from 30 to 50 d which would give a meaningful phase curve. I used only local determinations from data sets spanning no more than about 10 d. A period of $34\overset{d}{.}675 \pm 0\overset{d}{.}037$ was detected not only in the mean RVs and semi-amplitudes but also in the O-C from the local RV maxima with respect to the $1\overset{d}{.}372$ which were analyzed earlier and which were suggested to vary with a cycle of about 5600 d! A formal orbital solution for a fixed eccentricity of 0.8 (a free solution is unstable because of a small number of data points) leads to the periastron passage at HJD 2442788.088. (Note that the position of the periastron passage is not substantially affected by my rather arbitrary choice of the value of e since it is the shape of the RV curve which basically defines it.)

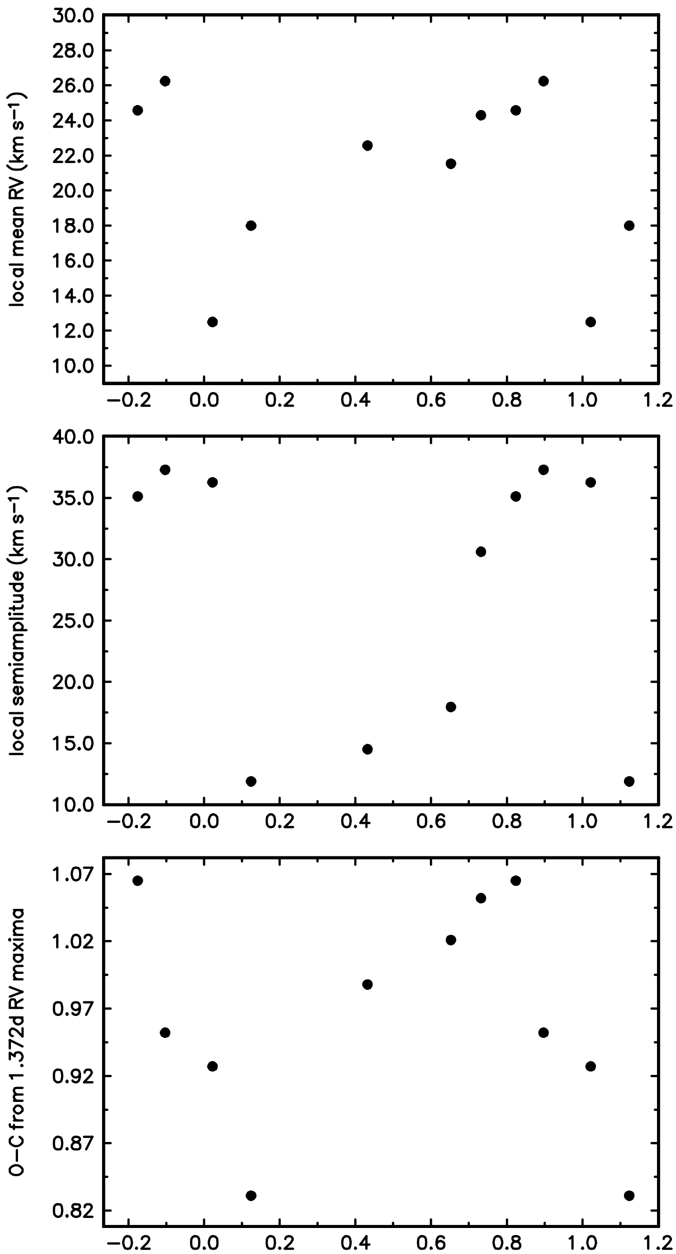

Fig. 10. Mean RV, semi-amplitude and O-C deviations of the RV maxima from the local $1\overset{d}{.}372$ fits plotted vs. phase of the $34\overset{d}{.}675$ period, with HJD 2442788.088 as phase zero

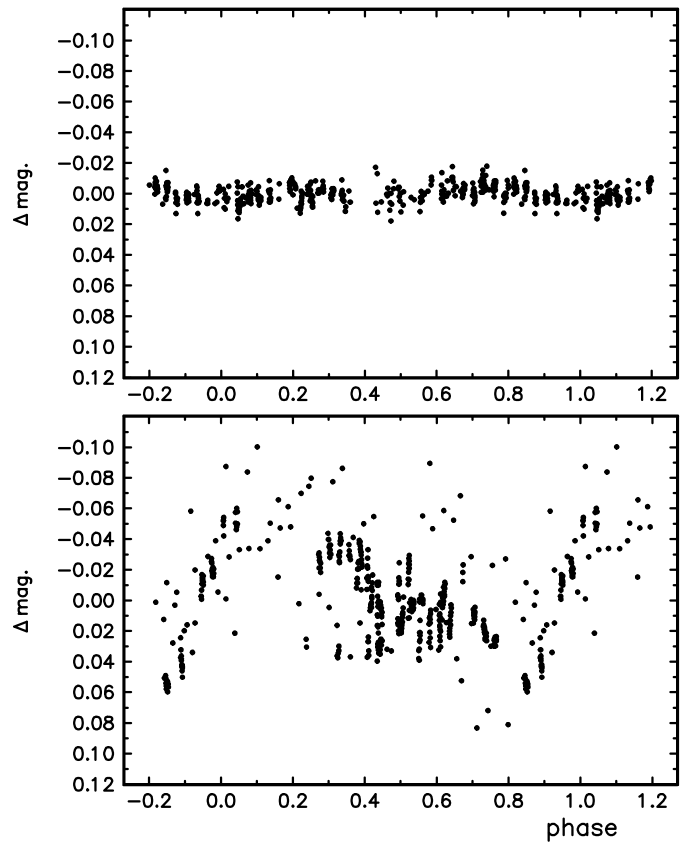

Fig. 11. The residual brightness of ω CMa after prewhitening for long-term changes plotted vs. phase of the $34\overset{d}{.}675$ period, with HJD 2442788.088 as phase zero. Data from epochs without, and with large secular changes are shown in the upper and bottom panels, respectively

Fig. 10 is the phase plot for all three considered quantities, with the calculated periastron passage adopted as phase zero.

Using the program HEC13, based on Vondrák's (1969, 1977) smoothing technique I prewhitened all blue and yellow observations for the long-term light variations. Then, I combined the more numerous blue-magnitude O-C residuals with the yellow residuals from the Hipparcos observations to obtain the largest possible data set. I subjected these O-C residuals to a period analysis, separately for the data from epochs without large changes and from active epochs. It is useful to realize that all the residuals from quiet epochs lie within $0\overset{m}{.}03$ which is the range identical to the range of the most stable comparison stars recorded by Hipparcos (see above). One can note, however, that the O-C residuals vary systematically over a period of several weeks. The period search was, therefore, carried out over the period range from 15 to 50 d. It indicated a number of possible, but weakly detected periods between 18 and 50 d. On the other hand, the best period detected in the data from active epochs is $34\overset{d}{.}666 \pm 0\overset{d}{.}011$, identical to that found from spectral data. Several other possible periods between about 35 and 42 d were also detected. There are no comparably good periods in the range from $0\overset{d}{.}4$ to $15\overset{d}{.}0$.

Given this, I tentatively plotted in Fig. 11 the residual light changes with the same period and epoch as the spectroscopic quantities shown in Fig. 10.

7. Other short periods?

Using various segments of photometric data prewhitened for variations on timescales of weeks and longer, I checked on the presence of periods in the range from $0\overset{d}{.}4$ to $3\overset{d}{.}0$. I found that the 1986-1987 observations by Balona et al. (1987) can indeed be best reconciled with a period of $1\overset{d}{.}4749 \pm 0\overset{d}{.}0029$ and a semi-amplitude $0\overset{m}{.}0045$ which is only about 1.5 times higher than the semi-amplitudes detected for the constant comparison stars. However, this periodicity cannot be detected in another subset, also from the same phase of strong emission (around HJD 2447900), where a period of $2\overset{\text{d}}{.}7428$, reminiscent of the period advocated by Clarke (1990), is formally detected.

8. Speculations in the absence of firm answers

The analyses presented above indicate several (in some cases mutually exclusive) ways to possible speculative interpretations. Since they can only be tested by new dedicated observations, I find useful to mention them explicitly.

8.1. Alternative models of ω CMa

The result displayed in Fig. 10 is potentially quite exciting since it may indicate that the semi-amplitude of the $1\overset{\text{d}}{.}372$ RV curve is largest around the phases of the periastron passage of the putative $34\overset{\text{d}}{.}675$ binary system. This hypothesis offers an explanation of the $1\overset{\text{d}}{.}372$ period as the tidal pulsational mode.

Note also that

$2\times 34\overset{\text{d}}{.}675^{-1} + 1\overset{\text{d}}{.}371906^{-1} = 1\overset{\text{d}}{.}3453^{-1}$.

The $1\overset{\text{d}}{.}345$ period is reminiscent of the periods found from the multiperiodic analyses of the RV data. This can be interpreted in at least two different ways. One possibility is that the medium-term light changes represent a beat period of the two short periods. This seems to contradict the simulations with artificial data, however. Another is to assume that the true physical periods are twice longer, i.e. $2\overset{\text{d}}{.}74$ and $2\overset{\text{d}}{.}69$ and represent in fact *the synodic and sidereal periods of rotation* of the primary star in the $34\overset{\text{d}}{.}675$ binary system. For a high eccentricity of the $34\overset{\text{d}}{.}675$ period, $2\overset{\text{d}}{.}7$ could be the proper value for the spin-orbit synchronization at periastron.

It will be important to decide whether the $1\overset{\text{d}}{.}372$ period undergoes a slow cyclic change or a periodic change with the $34\overset{\text{d}}{.}675$ period. If the former is confirmed, such a variation could — in principle — be explained in terms of the light-time effect in a wide binary. Already in 1981 I suggested (Harmanec 1982) that the recurrent shell phases observed for Be stars like BU Tau (HD 23862), V832 Cyg (59 Cyg) or γ Cas (HD 5394) could be causally related to the fact that these Be stars might be long-periodic binaries. Duplicity of BU Tau was indeed discovered by Gies et al. (1990) during a lunar occultation of the star and the authors explicitly suggested that the shell episodes of BU Tau are driven by tidal interactions near periastron. Duplicity of V832 Cyg was discovered by McAlister et al. (1984) by means of speckle interferometry but no relation to the spectral variations of the star has been demonstrated as yet. There is a suspicion that the major emission episodes of o And (HD 217675) occur with a period of its closer speckle-interferometric companion (see Harmanec et al. 1987 and references therein). One speckle-interferometric observation of ω CMa was obtained in the spring of 1996 (JD about 2450300) and no binary component at distances from $0\overset{''}{.}035$ to $1\overset{''}{.}5$ was found (Hartkopf 1997, priv.com., Mason et al. 1997). I estimate that for the Hipparcos parallax of $0\overset{''}{.}00353$ and orbital periods from 2700 to 8100 d, the angular projection of the semimajor axis of the putative binary would be $0\overset{''}{.}028$ — $0\overset{''}{.}060$. Clearly, the binary interpretation of the long-term changes of ω CMa is not ruled out and continuing interferometric observations are desirable.

8.2. What causes the changes with the $1\overset{\text{d}}{.}372$ period?

The true nature of the periodic $1\overset{\text{d}}{.}372$ (or $2\overset{\text{d}}{.}744$) changes remains unexplained. One seeks an explanation for the large-amplitude RV variations of the absorption-line cores, accompanied by lower-amplitude RV changes of the Balmer emission lines, occurring in antiphase to the absorption RV curve (Baade 1982a), and by virtually no variability of either brightness or the RV of the outer wings of the absorption line. All quantitative attempts to explain these changes by a low-mode of photospheric pulsations, corotating structures or orbital motion in a close binary led to serious problems but it is conceivable that a more sophisticated version of one of these models will succeed.

A natural explanation of the fact that the RV of the Balmer emission lines of ω CMa varies in *exact antiphase* to that of the absorption lines would be to assume that ω CMa is a close binary with an orbital period of $1\overset{\text{d}}{.}372$. Taken at face value, the semi-amplitude of the emission RV changes (of 5.1 km s^{-1} only) leads to rather extreme assumptions about the nature of the binary components and the binary model does not appear tenable. However, before the binary origin of the $1\overset{\text{d}}{.}372$ period is definitively ruled out, one should apply some disentangling technique, like Hadrava's (1995b) KOREL program, to spetral observations from a limited period of time (to eliminate the effects of varying emission strength). If two binary components with similar relatively broad-lined spectra were present, then the observed RV amplitudes would certainly be affected by both, the mutual blending of the two sets of lines and by the secularly varying strength of the emission. Note that for the binary system of two B stars V436 Per (1 Per) Harmanec et al. (1997) found that the direct RV measurements gave a RV curve with an amplitude of some 10 km s^{-1} only while the disentangling revealed that the true RV curves for both binary components have amplitudes of about 100 km s^{-1}.

9. A methodological remark

Waelkens & Rufener (1985) and Waelkens (1991) reported discoveries of multiperiodic light variations of some apparently non-emission B stars, with periods in the range from $0\overset{\text{d}}{.}8$ to $4\overset{\text{d}}{.}4$. They called them "slowly pulsating B stars or SPB" to distinguish them from β Cep variables with much shorter periods ($\approx 0\overset{\text{d}}{.}1$ – $0\overset{\text{d}}{.}25$). By its period, ω CMa would also qualify into this category. Clearly, one of the results of this paper represents a methodological warning that the detection of an apparent multiperiodicity with several rather close periods, typical not only for the SPB stars but also for the β Cep stars and some other Be stars (cf., e.g., μ Cen: Rivinius et al. 1998) should *also be tested* against the hypothesis of a single and slowly periodically variable period. This is even more desirable after the finding that a number of the β Cep and SPB stars are members of binary or multiple systems of stars (cf., e.g., Pigulski & Boratyn 1992,

Table A1. Journal of photometric observations of ω CMa

Source	Epoch (JD-2400000)	No. of obs.	Instr.	Phot. system	Comparison / Check
Cousins & Warren (1963)	32634.3–37081.2	42	1	$S'Pg$	all-sky
Feinstein (1968, 1975, 1976)	38104–42397^{+}	8	2	UBV	all-sky
Johnson et al. (1966)	38383.9–38721.9	3	3	UBV	all-sky
Johnson et al. (1966)	38417.8–38455.6	5	4	BV	all-sky
Feinstein (1968, 1975, 1976)	38470–39080^{+}	3	5	UBV	all-sky
van Hoof (1975)	40591.7–40611.7*	11	6	V	HD 55857 / –
Deutschman, Davis & Schild (1976)	41738 $\pm$ 15	1	5	UBV	all-sky
van Hoof (1975)	41757.5–41772.5*	5	7	V	HD 55857 / –
Baade (1982b) and priv.com.	44957.8–44962.9	210	8	$uvby$	HD 56876 / HD 55595
Mennickent, Vogt & Sterken (1994) and priv. com.	45312.7–48292.6	106	8	$uvby$	HD 56876 / HD 58612
Stagg (1987) and priv.com.	45749.5–45756.7	35	9	UBV	HD 55856 / HD 56876
Balona et al. (1987)	46374.7–46381.8	40	8	b	HD 55857 / HD 56342
Balona et al. (1987)	46390.4–46458.6	297	10	b	HD 55857 / HD 56342
Balona et al. (1987)	46761.3–46787.6	320	10	b	HD 55857 / HD 56342
Perryman et al. (1997)	47901.5–48798.2	174	11	V	all-sky

$^{+}$) JDs only known to $\pm$15 d; *) JDs only known to $\pm$0.1 d;

Column "Instrument": 1: Cape Observatory, a Fabry photometer prior to 1952, photoelectric photometry thereafter, transformed to Johnson B; 2: La Plata 0.80-m reflector, RCA 1P21 tube; 3: Catalina, RCA 1P21 tube; 4: Tonantzintla 1.0-m reflector, RCA 1P21 tube; 5: Cerro Tololo Inter-American Observatory 0.41-m reflector, RCA 1P21 tube; 6: La Silla Zeiss 0.15-m; 7: Boyden 1.5-m reflector; 8: ESO La Silla Danish 0.5-m reflector; 9: Cerro Las Campanas University of Toronto 0.4-m reflector, S25 tube; 10: South African Astronomical Observatory, Sutherland 0.5-m reflector; 11: Hipparcos $H_{\rm P}$ observations corrected to Johnson magnitude: The correction $V = H_{\rm P} + 0\overset{\rm m}{.}052$ was found from a comparison with overlapping La Silla data; observations coded as uncertain in the Hipparcos catalogue (with code > 2) were omitted

Aerts et al. 1998) since for such stars the slow periodic variations of the principal period of oscillation due to the light-time effect do inevitably occur. More generally, one should realize that many Fourier terms would be needed for a complete description of the very complicated signal which one observes in situations like this one.

10. Conclusions

This study of a well-observed Be star shows the enormous complexity of the variations observed. Several timescales were identified. There are periodic RV variations with a period of $1\overset{\rm d}{.}372$ and a variable amplitude. There are also long-term cyclic changes in the emission strength, and brightness and colours of the star. There are strong reasons to believe that the exact value of the $1\overset{\rm d}{.}372$ RV period varies. Most probably it undergoes a slow variation, possibly correlated with the long-term changes. The observed amplitude variation of the $1\overset{\rm d}{.}372$ RV curve can be formally described as the beating effect of two short periods, $1\overset{\rm d}{.}372$ and $1\overset{\rm d}{.}35$. Light variations prewhitened for the long-term changes and also the local mean RVs and locally derived RV amplitudes can be reconciled with a period of $34\overset{\rm d}{.}675$. There is also the possibility that even the value of the $1\overset{\rm d}{.}372$ period varies with this period.

One tentative interpretation considers a hierarchical system of three or even four stars. The long-term changes could be due to the most distant companion. It is noted that periods twice longer than the two short periods could be identified with the sidereal and synodic periods of a putative $34\overset{\rm d}{.}675$ binary system. The nature of the $1\overset{\rm d}{.}372$ RV variation is not clear and it is suggested that even this variation could be due to duplicity. At the moment, these suggestions are speculative, some even mutually exclusive. However, they can be tested and either confirmed or disproved by future well-planned observations.

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Appendix A: Appendix: details on photometric data sets used

A journal of photometric observations is presented in Table A1. Table A2 contains the values of the standard magnitudes of the comparison and check stars used by various observers which I adopted to bring the data onto a comparable scale. To transform Cousins & Warren's (1963) $S'Pg$ magnitudes into Johnson B

Table A2. Comparison and check stars and their standard magnitudes adopted here

Star	HD	V	$B-V$	$U-B$	$b-y$	$u-b$	v	Source UBV / $uvby$
HR 2733	55856	6.359	-0.174	-0.819	-0.086	0.125	6.277	Stagg (1986) / Hauck & Mermilliod (1980)
GY CMa	55857	6.128	-0.23	-1.01	-0.089	-0.121	6.011	BSC / Balona et al. (1987)
HR 2756	56342	5.365	-0.17	-0.65	-0.071	0.386	5.324	BSC / Balona et al. (1987)
HR 2774	56876	6.431	-0.138	-0.598	-0.061	0.461	6.410	Stagg (1986) / system 7, Sterken (1993)
HR 2841	58612	5.797	-0.10	-0.39	-0.032	0.845	5.828	BSC / system 7, Sterken (1993)

magnitudes I adopted the correction of $0\overset{\mathrm{m}}{.}21$, recommended by the authors. Moreover — for the purpose of the study of long-term changes only — I also created approximate V magnitudes from these observations, using $V = B + 0\overset{\mathrm{m}}{.}18$, following again a recommendation of the authors.

The $uvby$ data obtained at ESO come from two different sources: Baade's (1982b) observations, which were kindly put at my disposal by the author, and the measurements secured in the framework of the "Long-term Photometry of Variables" (LTPV) project which was initiated more than a decade ago (Sterken 1983, 1994). This latter set consists of 106 datapoints (nightly averages of 1–3 measurements) and its latest edition was kindly put at my disposal by Dr. C. Sterken. The details on the data reduction and transformation to the standard system can be found in Manfroid et al. (1991, 1994) and Sterken et al. (1993, 1995). I used the magnitude differences ω CMa $-$ HD 56876 to which I added the magnitudes of HD 56876 listed in Table A2. The calibrated Strömgren indices of HD 56876 are based on data from "System 7" (Sterken 1993) only.

The observations of ω CMa from the ESO long-term program have been analyzed by Mennickent, Vogt & Sterken (1994) who reported a very unusual light decrease, especially pronounced in b and v, between JDs 2446479 and ...499. Thanks to the fact that Dr. Sterken provided me with a complete documentation of their observations, I could recognize and correct the problem: a different attenuation was clearly used on these nights for the b and v filters. Fortunately, the comparison was observed through both of these attenuations on the night JD 2446479 and I used these measurements as the needed calibration to correct the measurements of ω CMa for $-0\overset{\mathrm{m}}{.}692$ in b and $-0\overset{\mathrm{m}}{.}745$ in v (note that HD 55876 has colours sufficiently similar to those of ω CMa).

Finally, I should mention that there is also a problem with the second set of van Hoof's (1975) observations. He observed ω CMa to be unusually faint: $4\overset{\mathrm{m}}{.}2$ in V. This is $0\overset{\mathrm{m}}{.}15$ fainter than the minimum observed by any other observer and in contradiction with one Fenstein's observation from the same night of V=$4\overset{\mathrm{m}}{.}01$. One could speculate that γ CMa = HD 53244 (V=$4\overset{\mathrm{m}}{.}12$) was observed instead of ω CMa by van Hoof at that time but the puzzle will probably remain unanswered since Professor A. van Hoof passed away a long time ago.

References

Abt H.A., Levy S.G., 1978, ApJS 36, 241

Aerts, C., De Mey, K., De Cat, P., Waelkens, C., 1998, *Pulsations in early-type binaries*, in Bradley & Guzik (1998)

Baade D., 1979a, PhD Thesis, Astronomical Institute, University of Münster, Germany

Baade D., 1979b, The Messenger (E.S.O.) No. 19, 4

Baade D., 1982a, A&A 105, 65

Baade D., 1982b, A&A 110, L15

Baade D., 1984, A&A 134, 105

Balona L., Štefl S., Aerts C., 1998, *Modelling of Rapid He I 667.8 Line Profile Variations In the Be Star 28 CMa*, in Bradley & Guzik (1998)

Balona L.A., Marang F., Monderen P., Reitermann A., Zickgraf F.-J., 1987, A&AS 71, 11

Bradley P.A., Guzik J.A. (Eds.), 1998, *A Half Century of Stellar Pulsations Interpretations: a Tribute to Arthur N. Cox*, Los Alamos, June 16-20, 1997, ASP Conf. Ser. (in press)

Breger M., 1990, Com. in Astroseismology No. 20, Publ. by Local Computing Center of the Austrian Academy of Sciences, Wien, Austria

Campbell W.W., Moore J.H. 1928, Publ. Lick Obs. 16, 1

Clarke D., 1990, A&A 232, 411

Cousins A.W.J., Warren P.R., 1963, Mon. Not. Astron. Soc. South Africa 22, 65

Dachs J., Eichendorf W., Schleicher H., Schmidt-Kaler T., Stift M., Tüg H., 1981, A&AS 43, 427

Dachs J., Hanuschik R., Kaiser D., Ballereau D., Bouchet P., Kiehling R., Kozok J., Rudolph R., Schlosser W., 1986, A&AS 63, 87

Dachs J., Hummel W., Hanuschik R.W., 1992, A&AS 95, 437

Deutschman W.A., Davis R.J., Schild R.E., 1976, ApJS 30, 97

Feinstein A., 1968, Zeit. Astrophys. 68, 29

Feinstein A., 1975, PASP 87, 603

Feinstein A., 1976, *Photometric UBVRI observations of Be stars*, priv. com.

Frost E.B., Barrett S.B., Struve O., 1926, ApJ 64, 1

Gies D.R., McKibben W.P., Kelton P.W., Opal C.B., Sawyer S., 1990, AJ 100, 1601

Hadrava P. 1990, Contr. Astron. Obs. Skalnaté Pleso 20, 23

Hadrava P., 1995a, *FOTEL3 User's guide*, Astronomical Institute, Academy of Sciences, Ondřejov, anonymous ftp sunstel.asu.cas.cz (147.231.104.100), file pub/fotel/fotel3.tex

Hadrava P., 1995b, A&AS 114, 1

Hadrava P., Harmanec P., 1997, A&A 315, L401

Hanuschik R., Kozok J.R., Kaiser D., 1988, A&A 189, 147

Hanuschik R.W., Hummel W., Sutorius E., Dietle O., Thimm G., 1996, A&AS 116, 309

Harmanec P., 1982, in *Be Stars*, IAU Symp. 98, Ed. by M. Jaschek and H.-G. Groth, Reidel, Dordrecht, 279

Harmanec P., 1983, Hvar Obs.Bull. 7, 55

Harmanec P., 1988, Bull. Astron. Inst. Czechosl. 39, 329

Harmanec P., Hill G.M., Walker G.A.H., Dinshaw N., Yang S., 1987, Publ. Astron. Inst. Czechosl. Acad. Sci. No. 70, 115

Harmanec P., Hadrava P., Yang S., Holmgren D., North P., Koubský P., Kubát J., Poretti E., 1997, A&A 319, 867

Hauck B., Mermilliod M., 1980, A&AS 40, 1

Horn J., Kubát J., Harmanec P., Koubský P., Hadrava P., Šimon V., Štefl S., Škoda P., 1996, A&A 309, 521

Johnson H.L., Mitchell R.I., Iriarte B., Wisniewski W.Z., 1966 Comm. Lunar Planet. Lab. 4, 99

Koubský P., Harmanec P., Kubát J., Hubert A.-M., Božić H., Floquet M., Hadrava P., Hill G., Percy J.R., 1997, A&A (Dec. 1997)

Manfroid J., Sterken C., Bruch A., et al., 1991, A&AS 87, 481

Manfroid J., Sterken C., Cunow B., et al., 1994, A&AS 109, 329

Mason B.D., Brummelaar T.T., Gies D.R., Hartkopf W.I., Thaller M.L., 1997, AJ 114, 2112

McAlister H.A., Hartkopf W.I., Hendry E.M., Gaston B.J., Fekel F.C., 1984, ApJS 54, 251

Mennickent R.E., Vogt N., Sterken C., 1994, A&AS 108, 237

Perryman M.A.C., Høg E., Kovalevsky J., Lindegren L., Turon C., 1997, ESA SP-1200, *The Hipparcos and Tycho Catalogues*

Pigulski A., Boratyn D.A., 1992, A&A 253, 178

Rivinius Th., Baade D., Štefl S., Stahl O., Wolf B., Kaufer A., 1998, *Multiperiodic line-profile variability and a tentative ephemeris for emission-line outbursts of the Be star μ Cen*, in Bradley & Guzik (1998)

Stagg C., 1986, *Short Term Variability in Be Stars*, PhD Thesis, Department of Astronomy, University of Toronto, Canada

Stagg C., 1987, MNRAS 227, 213

Štefl S., Baade D., Rivinius Th., Stahl O., Wolf B., Kaufer A., 1998, *Cirmcumstellar quasi-periods accompanying stellar periods of Be stars*, in Bradley & Guzik (1998)

Stellingwerf R.F., 1978, ApJ 224, 953

Sterken C., 1983, The Messenger 33, 10

Sterken C., 1993, in *Precision Photometry*, D. Kilkenny, E. Lastovica, J. Menzies (Eds.), South African Astronomical Observatory, 57

Sterken C., 1994, in *The Impact of Long-Term Monitoring on Variable-Star Research*, NATO ARW, Eds. C. Sterken, M. de Groot, NATO ASI Series C, 436, 1 Kluwer Academic Publishers

Sterken C., Manfroid J., Anton K., et al., 1993, A&AS 102, 79

Sterken C., Manfroid J., Beele D., et al., 1995, A&AS 113, 31

Stoy R.H., 1959, Mon. Not. Astron. Soc. South Africa 18, 48

van Hoof A., 1975, Inf. Bull. Var. Stars No. 992

Vondrák J., 1969, Bull. Astron. Inst. Czechosl. 20, 349

Vondrák J., 1977, Bull. Astron. Inst. Czechosl. 28, 84

Waelkens C., 1991, A&A 246, 453

Waelkens C., Rufener F., 1985, A&AS 152, 6

Zboril M., North P., Glagolevskij Yu.V., Betrix F., 1997, A&A 324, 949