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β Centauri: An eccentric binary with two β Cep-type components*

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Abstract. We introduce our observational study of the orbital motion and the intrinsic variability of the double-lined spectroscopic binary β Cen. Using 463 high signal-to-noise, high-resolution spectra obtained over a timespan of 12 years it is shown that the radial velocity of β Cen varies with an orbital period of 357.0 days. We derive for the first time the orbital parameters of β Cen and find a very eccentric orbit ($e = 0.81$) and similar component masses with a mass ratio $M_1/M_2 = 1.02$. β Cen forms a challenge for current evolution scenarios in close binaries and it is also a puzzle how a massive binary with such a large eccentricity could have formed in the first place. Both the primary and the secondary exhibit line-profile variations. A period analysis performed on the radial velocity variations of the primary after prewhitening the orbital motion leads to the detection of at least 3 pulsation frequencies while the star does not show any periodic photometric variability.

Key words. stars: binaries: spectroscopic – stars: variables: β Cep – stars: individual: β Cen

1. Introduction

The bright star β Cen (HD 122451, B 1 III, $m_V = 0.6$) has been known to be variable in velocity since the beginning of the twentieth century. Breger (1967) was the first to investigate the true nature of this variability. From his 52 spectroscopic data, covering a timespan of six months, he found a variation with a short period between 3 and 3.5 hours superimposed on a long term variation of the order of a year. In combination with the early B-type character, Breger suggested that β Cen is a β Cep star in a binary system.

In order to determine the orbital period more accurately Shobbrook & Robertson (1968) added the data of Breger to their 22 new spectra taken over four nights in 1967. They found 3 possible values for the orbital period: 236, 352 and 700 days of which they indicated a period of 352 days as the most probable.

Observations with the Narrabri Stellar Intensity Interferometer (Hanbury Brown et al. 1974) suggested that β Cen may be a binary system with components of approximately equal brightness. Finally, in 1999, Robertson et al. reported further investigation of β Cen which conclusively demonstrates binarity: interferometric observations with the 3.9 m AAT (Anglo-Australian Telescope) show two components having similar brightness and the 50 spectrograms taken in May 1988 by C. Waelkens reveal β Cen to be double-lined. Robertson et al. also report 5.59 and 6.28 c d^{-1} as candidate intrinsic frequencies of the primary.

In order to determine the orbital parameters and the pulsational frequencies we have intensively monitored β Cen in the past three years. The analysis of this data is the subject of this paper. We start with a description of the observations and a short explanation of the data reduction process. After taking a brief look at the reduced data, we discuss the results of our orbital determination in the third section. Section 4 presents a frequency analysis of the intrinsic pulsation of the primary. We end with some concluding remarks and our future plans in Sect. 5.

2. The observations and data reduction

β Cen was frequently observed with the CAT/CES and Euler/CORALIE combinations at La Silla during the period January–June 1998 and October 1999–August 2000. This resulted in 413 new high-resolution spectra: 177 CAT data (average $S/N = 700$) and 236 CORALIE data (average $S/N = 170$). We also included 50 CAT spectra of

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* Based on observations obtained with the ESO CAT/CES telescope and the Swiss Euler/CORALIE telescope, both situated at La Silla, Chile.

Table 1. Logbook of the observations of β Cen. N stands for the number of observations carried out during the given campaign, $\triangle T$ is the average integration time during that run (seconds), and S/N denotes the signal-to-noise ratio.

Date	Observer	N	$\triangle T$	Instrument	S/N
May 88	C. Waelkens	50	300	CAT/CES	400–1000
January 98	P. De Cat	8	24	CAT/CES	300–750
February 98	J. De Ridder	7	20	CAT/CES	250–550
March 98	C. Schrijvers	103	100	CAT/CES	250–1050
May 98	C. Schrijvers	28	240	CAT/CES	450–1000
June 98	C. Schrijvers	31	200	CAT/CES	550–1050
October 99	B. Vandenbussche	8	93	Euler/CORALIE	80–125
February 00	K. Uytterhoeven	105	50	Euler/CORALIE	160–250
April 00	K. Uytterhoeven	36	15	Euler/CORALIE	100–140
June 00	T. Reyniers	25	70	Euler/CORALIE	80–200
July 00	T. Reyniers	23	50	Euler/CORALIE	160–200
August 00	T. Maas	39	60	Euler/CORALIE	110–200

β Cen taken earlier during five consecutive nights in May 1988. The observation campaigns are listed in Table 1.

The observed spectral domain of the CAT data was the one centered on the Si III triplet at 4552.6, 4567.8, 4574.8 Å. During most of the CAT observing runs, we observed the three absorption lines of the triplet. The early campaign in 1988 was performed with a Reticon, leading to a resolving power of 100 000. For all the other runs until May 1998 we obtained spectra with a resolving power between 60 000 and 70 000. Of these spectra we could not use the λ 4575 Å line due to vignetting. The campaigns of May–June 1998 were performed with the very long camera so that we could only measure the two reddest lines of the triplet, with a resolving power of 160 000.

The reduction of the raw CAT data to one-dimensional normalised spectra was done with the ESO-MIDAS software package. We corrected the zero level of the CCD by subtracting a mean bias value in order to remove the background radiation. The variation of pixel sensitivity was eliminated by dividing each spectrum by a mean flatfield obtained by a quartz lamp. In the next step a wavelength calibration was performed by means of Th-Ar spectra. We divided the rebinned spectra by the response curve for their continuum, obtained by a spline function, to set the continuum at unity. We next carried out a barycentric correction. Finally all irregularities, such as ghosts and spikes, were removed from the spectra by visual inspection.

The Swiss 1.2 m Ritchey-Chrétien Euler telescope is equipped with the high-resolution échelle spectrograph CORALIE and a 2k by 2k CCD camera with 15 μm pixels. The resolving power amounts to 50 000 and the total wavelength range is 3900 Å–6800 Å. The CORALIE spectra are extracted on-line following a standard échelle reduction procedure. The wavelength calibration is obtained by the use of a Th-Ar calibration lamp, whose spectra are simultaneously recorded in the sky orders. For a full description of the reduction scheme we refer to Baranne et al. (1996).

The integration times of all the spectra were adapted to the atmospheric conditions and can be found in Table 1, as well as the S/N ratios. Visual inspection of our reduced data already clearly shows the double-lined character of β Cen, as found by Robertson et al. (1999) – see Fig. 1. Further on we will refer to the star producing the stronger and narrower SiIII lines as the primary and to the other star as the secondary. From the position of the lines caused by the secondary relative to those caused by the primary we roughly estimate the orbital period to be 356 days. The lines produced by the secondary stay about twice as long on the red side of those of the primary component as on the blue side. This indicates a highly eccentric orbit.

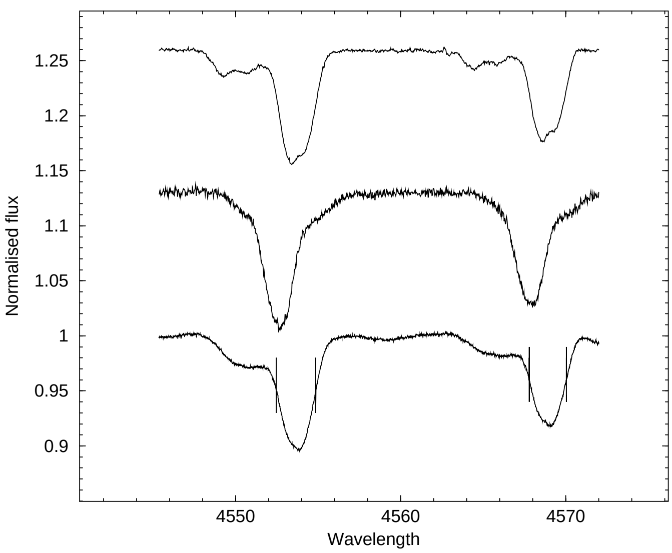

Fig. 1. The upper spectrum is an average of four CAT spectra taken on 13 March 1998 within a timespan of 33 min. It clearly shows subfeatures in the line profiles of both components. The middle spectrum is an average of 23 CORALIE spectra taken during the five consecutive nights 2–6 July 2000. It demonstrates the possibility to estimate the total line width of the profiles of the secondary. The lower spectrum is an average of 13 CAT spectra taken on one night in May 1988. The vertical lines denote the integration limits for calculation of the first velocity moment of the first and second line of the SiIII triplet caused by the primary.

Table 2. The orbital parameters of β Cen determined by means of respectively the SiIII line at λ 4552 Å and at λ 4567 Å.

Orbital element	λ 4552 Å	λ 4567 Å
$P_{\rm orb}$ (days)	357.01 ± 0.02	357.03 ± 0.02
v_γ (km s^{-1})	10.6 ± 0.3	11.2 ± 0.2
K_1 (km s^{-1})	63.7 ± 0.3	64.2 ± 0.3
E_0 (HJD)	2451600.29 ± 0.06	2451600.21 ± 0.06
e	0.815 ± 0.001	0.813 ± 0.001
$a_1 \sin i$ (AU)	1.21 ± 0.01	1.23 ± 0.01
ω (degrees)	62.9 ± 0.5	62.6 ± 0.5
$f_1(M)$ ($M_\odot$)	1.86 ± 0.03	1.93 ± 0.03

Furthermore, we notice clear variations in the line profiles of both the primary and the secondary (see Fig. 1). This confirms the earlier speculation that also the secondary exhibits pulsations (Robertson et al. 1999).

3. Determination of the orbital parameters

3.1. Primary component

In order to determine the parameters of the orbit of the first component relative to the mass centre, we derived the radial velocities from both the λ 4552 Å and λ 4567 Å line of the primary. Because of the considerable line-profile variations due to pulsations, we decided to calculate the first velocity moment instead of a Gaussian fit. In order to reduce the interfering influence of the secondary's line as much as possible, we took integration limits for the first moment calculation corresponding to an intensity value of about 0.95 and 0.96 for respectively the first and the second line (Fig. 1).

The radial velocities derived from both SiIII lines are in good agreement with each other: they differ at most 7 km s^{-1} which is less than 5% of the total peak-to-peak variation.

We went on to search for periodicity in the radial velocities with the Lafler & Kinman method (1965) and the String length method (Burke et al. 1970). Both methods are suitable for data with a large variation on a short timespan in comparison with the total period (which is what we expected here, due to the high eccentricity). They both lead to a period of 357 days in the radial velocities derived from the first line as well as those derived from the second line.

Next, we applied the Léhmann-Filhés method (1894) for the orbital parameter determination with the period of 357 days as starting value. The results are listed in Table 2. The values obtained from the λ 4552 Å and λ 4567 Å line are compatible. We used the average of the radial velocities determined by means of the two first lines of the SiIII triplet to derive the most accurate estimates for the orbital elements. These are listed in Table 3.

We indeed find an orbit with a very large eccentricity of 0.81 and an orbital period of 357.0 days.

Table 3. The orbital parameters of β Cen derived from all the data listed in Table 1 (except May–June 1998).

$P_{\rm orb}$ (days)	357.02 ± 0.02
v_γ (km s^{-1})	10.9 ± 0.3
K_1 (km s^{-1})	63.9 ± 0.3
E_0 (HJD)	2451600.25 ± 0.06
e	0.814 ± 0.001
$a_1 \sin i$ (AU)	1.22 ± 0.01
ω (degrees)	62.8 ± 0.5
$f_1(M)$ ($M_\odot$)	1.89 ± 0.03
K_2 (km s^{-1})	65.4 ± 1.1
$a_2 \sin i$ (AU)	1.25 ± 0.02
$f_2(M)$ ($M_\odot$)	2.0 ± 0.1
M_1/M_2	1.02 ± 0.02

3.2. Secondary component

We subsequently made an effort to determine also the orbital elements of the secondary component relative to the mass centre. It was impossible to determine a (Gaussian) fit to the line of the secondary during most of the orbital phases. We therefore calculated the radial velocities of the second component with the following procedure:
1. Because the line caused by the secondary is much broader than this caused by the primary (see Fig. 1), it is possible to determine its width when the radial velocities of the two components do not differ much. We assume this width to be constant, which is a reasonable supposition because rotational line-broadening is dominant.
2. When the line produced by the secondary is on the blue (red) side of this of the primary, we could determine the centre of the line with the knowledge of its width and its left (right) limit at the continuum. The corresponding Doppler velocity is a good estimate for the radial velocity of the secondary because the orbital amplitude is much larger than the pulsational amplitude.

In order to determine the left and right limits of the line as accurately as possible, we applied the above method to "average" line profiles, not to individual spectra. The number of spectra considered to average out depended on the S/N ratio, on the timespan of the sub-datasets and on the orbital phase as determined from the primary component data. We obtained 27 radial velocity values in that manner using the first line of the SiIII triplet. The results of the Léhmann-Filhés method applied to the radial velocities of the two components, with a fixed period of 357.01 days, were considered for the additional orbital parameters of the secondary. For the primary's parameters we relied on the outcome of the Léhmann-Filhés method applied to the primary's radial velocities only, since the latter are much more accurately determined. A summary of the final orbital parameters is given in Table 3.

Figure 2 shows the resulting phase diagram. The full and dashed line represent the best fitting orbit of respectively the primary and secondary. The full line explains 98.5% of the variability present in the data. This is a very high percentage, taking into account that there is

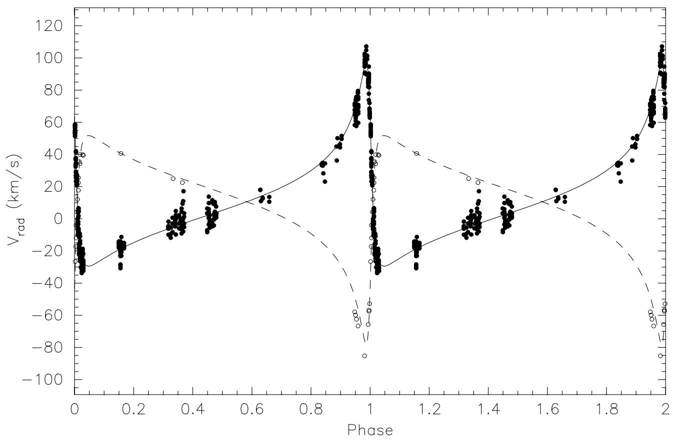

Fig. 2. The radial-velocity curves of the binary β Cen. The filled and open dots represent the observed radial velocities of respectively the primary and secondary component around the center of mass. The full and dashed line represent the best fitting orbit of respectively the primary and secondary, according to the parameters listed in Table 3.

still variability due to the pulsations of the primary in the first moment.

On the basis of the orbital parameters listed in Table 3 we find a mass ratio $M_1/M_2 = 1.02$. This result is in agreement with the similar brightness and effective temperature (Robertson et al. 1999) of the two components.

4. Intrinsic variability of the primary

To perform a frequency analysis of the intrinsic pulsation of β Cen we prewhitened the radial velocity data with the orbital solution presented in Fig. 2. We used two analysis methods: Stellingwerf's (1978) PDM (Phase Dispersion Minimisation) method and the Lomb-Scargle method (Scargle 1982). We started to search for frequencies in the interval [0,25] c d^{-1} with a frequency step of 10^{-3} c d^{-1}. Afterwards we zoomed in on the highest peaks using a frequency step of 10^{-5} c d^{-1}. In case of the PDM method we used the combinations 10 bins and 2 covers and 15 bins and 3 covers. Subsequent prewhitening was applied to determine the frequency spectrum. As stop criteria we used the false alarm test (Horne & Buliunas 1986) on the one hand and on the other hand the so-called $4\,S/N$ criterion (Breger et al. 1993). In the former case we considered the frequency as significant if the observed power exceeds the power level corresponding with a false alarm probability $p_o = 0.01$. In the latter case the noise level was assumed to be the average amplitude in an amplitude spectrum calculated with sampling interval $\Delta f = 5 \times 10^{-5}$ c d^{-1} in a domain around the suspected frequency.

We started our analysis with the second line of the considered SiIII triplet because this line was observed more frequently than the first line (463 versus 404 spectra). The total timespan of both datasets is 4474 days. The results of the period analysis are listed in Table 4. Figure 3 shows four Lomb-Scargle periodograms, corresponding with the successive phases of prewhitening (from top to bottom).

Table 4. A comparison between the amplitude of the detected frequencies, the amplitude corresponding with a false alarm probability (fap) $p_o = 0.01$ and $4\,S/N$ (four times the amplitude of the noise).

Frequency c d^{-1}	Amplitude km s^{-1}	fap km s^{-1}	$4\,S/N$ km s^{-1}
$f_1 = 6.51481$	4.2	1.7	3.2
$f_2 = 6.41356$	2.8	1.4	2.4
$f_3 = 6.49521$	2.0	1.3	2.0
$f_4 = 1.98662$	1.7	1.2	2.0

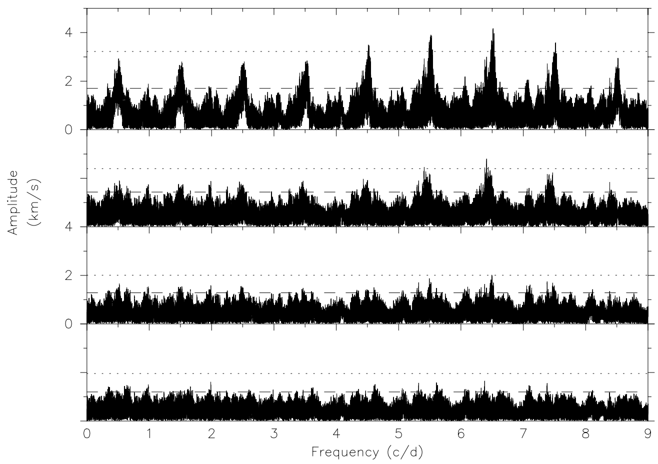

Fig. 3. Four Lomb-Scargle periodograms, corresponding with the successive phases of prewhitening (from top to bottom). The dotted and dashed line represent respectively the $4\,S/N$ level and the level corresponding to a false alarm probability $p_o = 0.01$.

The $4\,S/N$ level and the level corresponding to a false alarm probability $p_o = 0.01$ are represented by respectively a dotted and dashed line.

The false alarm test would result in the detection of at least 6 frequencies. The $4\,S/N$ criterion, on the other hand, is far less liberal and leads to three significant frequencies in our dataset: $f_1 = 6.51481$ c d^{-1}, $f_2 = 6.41356$ c d^{-1} and $f_3 = 6.49521$ c d^{-1}. In most recent period analyses one tends to use the $4\,S/N$ criterion as significance test, but we do stress that it was developed for multisite campaigns of δ Scuti stars and it is not clear how well it performs as a general criterion for all types of data of all kinds of variables. Nevertheless, we also adopt this criterion here and so accept only the three mentioned frequencies.

The linear pulsation model based on the 3 listed frequencies explains 51% of the variability in the data. In Fig. 4 the radial velocity of the first Si III line, folded with f_1, is shown in the upper panel. In the middle panel we show the residuals after removal of f_1 and folded with f_2. In the lower panel the residual data after removal of f_1 and f_2, folded with f_3, are shown.

We finally note that we could confirm the first two frequencies f_1 and f_2 by performing a frequency analysis

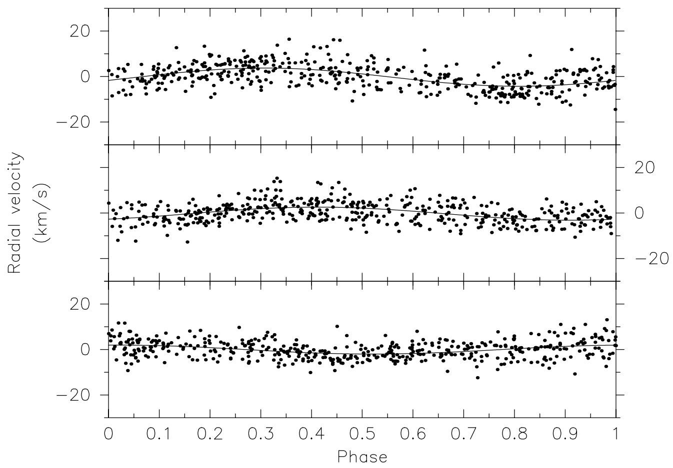

Fig. 4. Radial velocity curves measured from the λ 4567 Å line of the primary, phased to the frequencies $f_1 = 6.51481$ c d^{-1} (top), $f_2 = 6.41356$ c d^{-1} after prewhitening with f_1 (middle) and $f_3 = 6.49521$ c d^{-1} after prewhitening with f_1 and f_2 (bottom). The dots represent the data, while the full line is the fit.

on the smaller dataset determined with the λ 4552 Å SiIII line.

Comparing our results with previous spectroscopic studies of β Cen, we notice that the first frequency found by Robertson et al. (1999, 5.59 c d^{-1}) is a 1 c d^{-1} alias of our f_1. Furthermore, one of the two alternative possible values Breger (1967) obtained for the high frequency (6.58 c d^{-1}) is very close to it. Our f_2 was also found approximately by Shobbrook & Robertson (1968, 6.39 c d^{-1}) and Lomb (1975, 6.37 c d^{-1}).

5. Conclusions

We conclude that β Cen is a double-lined spectroscopic binary with two pulsating stars orbiting each other in a very eccentric orbit with a period of 357 days. Very few spectroscopic binaries consisting of two main-sequence type components are known with extremely high eccentricities. The highest eccentricities for such systems so far are found for Gl 568 A with $e = 0.9752 \pm 0.0003$ (Duquennoy et al. 1992), HD 2909 with $e = 0.949 \pm 0.002$ (Mazeh et al. 1995) and HD 210647 with $e = 0.904$ (Griffin 1984). In these three cases, however, it concerns much cooler main-sequence type components and longer orbital periods than what we have found for β Cen. De Cat et al. (2000) recently also discovered a remarkable double-lined spectroscopic eccentric binary with a B9IV-type primary component and an eccentricity of 0.73. The primary is an SPB star with dominant frequency 1.1516 c d^{-1}. At present it is not clear if this frequency results from resonant excitation. We also mention HR 1952, a binary system, consisting of a B.2V and B5V component, with a large eccentricity $e = 0.781$ (Petrova & Orlov 1999). However, we failed to find any information on pulsation in any of the components.

Our findings for β Cen, and for the other examples mentioned above, imply serious problems for the theory of binary formation and of tidal effects in close binaries. We do not understand how β Cen could be formed with standard formation scenarios, as there simply cannot have been room to accommodate the two massive pre-main-sequence progenitors of the current stars. Moreover, the primordial eccentricity of β Cen must have been even higher than the present value we derive, as tidal interactions induce circularization of the orbit. Goldman & Mazeh (1994) have studied tidal evolution in highly eccentric orbits in order to "avoid" such problems – with some succes, but their study was focussed on the few low-mass spectoscopic binaries mentioned above and so is not applicable to β Cen. We are thus left with a puzzle as far as the history of β Cen is concerned.

Since β Cen is relatively nearby, with a parallax of $\pi = 6.21 \pm 0.56$ mas, further interferometric observations should allow the determination of the orbital inclination, and subsequently of the individual masses and radii. This could shed some new light on the true nature of the two components. Due to the similarity of both components and their brightness, this binary is also ideally suited to serve as a calibration source for the new interferometric instruments which are currently being built and tested for the VLTI.

A distinct short-period photometric variation with amplitude of about 0.04 mag was observed by Balona (1975) on one night. No period could be derived in these data, however. The lack of other claims of photometric variability of the brightest among all β Cep stars indicates the excitation of pulsation modes with a relatively high degree only. Our results clearly point out that one cannot hope to find a complete frequency spectrum of the p-modes in β Cephei stars from ground-based photometry. This is important in view of the future seismological space missions of which the programmes are currently being decided upon.

We will continue our study of β Cen by trying to identify the non-radial modes from the line-profile variations with different methods. Such a study is quite extensive and was therefore omitted here. We will report on our findings in a future paper. Depending on the orbital inclination, a comparison between the pulsational behaviour of both components at periastron and apastron may give clues about the role of tidal effects on the pulsational behaviour. We therefore will continue our monitoring of β Cen in peri- and apastron.

From an astrophysical point of view, this binary offers a unique opportunity to study the interplay between binarity, rapid rotation, and pulsation since both components are line-profile variable stars. The equatorial rotation velocity of the primary is about half of the one of the secondary, which is quite remarkable as well and forms yet another challenge to current formation and evolution scenarios of massive binaries.

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