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An abrupt decrease in the rotational period of the chemically peculiar magnetic star CU Virginis

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Abstract. Spectroscopic and photometric observations of the chemically peculiar star CU Vir over 40 years show that the period of variations decreased by 0.005 % between 1983–1987. The assumption of the rigid rotator model for this star implies an abrupt change of the rotation rate. We find no spectroscopic evidence that the star is a close binary, ruling out a possibility that the period decrease is caused by the mass exchange.

Key words: stars: chemically peculiar – stars: variables: other – stars: rotation – stars: individual: CU Vir

1. Introduction

CU Virginis (HD 124224, HR 5313) is one of the best studied Magnetic Chemically Peculiar (MCP) stars belonging to the Si-group. It shows light, spectrum and magnetic field variations with one of the shortest periods among the CP stars. The first photometry of CU Vir was made by Hardie (1958) who confirmed the period of spectroscopic variations P=$0\overset{d}{.}52067$ previously reported by Deutsch (1952). All subsequent spectroscopic and photometric observations up until 1985 (see Table 2 for references) appeared to follow the same period. After 1985, the situation changed. First, Adelman et al. (1992) performed a period analysis of CU Vir UBV and *uvby* photometry from 1955 to 1989 and found a satisfactory fit of the data with a constant period of $0\overset{d}{.}5206800$. However, the authors mentioned an existance of the small phase shifts between some data sets. Pyper (1994, 1997), on the basis of her photometric observations from 1987-1996, found an increasing phase shift of the light minima after 1985 (Fig. 1) . At the same time the shapes of the light curves remained essentially unchanged. Pyper found that the 1987-1996 observations did not fit the period of Adelman et al. (1992), but were better fit by a longer period of $0\overset{d}{.}5207030$. A similar phase shift was also found by Kuschnig et al. (in prep.) in their spectroscopic study of CU Vir. All these facts forced us to make new spectroscopic and magnetic field observations of CU Vir and to repeat a careful analysis of all available data from 1955 to present.

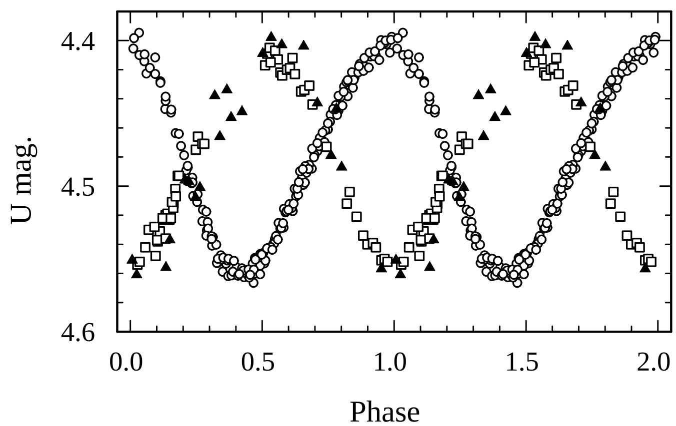

Fig. 1. Photometric U+u variations plotted with the period P1=$0\overset{d}{.}5206778$. Table 1, data set #1 are open squares; data sets #10-11 are closed triangles; and data set #26 are open circles. All data are normalized to correspond to Hardie's U magnitudes.

2. Observations and reduction

Table 1 contains information about all the photometric, spectroscopic and magnetic data that we used in our period analysis. We divided all data by years; the JD range of each observational run is in the second column of Table 1. The number of observations is given in the fourth column. We present below our new observations together with a short description of the previous observational data.

2.1. Photometry

The photometric observations represent the most extensive data sets. The new Strömgren four-color photometric data were obtained with the Four College Automatic Photometric Telescope (FCAPT) in 1991-1997. Both the telescope and the reduction procedure are discussed by Pyper et al. (1993). The data are too

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Table 1. Observational data sets used in the paper

Set No	JD(2400000+)	Data type	N	Reference
1	35178-35278	UBV	54	Hardie (1958)
2	38843-39276	$V_{\rm r}$: $H\gamma$	16	Abt & Snowden (1973)
3	39914-40023	UBV	95	Blanco & Catalano (1971)
4	40019-40379	W_λ: $H\gamma$, Si II 3862, 4128-31, 4201	25	Krivosheina et al. (1980)
5	41444-41459	UBV	11	Winzer (1974)
6	39506-42879	W_λ: Si II 4128-31, 4201, He I 4026, 4471	20	Hardorp & Megessier (1977)
7	42432-42616	uv photometry	8	Molnar & Wu (1978)
8	42851-43651	B_{eff}	14	Borra & Landstreet (1980)
9	43245-43323	W_λ: He I 4026	69	Pedersen (1978)
10	44338-44746	$uvby\beta$	12	Pyper & Adelman (1985)
11	45441-45478	$uvby\beta$	11	Pyper & Adelman (1985)
12	45386-45391	W_λ: He I 4026	9	Hiesberger et al. (1995)
13	46101-46811	W_λ: Si II 6347	14	Hatzes (1988)
14	46451-46455	W_λ: Si II 4128-31	5	Bohlender & Landstreet (priv. comm.)
15	46906-46985	UBV	33	P10 1987
16	47158-47261	UBV	171	P10 1988
17	47258-47307	β-index	25	Musielok et al. (1990)
18	47520-47702	UBV	127	P10 1989
19	48368-48432	uvby	16	FCAPT 1991
20	48719-48810	uvby	48	FCAPT 1992
21	49115-49165	uvby	144	FCAPT 1993
22	49445-49549	uvby	149	FCAPT 1994
23	49510-49519	W_λ: He I 4471	19	Kuschnig et al. (in prep)
24	49798-49806	$V_{\rm r}$: $H\delta$; W_λ: $H\delta$, Si II 4128-31, 4201	19	Kuschnig et al. (in prep.)
25	49797-49906	uvby	268	FCAPT 1995
26	50122-50241	uvby	305	FCAPT 1996
27	50547-50574	uvby	119	FCAPT 1997
28	49470-49499	W_λ: Si II 6347	7	Table 2 (1994)
29	50133-50255	W_λ: Si II 6347	33	Table 2 (1996-1997)
30	50243-50521	B_{eff}	14	Table 4 (1996-1997)

extensive to be printed, so they are given in Table 5 in electronic form.

From previously published photometric observations only one set made in 1964-66 by Abuladze (1968) was not included because of extremely large dispersion of the observational points. From uv-set #7 (hereafter "set #" refers to Table 1), we used only the photometry in the 3330 Å spectral band which is close to the U and u bands.

There is a good set of uvbyβ photometric observations made in May 1974 (Weiss et al. 1976), but their data are not available as they are published only as plots.

2.2. Equivalent widths and radial velocity measurements

New spectroscopic observations of CU Vir were made in June 1994 and in March – May 1997 at the coudé spectrograph of the 2.6 m telescope of the Crimean Astrophysical Observatory with the CCD detector attached. Some of the observations were made with the Zeeman analyzer using the Stokesmeter (Plachinda et al. 1993). The observed spectral region, 6325 – 6385 Å contains two strong Si II lines. All spectra were taken with a linear reciprocal dispersion of 2.5 Å mm^{-1} and corresponding spectral resolution of about 0.2 Å. The signal-to-noise ratio were in the range 150 – 300. Magnetic measurements will be described below.

The reduction of the spectra was made using the software "SPE" written by S. Sergeev at the Crimean Observatory. The reduction procedure includes the night sky subtraction, flat field correction, normalization of spectra to the continuum, cosmic ray subtraction by visual inspection of the spectra and wavelength calibration.

The heliocentric Julian dates of the midpoints of the exposures, and equivalent widths of the Si II λ 6347 line are given in Table 2.

The previous spectroscopic observations consist of equivalent widths and radial velocity measurements. The latter were measured for hydrogen lines by Abt & Snowden (1973) and by us using spectra obtained in 1994 at Observatoire de Haute Provence (kuschnig et al, in prep.). Radial velocities were measured for the center of gravity of the $H\beta$ line core and are given in Table 3 together with the heliocentric Julian dates. The typical rms is about 1 km s^{-1}.

For the period analysis we used the equivalent widths of the Si II lines because they usually vary in phase with the light variations. Equivalent widths and radial velocities of He I and hydrogen lines, and β-photometry were used as a final check

Table 2. Journal of spectroscopic observations of CU Vir made at the Crimean Astrophysical Observatory in 1994-1997.

JD(2400000+)	W_λ: Si II 6347, mÅ
49470.295	335
49470.320	281
49471.356	305
49472.377	363
49472.393	326
49496.344	301
49499.266	509
50133.549	491
50133.566	509
50133.583	501
50134.557	490
50134.571	503
50134.603	496
50174.451	315
50174.479	351
50176.345	409
50191.418	487
50191.433	474
50191.433	461
50210.412	361
50210.425	380
50233.277	295
50233.317	337
50233.358	417
50233.454	493
50233.472	507
50233.512	508
50253.288	541
50253.303	538
50253.363	513
50253.378	463
50254.297	507
50254.311	525
50254.356	520
50254.371	525
50255.275	462
50255.289	470
50255.305	490
50255.373	503
50255.387	518

on the validity of new periods. For observational set #4 only plots of the equivalent widths are published by Krivosheina et al. (1980), but we have all the information in digitized form which is available through e-mail request to Ryabchikova. We also corrected typographic errors in the JD's for set #12.

We excluded the spectroscopic data by Peterson (1966) from our analysis because the small number of points together with the quality of the equivalent widths measurements on photographic plates did not allow us to properly determine the maxima and minima of the spectral variations.

Table 3. Radial velocities, measured by $H\beta$ line.

JD(2400000+)	$V_{\rm r}$, km s^{-1}
49798.489	-13.11
49798.622	-10.97
49799.434	-2.36
49799.575	-22.50
49799.612	-8.18
49800.410	-1.40
49800.502	-0.97
49800.599	-6.86
49801.412	-1.93
49802.415	-2.22
49803.438	-3.75
49804.444	-9.11
49804.468	-8.65
49806.413	-12.00
49806.435	-13.58
49806.452	-13.86
49806.469	-16.25
49806.484	-16.33
49806.500	-15.36

2.3. Magnetic field measurements

The effective magnetic field is a component of the magnetic field vector along the line of sight, averaged over the stellar disk. We have two sets of effective magnetic field measurements separated by 20 years (data sets #8 and #29). The first set was made with a photoelectric polarimeter which measured the circular polarization in the wings of the $H\beta$ line (Borra & Landstreet 1980).

New observations of the effective magnetic field were carried out with the Stokesmeter and CCD detector in 1996-1997 using the strong Si II $\lambda\lambda$ 6347.09 and 6371.36 lines with effective Landé factors 1.167 and 1.333, respectively. The Stokesmeter is mounted in front of the entrance slit of the coudé spectrograph of the 2.6 m telescope. It consists of two rotating achromatic quarterwave plates and a plate of Iceland spar between them to separate right- and left-circular polarization spectra. The typical exposure time for magnetic measurements was about one hour which corresponds to 0.08 of the rotational period.

Synthetic spectrum calculations show that both Si II lines are practically free of blends in the CU Vir spectrum. Unfortunately silicon has a nonuniform distribution on the stellar surface, therefore the effective magnetic field measured with Si II lines may differ from that measured with the hydrogen polarimeter. As was shown by Kuschnig et al. (in prep.), the silicon distribution on the surface of CU Vir does not have a very complex structure. It consists of one depleted spot and a larger zone rich in silicon, so we do not expect there to be significant differences between magnetic measurements made with the Si II lines and the $H\beta$ line. We measured a shift between the centers of gravity of the right- and left-circular polarization line profiles and then converted it to the effective magnetic field.

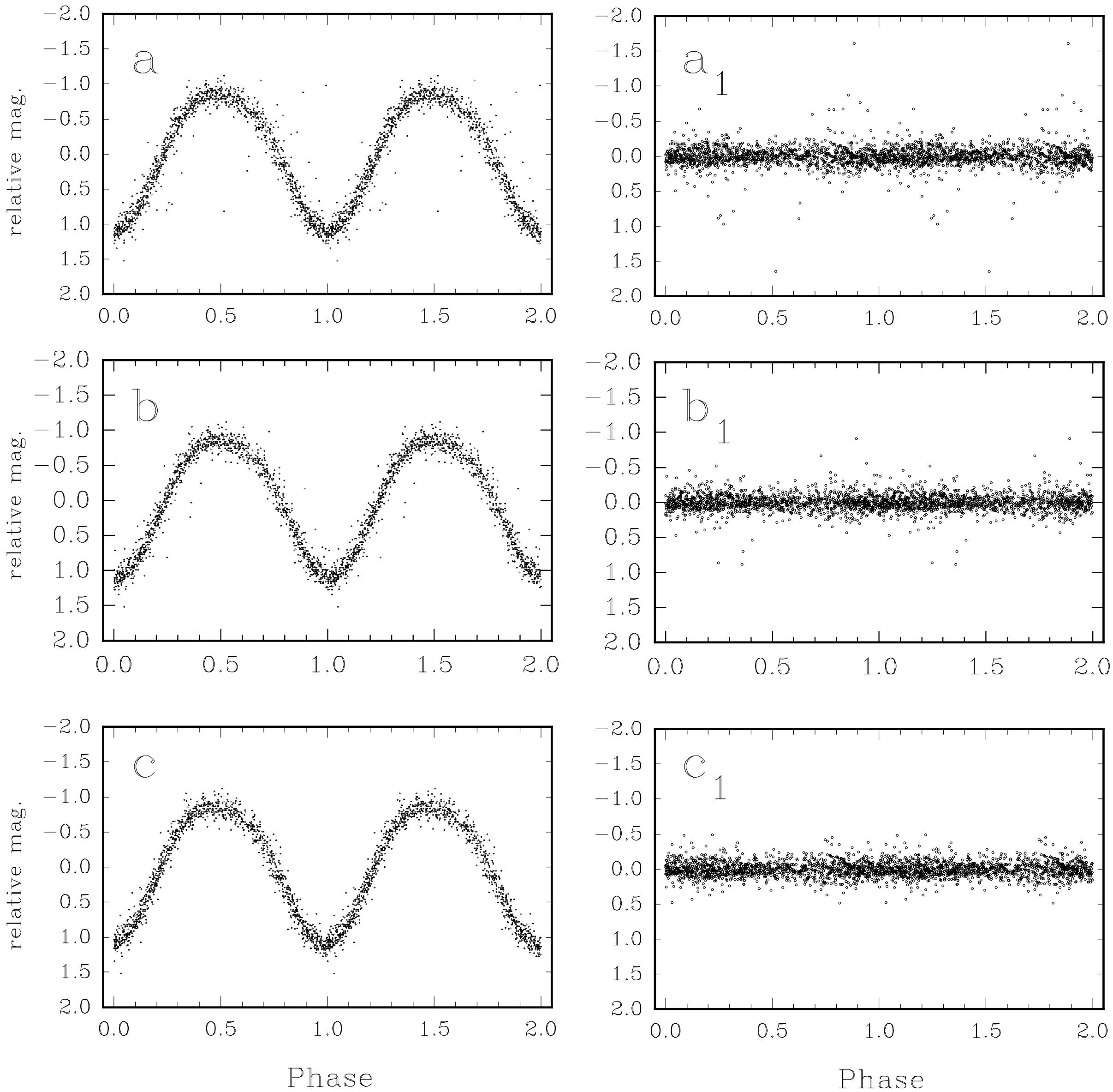

Fig. 2a–c1. Photometric variations vs. phases calculated with three different period approaches. **a** with a constant period $0^{\rm d}.52070281$; **b** with a linearily changing period (Sect. 3.1); and **c** with two periods constant periods P1=$0^{\rm d}.5206778$ and P2=$0^{\rm d}.52070308$. In **c**, combined B+b (**b**) normalized magnitudes are from Table 1, data sets #1, 3, 5, 10, 11 (P1) and data sets #15, 16, 18-22, 25, 26 (P2). Right panels show the deviations from the mean curves.

New measurements of the effective magnetic field are presented in Table 4. Each value is the result of averaging both Si II lines. The rms of the magnetic measurements is ± 185 G.

The low accuracy of the magnetic measurements in CU Vir does not permit them to be used in a period search. Since the two data sets are well-separated in time, we mainly consider them as additional support for our period solutions.

3. Period search

Because the photometric sets provide the largest part of the observational data and usually are more accurate than the spectroscopic data from the point of view of the dispersion, they were given a higher priority in the period analysis.

The light curves of CU Vir have slightly different amplitudes and shapes in different spectral bands. Therefore we first normalized all data by their amplitudes to obtain homogeneous data sets. The same procedure was done with the spectroscopic observations. We then divided our data into two groups: U+u+W_λ(Si II 6347) and B+b+W_λ(Si II 4128-31, 4201). The intensity variations of the Si II 6347 line is closer in shape to the U+u and possibly the y light curves while those of Si II 4128-31 have a similar shape to the B+b light curve. Three different approaches were used for period analysis, discussed below.

Table 4. Journal of effective magnetic field observations of CU Vir made at the Crimean Astrophysical Observatory in 1994-1997.

JD(2400000+)	$B_{\rm eff}$, G
50243.308	-160
50243.334	-271
50243.362	-222
50243.391	-596
50243.420	-417
50487.545	-136
50487.573	-148
50487.610	-551
50520.521	-944
50520.548	-443
50520.567	94
50520.589	132
50520.611	410
50558.333	-518
50566.336	-1084
50566.360	-724
50566.382	-263
50572.277	510
50584.282	1258
50584.305	1052
50584.325	1104

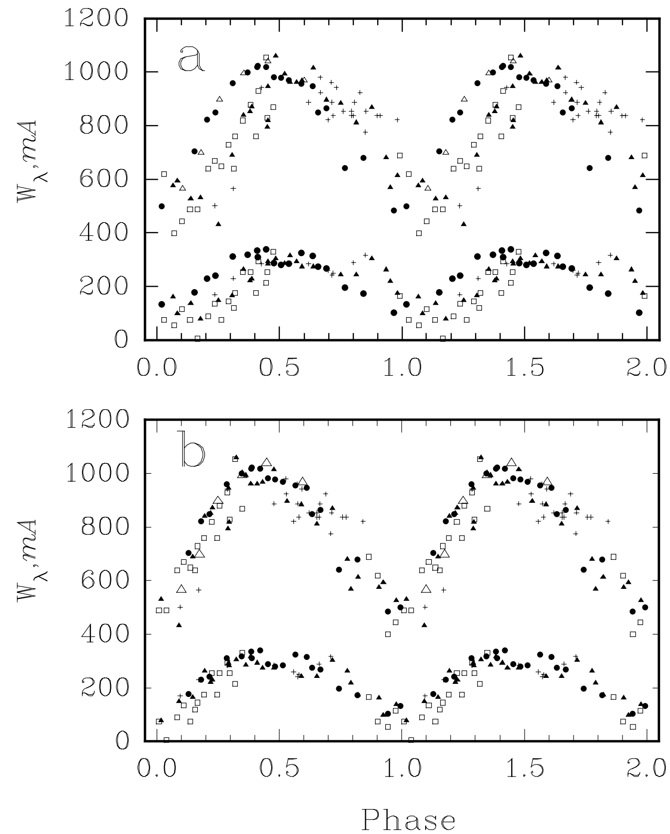

Fig. 3a and b. Spectroscopic variations vs. phases calculated with the linearly changing period (**a**) and with two constant periods (**b**) (see Fig. 3). W_λ(Si II 4128-31 and 4201) are plotted; Table 1 data sets #4 and 6 (P1) are represented by filled triangles and open squares, respectively; and data sets #14 and 24 (P2) by open triangles and filled circles, respectively.

3.1. Constant period

First we searched for a constant period over the whole range of the photometric data using Stellingwerf's (1978) method. The best period is $0\overset{\rm d}{.}52070281\pm0.00000016$ and it is defined mainly by the recent more extensive photometric data sets. Fig. 2a represents a plot of all data with the constant period (left panel). The right panel shows a plot of the deviations from the mean curve. The rms is 0.168. One may easily see that a few data sets do not fit at all with this period. Note, the the error in the period determinations is mainly defined by the entire time interval of the data used, therefore it is smallest for the constant period because the time interval is the largest, more than 40 years.

3.2. Linearly changing period

The search for the linearly changing period was done using the method by Cuypers (1986) realized in Pelt's (1992) package. The best fit to all our data was achieved with the following ephemeris:

$$JD(\mathrm{B\,light\,max}) =$$

$$2435178.9200 + \frac{0\overset{\rm d}{.}52066138}{1 + 0\overset{\rm d}{.}52066138 \cdot S \cdot (t - t_0)},$$

where t_0=2435178.92 and S$=-5.73 \cdot 10^{-9}$. This corresponds to $\dot{\rm P}\approx 1.5 \cdot 10^{-9}$ days per cycle. A plot of all photometric data with this period is shown in Fig. 2b. Again, the right panel of Fig. 2b shows deviations of the points from the mean curve with the rms being 0.127. The linearly changing period shows practically the same scatter in the final plot for the photometry as does a solution with 2 different periods for all but the # 5 data set, which is definitely shifted by about 0.2 of the period. This shift cannot be explained by any incorrectness of the reduction or normalization procedure because Winzer's data were always included in any period search by previous investigators, and showed a very good phase agreement with all photometric and spectroscopic variations reported before 1985.

Moreover, when we plot the equivalent width data with the linearly changing period (Fig. 3a) we obtain noticible phase shifts between the different data sets.

3.3. Two periods solution

First we constructed an O-C diagram with the ephemeris,

$$JD(\mathrm{B\,light\,min}) = 2435178.6541 + 0\overset{\rm d}{.}5206778 \cdot E$$

The period was estimated by Pyper (1994) as the one that best fit the photometric data from 1955-1984. Then we measured the phases of the maxima for each data set; they are plotted in Fig. 4a and b. The phases of the maxima and minima were found by a sinusoidal fit to the observational points. It is seen that our data can be fit by two straight lines

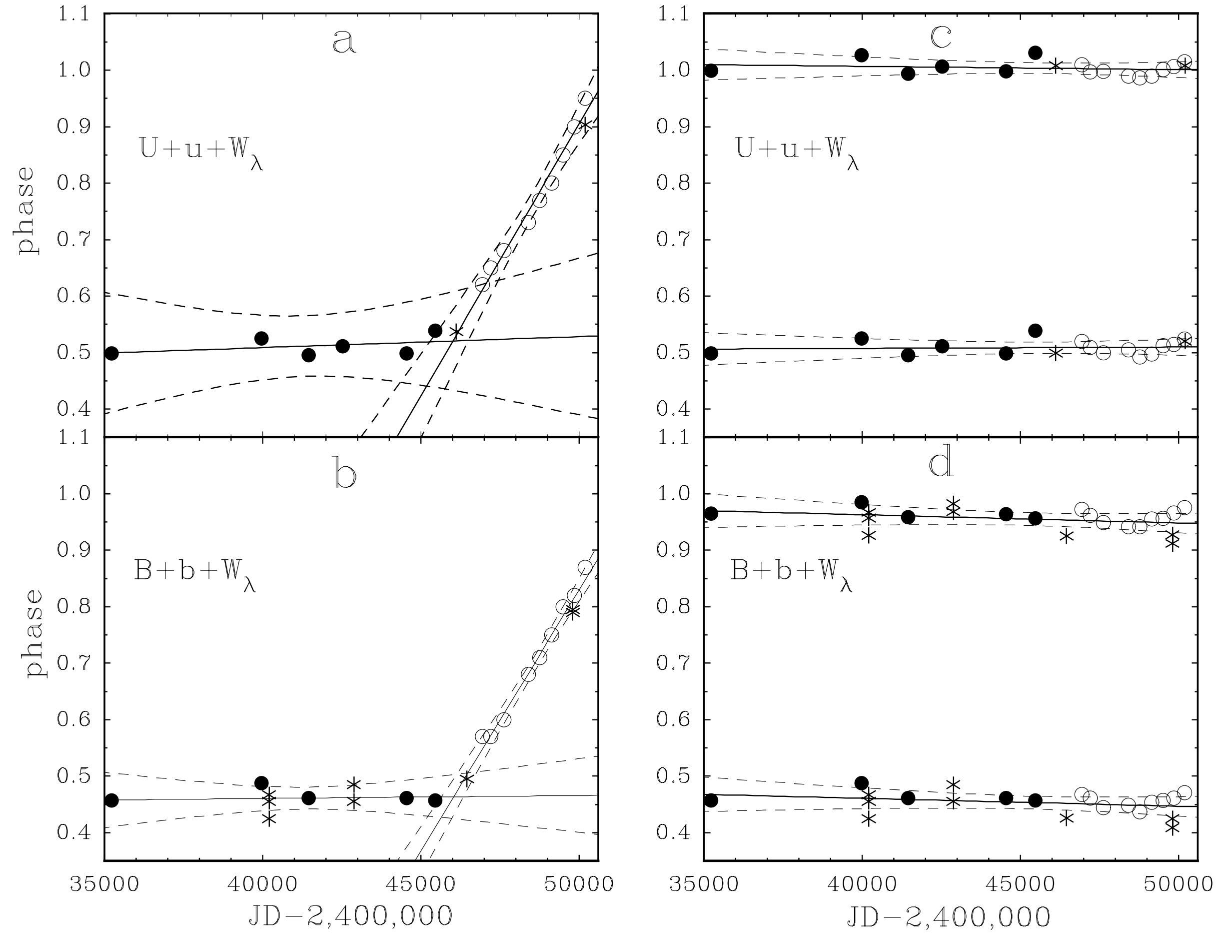

Fig. 4a–d. O-C diagrams for CU Vir with one constant period P1=0$^{\rm d}_{.}$5206778 (**a**,**b**), and with two constant periods, P1 and P2=0$^{\rm d}_{.}$52070308 (**c**,**d**). Photometric observations before 2446000 are shown by filled circles, those after 2446000 are shown by open circles. Spectroscopic observations are shown by asterisks; in (a,c) W_λ(Si II 6347) are plotted, in **b** and **d** W_λ(Si II 4128-31, 4201) are plotted. In **a** and **b**, the dashed lines represent 99% confidence levels. In plots **c** and **d** the upper line represents light and spectrum minima, and the lower line represents maxima.

that intersect near epoch JD=2446000 (1985). Period analyses perfomed separately for two groups of data before and after 2446000 by Stellingwerf's (1978) method resulted in two different periods: 0$^{\rm d}_{.}$5206778±0.00000020 (JD<2446000) and 0$^{\rm d}_{.}$52070308±0.00000019 (JD>2446000). The O-C diagram obtained with two periods is shown in Fig. 4c,d for maxima and minima and for different spectral bands. The U+u and B+b light curves give slightly different phases of minimum, therefore we averaged them and finally obtained the following ephemeris which fit all photometric and spectroscopic observations for 40 years (more than 29000 rotations) of the observations:

$$\mathrm{JD(U,B\ light\ min)} = 2435178.6417 + \begin{array}{l} 0^{\rm d}_{.}5206778 \cdot E \quad (JD < 2446000) \\ 0^{\rm d}_{.}52070308 \cdot E \quad (JD > 2446000) \end{array}$$

Those who would like to use the maximum as a starting phase can use the following moment JD(B light max)=2435178.9025.

Combined B+b light curves obtained with the above two periods for all photometric observations are plotted on Fig. 2c (left panel). The deviations from the mean curve are shown in the left panel of Fig. 2c. The rms is 0.114. According to the Fisher test the rms-values in all three approaches for the period search are different with 99.3% confidence level. Combined Si II intensity variations are plotted on Fig. 3b ($\lambda\lambda$ 4128-31, 4201). Note that we slightly shifted the equivalent widths from different spectroscopic sets by constant values. These shifts may arise from different treatments of the continuum as well as from different registration (CCD, Reticon, photographic plates), and have no influence on the period search procedure. Fig. 5 displays combined curves of the effective magnetic field variations (a); He I 4026 (b); and He I 4471 (c) line intensity variations. Here we did not need any vertical shifts to combine the spectroscopic data. Fig. 6 represents the hydrogen line equivalent width variations (a); variations of the β-index (b), and radial velocity variations (c).

3.4. Does a period change still continue?

Continuing observations with the FCAPT are being made in order to see whether the period of CU Vir continues to change or has stabilized. A period search of the P10 data (data sets #15, 16, 18) using the Scargle (1982) algorithm, yielded a slightly shorter period of 0$^{\rm d}_{.}$5206987. O-C diagrams of the P10 and FCAPT data using this period are plotted in Fig. 7. Investigators of eclipsing binary light curves (e.g., Cherewick & Young 1975) have found that a continually varying period results in an ephemeris

$$JD = JD_0 + P_0 \cdot E + (\alpha/2) \cdot E^2,$$

where α is the rate of change of the period ($\mathrm{d\,cyc}^{-1}$). If the FCAPT data for 1997 are included, least squares quadratic polynomial regressions of the u and b data result in $\alpha = 1.97 \cdot 10^{-9}$ and $\alpha = 1.88 \cdot 10^{-9}$, respectively. At present, the residuals of these fits are only slightly better than those for a linear regression on the same data. There is an additional indication of the continually changing period in the O-C diagrams (Fig. 4), where the open circles do not lie on the straight line but rather lie on the parabolic line, which is typical for a changing period. Several more years of observations will be necessary to determine whether the period of CU Vir is still changing.

4. Summary

Figs. 2-6 clearly show that we succeeded in fitting all available observational data obtained for CU Vir for more than 40 years with a combination of two different periods. This is not meant to imply that the period changed instantaneously but that it changed in a time period that is short compared to the more than 40 years of observations of CU Vir. A crude estimate of the speed of the period change gives $\dot{\mathrm{P}} \geq 10^{-8}$ days per cycle. The abrupt change in period near JD 2446000 (1985) raises some difficult questions about the cause of such a change. Since all successful models of the variations of CP stars use rotation as their primary cause, our results imply that CU Vir abruptly slowed its rotation at this time. The problem is in how this could be accomplished, since this implies a sudden loss of angular momentum unprecedented in the study of CP stars. In fact, the only stars that show such effects are close binaries where mass exchange is taking place. The spectroscopy shows no clear evidence that CU Vir is a close binary. All radial velocity variations including those of the hydrogen line cores can be explained in the frame of the oblique rotator model with inhomogeneous abundance and temperature distributions over the stellar surface (Ryabchikova 1991). Abt & Snowden (1973) showed that any solution of the radial velocity variations originating from binary system orbits leads to an estimate for the inclination angle i $\leq 7^o$. If this were the case, the equatorial rotational velocity would have to be larger than 1000 $\mathrm{km\,s}^{-1}$. Our new binary system solution gives a slightly larger inclination, i $\leq 14^o$, but even in this case the equatorial rotational velocity, 650 $\mathrm{km\,s}^{-1}$ still exceeds the critical rotational velocity for main sequence stars.

Wolff (1981) considered various braking mechanisms for CP stars and found that loss of angular momentum due to accretion from a surrounding nebula takes place on time scales of about 10^8 yr. Likewise, mass loss due to an intense stellar wind can result in loss of angular momentum over similar time scales. Thus, both of these mechanisms act over time scales many orders of magnitude greater than is observed for CU Vir. These mechanisms might explain a slow change of the period which possibly is presently occurring. Additionally, a stellar wind could be detected by spectral signatures, which have not been observed. However, Leone et al. (1994) found radio radiation from CU Vir at 6 cm. Later Leone et al. (1996) observed the radio spectrum at 1.3, 2, 6 and 20 cm. They interprete their observations as gyrosynchtron emission coming from the circumstellar regions which are close to the star. This could be the result of a stellar wind. In this case, the following scenario can be considered as a possible explanation of the rapid change in the rotational period. A weak stellar wind exists in CU Vir. The matter is trapped by the magnetosphere of the star so no significant mass loss occurs. When the trapped matter exceeds

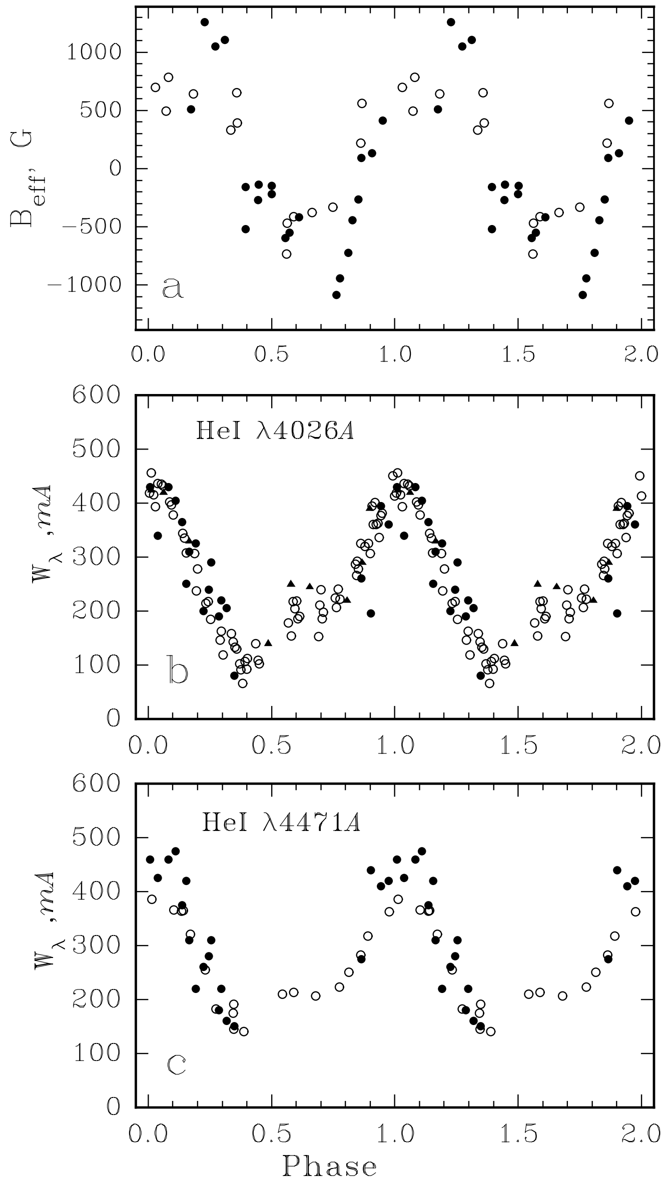

Fig. 5a–c. Combined effective magnetic field variations (**a**); W_λ(He I 4026) (**b**); and W_λ(He I 4471) (**c**). **a** Table 1, data sets #8 (P1) and 30 (P2) are represented by open circles and by filled circles, respectively. **b** Data sets #6 and 9 (P1) and 12 (P2) are represented by filled circles, open circles, and filled triangles, respectively. **c** Data sets #6 (P1) and 23 (P2) are represented by filled circles and open circles, respectively.

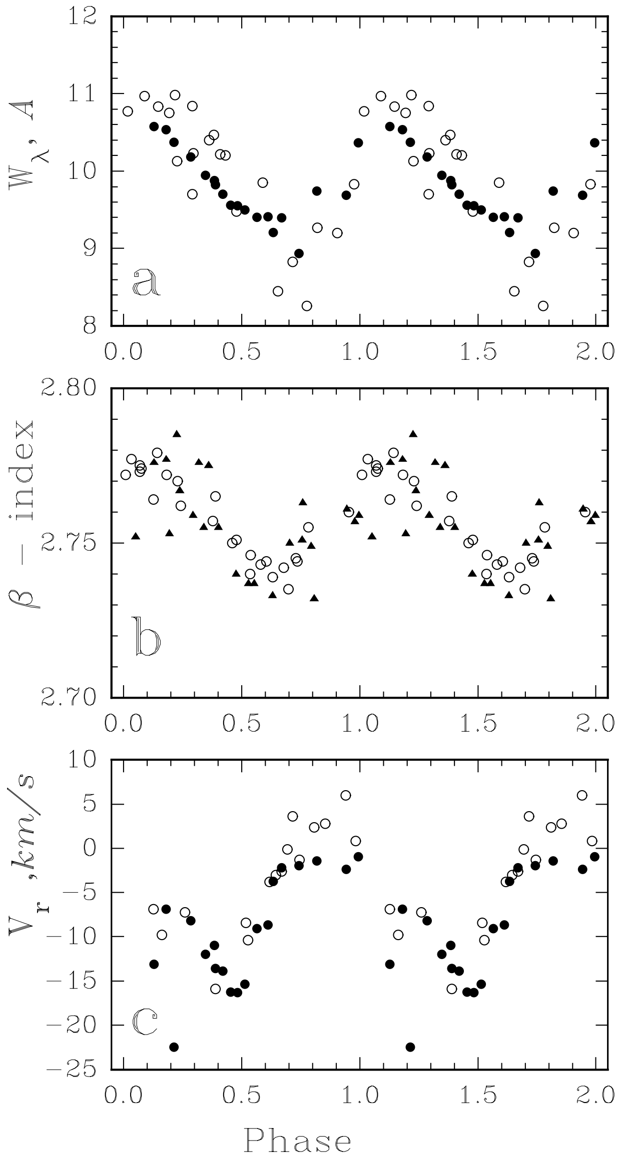

Fig. 6a–c. Combined hydrogen line variations. **a** Normalized W_λ of Balmer lines vs. phases. Table 1, data set #4, $H\gamma$ (P1) are open circles; and data set #24, $H\delta$ (P2) are filled circles. **b** β-index vs. phase. Table 1, data sets #10-11 (P1) are filled triangles; and data set #17 (P2) are open circles. **c** Radial velocity vs. phase. Table 1, data set #2 (P1) are open circles, and data set #24 (P2) are filled circles.

some critical mass, it may be thrown off, and the magnetic field works as a trigger mechanism.

Another possibility is migrating spots, since the periodic variations of the CP stars are thought to be due to the non-uniform distribution of chemical abundances in their atmospheres combined with rotation. However, none of the dozens of CP stars that have been relatively well observed over time intervals of several decades have shown any evidence of such spot motion. Again, the abruptness of the period change is difficult to explain with such models. Kuschnig, et al. (1997) discuss the atmospheric models of CU Vir in more detail.

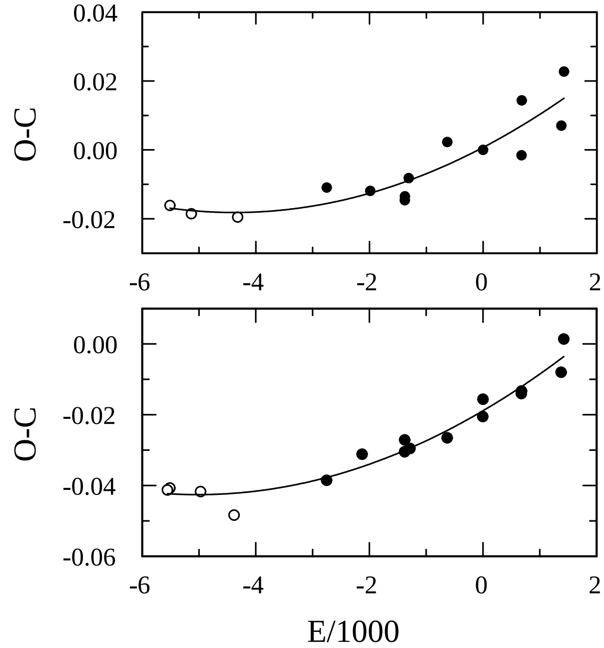

Fig. 7a and b. O-C diagrams, calculated with P=0$^{\rm d}$.5206987 for the CU Vir U+u (**a**) and B+b (**b**) minima from the P10 UBV (Table 1, data sets #15, 16, 18) and FCAPT uvby (data sets #19-22, 25-27) data. In both plots, the P10 data are open circles and the FCAPT data are closed circles. The solid lines are least squares quadratic regressions.

Shore & Adelman (1976) proposed that CP stars that were not in binary systems could experience free body precession due to a distortion in the shape of the star by the magnetic field. The precession periods are predicted to be about 5 to 10 years for the shortest period MCP stars (e.g., CU Vir). Changes in both the shapes of the light curves and the times of maxima and minima are predicted. However, any precessional changes must eventually be periodic in nature and we have no evidence for that so far, although the period may still be changing (see Sect. 3.3). Thus, if a precessional period does exist it must be on a longer time scale than is predicted and there is the additional problem of the apparently constant period prior to 1984. Also, the shapes of the light curves appear to be very stable over the more than 4 decades of observations of CU Vir. It is hoped that several more years of observations will help to clarify what is happening with the period of CU Vir.

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