

A detailed spectroscopic analysis of ε Per^{*}

I. Determination of the orbital parameters and of the frequencies

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Received 20 October 1999 / Accepted 4 May 2000

Abstract. We present the analysis of 445 high signal-to-noise spectra of the Si III triplet at 4553 Å, 4568 Å, 4575 Å of the line-profile variable star ε Persei. The data were gathered during 14 consecutive nights and fully cover the orbital cycle of the binary. The orbital parameters that we derive from our data for the close binary are in full agreement with those found in 1995 by Tarasov et al. Our data does not offer a conclusive test of the presence of the 4156-d period.

With the CLEAN-method, we identify 5 periods in the intensity variations across the line profiles, after the latter are corrected for the binary motion: 5.300, 5.890, 6.250, 6.875, and 10.585 c d⁻¹. The results of our frequency analysis are consistent with previous ones based on the CLEAN algorithm. In terms of sinusoidal variations with constant phase, we thus find that the line-profile variations have a multiperiodic pattern. The Hipparcos photometry reveals yet another candidate frequency of 5.23280 c d⁻¹. It is not clear yet if this frequency is connected to those found in the spectra.

With the PDM-method, we find some indications leading to the “super” period $P_{\text{super}} \equiv 1^d 11878$, as introduced by Harmanec (1999). On the other hand, many other periods between 1 and 3 days are equally likely than P_{super} . Some of the frequencies found using CLEAN are integer submultiples of P_{super} .

We do not have a sufficient amount of data to estimate the importance of tidal effects for the line-profile variability near periastron for ε Persei.

Key words: line: profiles – stars: oscillations – stars: early-type – stars: individual: ε Per – stars: binaries: spectroscopic

1. Introduction

The star ε Persei (HD 24760, HR 1220, HIP 18532) is one of the most complicated line-profile variables of the northern hemi-

sphere. Already at the beginning of this century, radial-velocity variations of ε Per were reported by Frost & Adams (1904). They found a considerable difference in the appearance of the same lines on different plates and stated that “the lines of this star are complex”.

In the past ten years, several studies based on high-resolution line-profile data were published (e.g. Smith et al. 1987, Gies & Kullavanijaya 1988, Harmanec 1989, Gies et al. 1999). Non-radial pulsation on the one hand (e.g. Gies et al. 1999), and corotating structures above the photosphere on the other hand (Harmanec 1999), are the recently proposed explanations for the observed profile variations. It is clear that, although this object is already observed intensively with accurate instrumentation, its behaviour is far from understood. One of the reasons could be that most of the existing high-quality spectroscopic data sets have a very limited time base of a few days. We here present a data set of high-resolution spectra spread over 14 consecutive nights.

Tarasov et al. (1995) have recently given a thorough history record of the research performed on the star. We refer to their paper for all the relevant references instead of repeating their overview. They also show that ε Per is the primary component of a close binary with a very eccentric orbit ($e = 0.54$) and a rather short period of about two weeks. Tarasov et al. also suggest that the 14-day binary system moves in orbit with a second distant companion, with a likely period of 4156 days.

Recently, the line-profile variations have been interpreted several times and by several authors in terms of non-radial pulsations. In the new study by Gies et al. (1999), a compilation of the different non-radial pulsation frequencies found earlier is given. Up to four different modes were reported by different authors, with periods ranging from 2 to 13 hours. The degrees of the modes reach values up to $\ell = 6$ (Smith et al. 1987, Gies & Kullavanijaya 1988, Telting & Schrijvers 1997). Gies et al. (1999) also present an analysis of new dedicated IUE and ground-based data. Both new data sets have a time spread of 6 days. Gies et al. (1999) derive six periods from the new data, of which several are consistent with previous studies. The degrees of the modes range from 3 up to 5. Obviously, it is very difficult to derive an unambiguous picture about the active non-

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Table 1. Logbook of our observations of ε Per. The HJD of the beginning and the end of each night is given with respect to the reference epoch $t_0 = \text{HJD } 2450300$. For each night, N gives the number of spectra, $\Delta t_{\min}$ and $\Delta t_{\max}$ respectively the shortest and the longest integration times and S/N the average signal-to-noise ratio.

date	HJD _{start}	HJD _{end}	N	$\Delta t_{\min}$	$\Delta t_{\max}$	S/N
16/10/1996	73.37	73.67	27	431	1200	120
17/10/1996	74.34	74.68	41	465	929	165
18/10/1996	75.35	75.68	47	213	1119	175
19/10/1996	76.36	76.68	35	341	1200	155
20/10/1996	77.34	77.68	46	264	1133	170
21/10/1996	78.35	78.69	43	306	1200	170
22/10/1996	79.33	79.70	82	221	482	230
23/10/1996	80.33	80.70	28	399	1200	200
24/10/1996	81.34	81.40	7	723	1099	225
25/10/1996	82.33	82.50	21	476	1191	220
26/10/1996	83.33	83.36	3	1200	1200	115
27/10/1996	84.33	84.70	19	384	1130	185
28/10/1996	85.32	85.62	30	262	817	195
29/10/1996	86.33	86.69	35	549	1200	200
total	73.37	86.69	464	213	1200	190

radial pulsation modes, since every new data set leads to a yet different set of modes. Gies et al. (1999) presented evidence that may hint at a photospheric connection in the sense that the strengthening of wind features follows times of strong constructive interference between the apparent periodicities (see their Fig. 11).

We emphasize that, in the case a pulsational model would apply to the star, the very eccentric orbit is interesting. The high eccentricity could have a strong influence on the selection of the pulsation modes: forced oscillations could occur near periastron while the free oscillation modes could be dominant near apastron. There is no observational evidence yet that the modes in ε Per are of a forced nature. Since our data set is one of the first that fully covers the orbital phase, our analysis might shed some light on the effect of the tidal forces that are active in the binary.

An alternative explanation for the observed rapid variations of ε Per is presented by Harmanec in several papers. We refer to his most recent one (Harmanec 1999), in which he advocates that the variations of the star need not be due to non-radial pulsation, but can also be caused by corotating structures situated slightly above the stellar photosphere. In his model, one physical period (1.12 days) with a complicated phase behaviour is proposed as an explanation for the variability.

It is important to understand the variations in ε Per for several reasons. Our interest in ε Per is threefold. This object is a rapidly rotating (BSC: $v \sin i = 153 \text{ km s}^{-1}$) variable component of a close binary system. First of all, we want to redetermine the orbital parameters of the close binary and decide whether or not Tarasov et al.'s proposition of having a second distant companion is compatible with our data. Second, we seek to derive the frequencies that govern the line-profile variations with a high precision in order to decide what physical mechanism causes

the variability. Third, we wonder if the tidal forces in the close binary are sufficiently strong to imply an effect on the variability of the primary, i.e. we want to study if a trend between the line-profile variability and the orbital phase is present.

Our study will be published in two separate papers. This paper focuses on the binary motion and on the periods of the line-profile variability. A second forthcoming paper will be completely devoted to the modelling of the line-profile variations in terms of the two models that are currently proposed in the literature to explain the intrinsic variability. The results of the modelling will allow us to interpret the observations and to evaluate the influence of the binarity on the variations of the line-profiles.

This paper is organised as follows. A description of the numerous high-resolution, high signal-to-noise spectroscopic data that we have gathered during a complete orbital period is presented in Sect. 2. In Sect. 3, we determine the radial velocity of the star and the orbital motion is studied in Sect. 4. The variability of the primary component is investigated in Sect. 5. Finally, Sect. 6 contains a discussion of our results and of what is to come in the second paper.

2. Observations and data reductions

The data were obtained with the 1.52m telescope at the Observatoire de Haute Provence, using the AURELIE Spectrograph (Gillet et al. 1994). The detector was a linear array. The data were obtained in 14 consecutive nights, ranging from 16 October 1996 until 29 October 1996. The spectral domain was centered on $4560 \text{ \AA}$ in order to get the Si III-triplet with lines at $\lambda\lambda$ 4553, 4568, and 4575. The resolving power was about 60000. The integration time was between 5 min and 20 min, depending on weather conditions. This results in a signal-to-noise ratio in the range 150–200 at a 2σ level. A logbook of the observations is given in Table 1. Our data will be published electronically after the appearance of the forthcoming second paper on the modelling of the variations.

Each spectrum was corrected for the pixel-to-pixel response through division by the mean of 5 flat field spectra obtained using a tungsten lamp. The wavelength calibration was done using a cubic spline fit for about 40 lines of a thorium lamp. The spectra were normalized to the continuum by a cubic spline function, and the heliocentric corrections were applied. We rebinned all spectra such that $\Delta\lambda = 0.025 \text{ \AA}$. After inspection of the data, we retained 445 usable profiles.

In Fig. 1, grey-scale representations of the time series obtained during two consecutive nights are shown, together with some line-profiles of the Si III-line at $\lambda = 4552.654 \text{ \AA}$. It is evident by looking at the grey-scale representation that the line-profile behaviour during the two nights is quite different.

3. The radial-velocity variations

There are different ways to determine the radial velocity from high-resolution line-profile data. A first one is to make a Gaussian approximation of the line-profile. For deep, sharp lines without subfeatures, such an approximation is justified, and μ ,

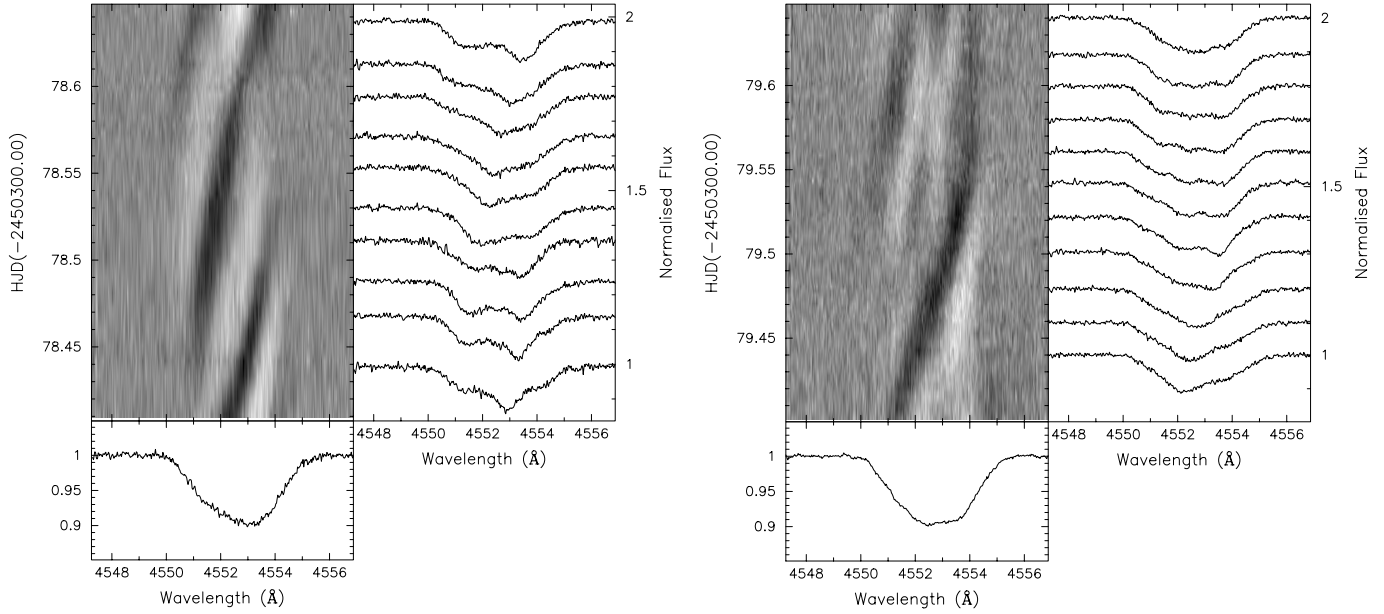


Fig. 1. Top left: grey-scale representation of the residual spectra with respect to the nightly average profile. Bottom left: the average profile of that night. Right: some of the observed line-profiles of that night, shifted according to the time of measurement. Left panel: data of 21 October 1996, right panel: data of 22 October 1996.

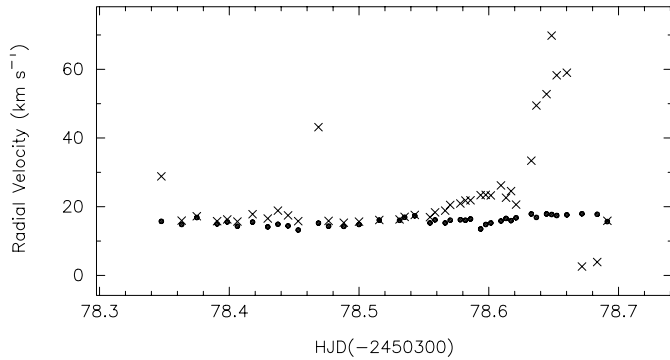


Fig. 2. The average radial velocities of the Si III-triplet of ε Per for a representative night, i.e. 21 October 1996. The crosses denote the Gaussian approximation of the radial velocity v_{Gauss} while the dots denote the normalised first moment M_1/M_0 .

being the mean of the Gaussian, will be a good estimation of the radial velocity.

In the case of ε Per, prominent moving bumps and troughs are superposed on very broad absorption lines (see Fig. 1). Nearly all the profiles show such moving patterns. According to their position, these bumps and troughs can “pull” the Gaussian fit to the red/blue wing of the considered absorption line, which leads to an over-/underestimate of the radial velocity. In the case of such observations, it is more appropriate to use the normalised first moment M_1/M_0 , as defined by Aerts et al. (1992), to approximate the radial velocity. The moments of a line-profile, however, strongly depend on the choice of the integration limits. With too narrow limits, much information about the line wings is lost, while too broad ones introduce additional noise. Moreover, we are dealing with a spectroscopic

binary. The use of “dynamic” integration limits to calculate the moments is therefore preferred. The integration limits are determined for each spectrum separately by visual inspection of the local continuum. In this way, differences in line-width during the pulsation cycle are also accounted for in an accurate way.

The radial velocities were calculated by means of both Gaussian fits and M_1/M_0 with dynamic integration limits. We determined them for each of the Si III-lines separately, using $\lambda_c = 4552.654 \text{ Å}$, 4567.872 Å , and 4574.777 Å (Moore 1945) as central wavelengths for respectively the first, second, and third Si III-line. Next, the average radial velocity for the Si III-triplet was determined.

In Fig. 2, we compare the Gaussian radial velocity v_{Gauss} with the normalised first moment M_1/M_0 for a representative night. From this figure, it is evident that M_1/M_0 is more accurate than v_{Gauss} , especially for the profiles with considerable subfeatures. Therefore, the results of analyses based on radial-velocity measurements that are obtained by means of Gaussian fits or that rely solely on the line centre should be treated with caution. Hereafter, the term “radial velocity” is used to denote the normalised first moment M_1/M_0 .

The signal-to-noise ratio is an indication of the quality of the measured profiles while the standard deviation of the average radial velocity of the three lines is a good estimator of the error of the measured velocities. These standard deviations range from 0.22 km s^{-1} up to 6.92 km s^{-1} , reflecting velocity differences from 0.4 km s^{-1} up to 13.5 km s^{-1} between the three Si III-lines. The shape of the velocity curves of the individual Si III-lines is roughly the same, but these curves are shifted from one to another. These shifts, and hence the large standard deviations of the averaged radial velocities, are not due to our choice of the central wavelengths. Differences between different sets of

Table 2. The triple-star solutions for ε Persei, as found by Tarasov et al. (1995). The row “rms” contains the root-mean-square error of one observation of unit weight. All epochs are in HJD - 2400000.

element	comp 1 & 2	comp 1 & 2 vs. 3
P_{orb} (d)	14.075897(64)	4156(26)
K (km s $^{-1}$)	16.8(13)	5.1(38)
E_o (HJD)	47767.484(125)	49343(508)
e	0.540(45)	0.40(26)
ω (deg.)	110.3(63)	25(50)
$a \sin i$ (au)	0.018295	1.78561
$f(m)$ ($M_{\odot}$)	0.004143	0.04424
$v_{\gamma, \text{joint}}$ (km s $^{-1}$)	7.47(51)	
rms (km s $^{-1}$)	3.98	

central wavelengths found in the literature can only account for approximately 3 km s $^{-1}$, which is insufficient to explain the observed velocity differences. For early B-stars, both the first and the second Si III-line are blended with shallow absorption lines (Kilian et al. 1991). Since ε Per is a rapid rotator, these blends are smeared out and hence difficult to detect. We can not correct for these blending effects.

4. Determination of the orbit

Recently, Tarasov et al. (1995) suggested that ε Per is the primary component of a triple system. They also present accurate orbital parameters of the system for the first time. Their final orbital solution for the close binary and for the wide system is given in Table 2. As in all other tables, the standard errors (if present) are given in brackets in units of the last decimals. Tarasov et al. (1995) based their analysis on 717 spectroscopic observations spread over more than 85 years. Our search for the orbital parameters is based on the 445 new line-profiles spread over only 14 days.

4.1. ε Per as a close binary

We used a modern version of the VCURVE-code (Bertiau & Grobben 1969) to determine the orbital parameters of the short-period binary. This code for computing orbits is based on the Lehmann-Filhés method for the initial input data and on the Schlesinger method for orbits of high eccentricity ($e > 0.05$). Orbits were determined using the averaged radial velocities of the Si III-triplet. Several different options were explored. The final set of orbital parameters found for the averaged radial velocities are given in Table 3, which we now comment.

In first instance, we treated the orbital period P_{orb} as a free parameter. VCURVE then converges to an orbit with a period of 13.8 days, which is slightly shorter than the one found by Tarasov et al. (see Table 2). Also minor differences in system velocity v_{γ} are found, but the other parameters are compatible with those listed in Table 2. To allow a fair comparison with the solution found by Tarasov et al., we next fixed the orbital period at 14^d.075897.

The large standard errors of the individual measurements (see above) already suggest that the standard errors given in Table 3 are an underestimate of the “real” errors of the orbital parameters. To check this, we determined the orbital parameters using the radial velocities of the three Si III-lines separately with the orbital period fixed at 14.075897 days (Table 4, columns 1–3). Afterwards, we calculated the average of every orbital parameter with its corresponding standard deviation (Table 4, column 4). Comparing these averages with the last column of Table 3, we see that the orbital parameters themselves are in full agreement, but that the errors given in Table 3 are one order of magnitude lower.

In the majority of studies about binary systems, several lines of low resolution spectra are used to determine an accurate average radial velocity. Here, the radial velocities of the individual Si III-lines of our high resolution spectra were used to determine the individual orbits. Apart from expected differences in system velocity v_{γ} (see above), also notable differences in eccentricity e are found, and to a lower extent in other orbital parameters. These differences are due to the uncertainty of the used rest wavelengths and to the blending effects of the Si III-lines. We emphasize that none of the papers in which orbits are determined focus on such differences because the quality of the spectra usually does not allow this.

The possibility of assigning a weight to each used radial velocity was explored in three different ways. We used weights based on the signal-to-noise ratio, weights based on the standard deviations of the individual velocities, or no weights at all. The three solutions lead to orbital parameters which differ less than one standard error (see Table 3).

In our study, all the individual velocities of ε Per are considered. Molenberghs et al. (1999) propose a new method to derive the orbital parameters of a binary that consists of an intrinsic variable. They develop a way to combine nightly averaged velocities for nights on which a full cover of the intrinsic variability cycle is obtained with individual velocities for poorly covered nights. Their method is developed to treat cases for which the intrinsic variability has a period that is much shorter than the orbital period. For ε Per, no essential difference is found between their and our solution for the case of a free orbital period (see Molenberghs et al. 1999, who used only the first line at 4553 Å; in this case, one finds an orbital period of 13.4 days).

The orbits with a free period are only slightly favoured in terms of rms, while the other parameters have smaller standard errors when using a fixed period. Because of this reason, and since our data span slightly less than 14 days, we finally prefer the solution with the period fixed to the value derived by Tarasov et al. (1995) and without using relative weights (the quality of the spectra does not differ that much). The orbital parameters derived for this configuration are given in bold in Table 3. Fig. 3 shows a comparison of the measured radial velocities with a theoretical curve based on the obtained orbital parameters. As can be seen on the figure, the orbit fits the radial-velocity measurements very well. The orbital parameters that we find are in good agreement with those given by Tarasov et al. (1995).

Table 3. The orbital parameters for the average radial velocity of the Si III-triplet. We used weights based on the signal-to-noise ratio (S/N), on the standard deviations (s.d.) and no weights at all (no). The row “rms” contains the root-mean-square error of one observation of unit weight. All epochs are in HJD -2450300. The final orbital solution that we prefer is given in bold.

weights	PERIOD FREE			PERIOD FIXED		
	S/N	s.d.	no	S/N	s.d.	no
P_{orb}	13 ^d 82(7)	13 ^d 81(6)	13 ^d 84(7)	14 ^d 075897	14 ^d 075897	14^d075897
K (km s ⁻¹)	15.5(1)	15.2(2)	15.4(1)	15.5(1)	15.2(2)	15.3(1)
E_o (HJD)	84.51(2)	84.49(2)	84.51(2)	84.48(1)	84.45(2)	84.48(1)
e	0.569(7)	0.556(8)	0.564(7)	0.566(7)	0.549(8)	0.559(7)
ω (deg.)	111(1)	110(1)	111.3(9)	108.8(7)	107.7(8)	109.1(7)
$a \sin i$ (A.U.)	0.0162	0.0161	0.0162	0.0165	0.0164	0.0165
$f(m)$ ($M_{\odot}$)	0.0030	0.0029	0.0030	0.0030	0.0030	0.0030
v_{γ} (km s ⁻¹)	10.88(8)	10.95(8)	10.89(8)	10.71(6)	10.73(7)	10.71(6)
rms (km s ⁻¹)	0.8850	0.9350	0.8944	0.8909	0.9420	0.8999

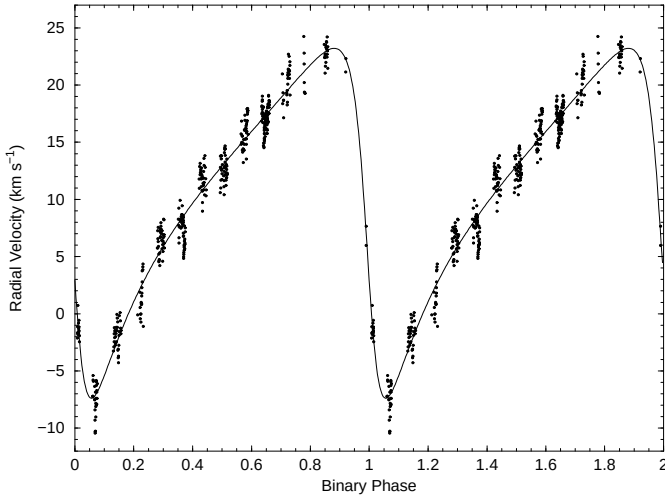


Fig. 3. The orbital velocity of ε Per for the close binary system. The full line denotes the orbital solution by considering all the radial-velocity data without using weights and with a fixed orbital period $P_{\text{orb}} = 14^{\text{d}}075897$. Binary phase zero corresponds to the periastron passage E_o . The dots denote the measured radial velocities.

4.2. ε Per as a triple-star

Tarasov et al. (1995) suggest that the close binary moves in an orbit of 4156 days with a yet unknown third component. We confronted this finding with the system velocities v_{γ} found for the three Si III-lines for the close binary at the time of our measurements. The period of the third component is very long, so it is justified to consider the system velocity of the close binary as constant during a time span of 14 days. The result of the confrontation is presented in Fig. 4. The full line denotes the theoretical curve based on the parameters found by Tarasov et al. (1995) (see Table 2). Since there are large errors on these orbital parameters, we calculated the total area in the phase-velocity diagram that can be reached with orbits corresponding to a combination of orbital parameters within the given standard errors (see Table 2). This area is given in grey in Fig. 4. The triple-star period was fixed to be 4156 days because the triple-star phase depends on it in a non-linear way. Phase zero corresponds to HJD

Table 4. The orbital parameters using the radial velocities of the three Si III-lined separately (4553 Å, 4568 Å, 4575 Å) and the average of every orbital parameter with its corresponding standard deviation (average). The orbital period was fixed on 14^d075897. No weights were used. The row “rms” contains the root-mean-square error of one observation of unit weight. All epochs are in HJD -2450300.

	4553 Å	4568 Å	4575 Å	average
K (km s ⁻¹)	14.9(1)	15.5(2)	15.7(3)	15.4(4)
E_o (HJD)	84.39(3)	84.46(2)	84.55(2)	84.47(8)
e	0.468(8)	0.568(9)	0.62(1)	0.552(77)
ω (deg.)	107.1(9)	107.9(9)	113(1)	109(3)
$a \sin i$ (A.U.)	0.0170	0.0165	0.0159	0.0165(5)
$f(m)$ ($M_{\odot}$)	0.0033	0.0030	0.0027	0.0030(3)
v_{γ} (km s ⁻¹)	13.25(8)	11.24(8)	7.51(9)	10.71(291)
rms (km s ⁻¹)	1.179	1.157	1.140	

2449343, the periastron passage for the triple-system, as given in Table 2. The dots denote the system velocities of the orbital solutions for the close binary using the Si III lines separately, respectively (1) (13.25 ± 0.08) km s⁻¹ for 4553 Å, (2) (11.24 ± 0.08) km s⁻¹ for 4568 Å and (3) (7.51 ± 0.09) km s⁻¹ for 4575 Å (see Table 4). The error bars are smaller than the dots.

From Fig. 4, it is tempting to conclude that our system velocities for the close binary are not convincingly consistent with Tarasov’s 4156-day orbit. Only the system velocity derived from the 4575 Å line seems to fall within the grey area. This is the only Si III-line of the triplet which is not affected by blending effects. Moreover: (1) the uncertainty of the rest wavelengths can account for velocity differences of about 3 km s⁻¹, (2) we are not able to correct for possible differences in the zero-point of our data with respect to those of Tarasov et al. (1995), (3) the errors on the individual orbital parameters (Table 4, columns 1–3) are underestimated. Therefore, our data does **not** present an ideal case to test the reality of the 4156-day period.

5. Frequency analysis

After having determined the solution for the orbital velocity of ε Per, we shifted the spectra to the velocity frame relative to

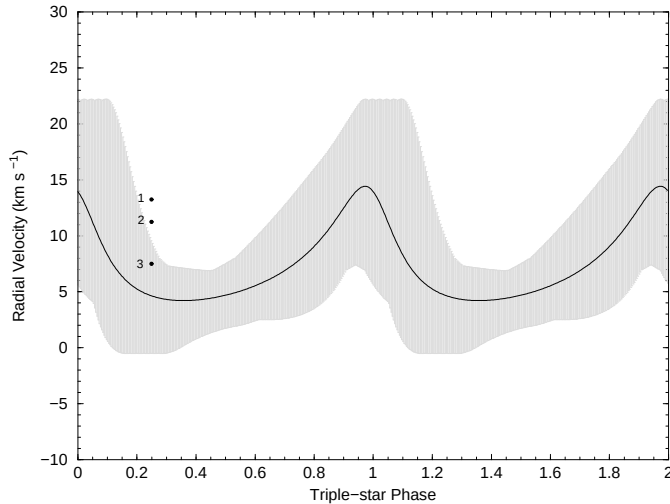


Fig. 4. The orbital velocity of the close binary system (with ϵ Per as primary) with a distant third star. The full line denotes the orbital solution as given by Tarasov et al. (1995) (see Table 2) with a period of 4156 days. The triple-star phase zero corresponds to the periastron passage HJD 2449343. The dots denote the system velocities of the orbital solutions for the close binary using the Si III lines separately, respectively (1) $(13.25 \pm 0.08) \text{ km s}^{-1}$ for 4553 Å, (2) $(11.24 \pm 0.08) \text{ km s}^{-1}$ for 4568 Å and (3) $(7.51 \pm 0.09) \text{ km s}^{-1}$ for 4575 Å (see Table 4). The error bars are smaller than the dots. The area that can be reached by calculating all different orbits using combinations of the orbital parameters within the given standard errors (see Table 2), is given in grey.

the early-B star itself. We next applied two distinct methods to search for intrinsic periodicities in the spectra: we looked for periodicities in the moments of the line-profiles, and for periodicities in the normalized intensity as a function of position in the line-profiles. The methods are complementary to each other: low-degree non-radial pulsation modes tend to show up in the first few velocity moments, whereas modes of higher degrees will only show up as intensity variations across the profiles. Additionally we have analysed the Hipparcos photometry of ϵ Per to see if any periodic signal is present in that data.

5.1. Spectra

5.1.1. Moments

The equivalent width (EW) and the first three velocity moments ($\langle v \rangle$, $\langle v^2 \rangle$, $\langle v^3 \rangle$) of the time series of profiles of the Si III-lines were computed. The three moments are related to the centroid (or radial velocity), the variance (or width) and the skewness of the profiles. Different versions of the moment definitions appear in the literature. We use the definition as given by Aerts et al. (1992). All three velocity moments are normalized by the equivalent width. The boundaries needed to perform the integration to obtain the moments were chosen from the requirement that the wings of the average profile meet the continuum.

Special care has been taken when shifting the spectra to the velocity frame relative to the star itself. If this shift is done in a

proper way, the average of the odd moments must be zero (Aerts et al. 1992).

In our first attempt, a “global” shift with our final orbit as given in Table 3 was applied. In this case, we find averages of the odd moments which differ from zero: the average of $\langle v \rangle$ for the three Si III-lines separately is respectively 2.80 km s^{-1} , 3.67 km s^{-1} and -2.06 km s^{-1} . This is not surprising, since differences in gamma velocities (and eccentricity) are found when using the radial velocities of the three Si III-lines separately to determine the orbit for the close binary (see Table 4).

In order to have more appropriate velocity moments for the three Si III-lines separately, we next applied an “individual” shift of the spectra with the orbits determined for the individual Si III-lines as given in Table 4. Fig. 5 shows the variations in these moments of the 4553 Å line. The average of the odd moments is indeed (close to) zero.

The results of the frequency analysis of the velocity moments calculated after respectively a “global” and an “individual” shift were compared, but no essential differences were found. We therefore concentrate on the results after the “individual” shifts.

The HWHM of the window function of our 445 spectra, 0.035 c d^{-1} , gives the frequency resolution in the power spectra, and estimates the error of the derived frequencies. These errors do not depend on the window function only, but also on the rms errors of individual measurements of the respective quantities. At present, a statistically correct method to include the rms of individual data is not available. The formal use of other methods, that are not designed to find the errors of frequencies, was explored by us in an attempt to find more realistic error estimates (e.g. use of VCURVE, non-linear fitting, etc.). Our exercise shows that the “true” rms errors of the frequencies must be between 0.001 c d^{-1} and 0.035 c d^{-1} . Therefore, a frequency resolution of 0.005 c d^{-1} was used during the frequency analysis of our spectroscopic data.

We CLEANed the periodograms to remove the window function, using 400 iterations with a gain of 0.2 (see Roberts et al. 1987). The bottom four panels on Fig. 6 show the results of our frequency analysis for the three lines in the Si III-triplet. In Table 5 we list the corresponding frequencies of the coinciding peaks in the moments of the three separate Si III-lines. Their order of appearance in the list of the highest peaks is indicated between brackets. Missing numbers correspond to spurious frequencies that do not coincide for the three lines. Below every column, we give the total variance reduction (f.v.: fraction of the variance) in the data using the listed common frequencies.

The periodograms of the EW and of $\langle v \rangle$ are very noisy and the frequencies found for the three different absorption lines hardly agree. This result agrees with the findings of Gies et al. (1999). Two peaks seem to coincide in all three periodograms of $\langle v \rangle$: one near 7.155 c d^{-1} and another one near 0.500 c d^{-1} . The peaks near 0.500 c d^{-1} are more prominent, but the agreement is less convincing than for the 7.155 c d^{-1} peak.

The periodograms of the second and third moment show very prominent peaks. Our findings indicate that the higher-order moments contain useful and additional information com-

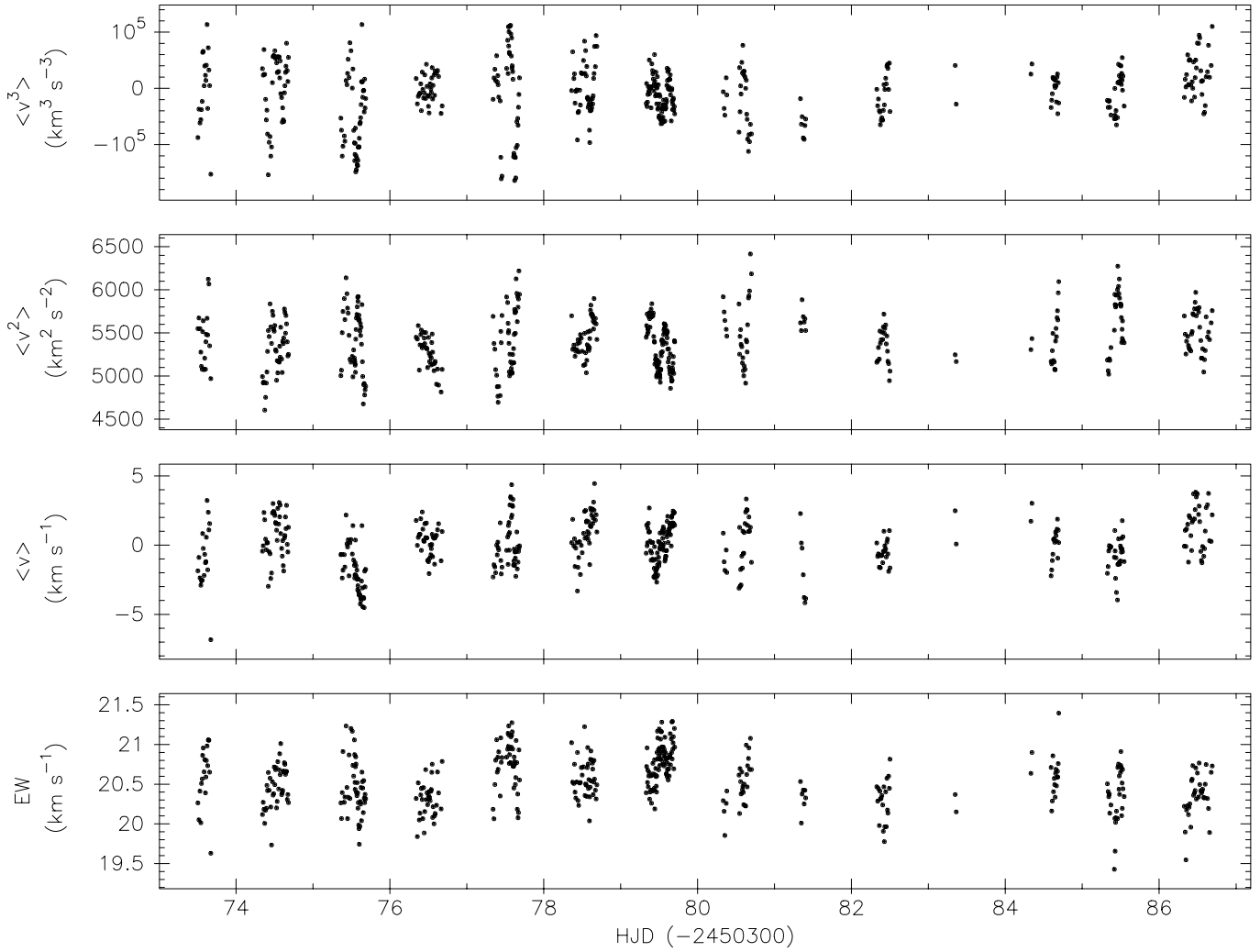


Fig. 5. The variations of the equivalent width and the first three velocity moments of the 4553 Å line of ε Per.

pared to the radial velocity (first moment). This points out the importance of a moment analysis for the interpretation of the line-profile variability (see Paper II).

Frequency analysis with the CLEAN method is most suited for variables with sinusoidal variations. Harmanec (1999) proposed a model of corotating structures situated slightly above the stellar photosphere, in which a single-periodic variation with a complicated phase curve is assumed. In this model, two periods are important: (1) the “super” period $P_{\text{super}} \equiv 1^{\text{d}}11878$ (Harmanec 1999), of which some frequencies recovered in earlier studies are submultiples, and (2) $P_{\text{rot}} \equiv 2^{\text{d}}23756$, twice the super period, which was one of the periods with the best fit in Harmanec’s analysis (1999) and which was already attributed to be the “rotational” period of ε Per in previous studies. Coinciding peaks corresponding to periods quite close to P_{rot} are already found from the CLEAN-analysis of the odd moments (see above).

In order to be able to check the reality of periods close to P_{rot} and to search for P_{super} , we complemented our frequency analysis with the use of the PDM-method (Stellingwerf 1978),

which allows non-sinusoidal variations with complicated phase curves, as have been proposed to occur in ε Per (Harmanec, 1999). To allow a fair comparison with Harmanec (1999), we used the same binstructure $(N_{\text{bins}}, N_{\text{covers}}) = (70, 5)$. For the first three moments of the three Si III-lines, we performed a PDM-analysis with a frequency resolution of 0.0001 c d^{-1} . The deepest minima in the θ -statistics all correspond to frequencies below 1 c d^{-1} . In Fig. 7, we zoom in on the frequency interval $[0, 1]$ of the θ -statistics of $\langle v \rangle$, $\langle v^2 \rangle$ and $\langle v^3 \rangle$ of the three Si III lines. We do find small peaks which correspond to P_{rot} and to P_{super} (indicated by a dashed line), the latter being more clearly present. Many peaks occur, however, and it is not possible to decide upon the reality of P_{rot} or P_{super} from the θ -statistics alone. In Fig. 8, a phase plot with P_{super} for $\langle v \rangle$, $\langle v^2 \rangle$ and $\langle v^3 \rangle$ of the 4553 Å line is given. They show that variations with P_{super} are present, especially in the higher-order moments. We must stress that many of the other local minima in the θ -statistics give rise to phase plots of equal quality. In this respect, it is not clear to us how significant P_{super} nor P_{rot} is.

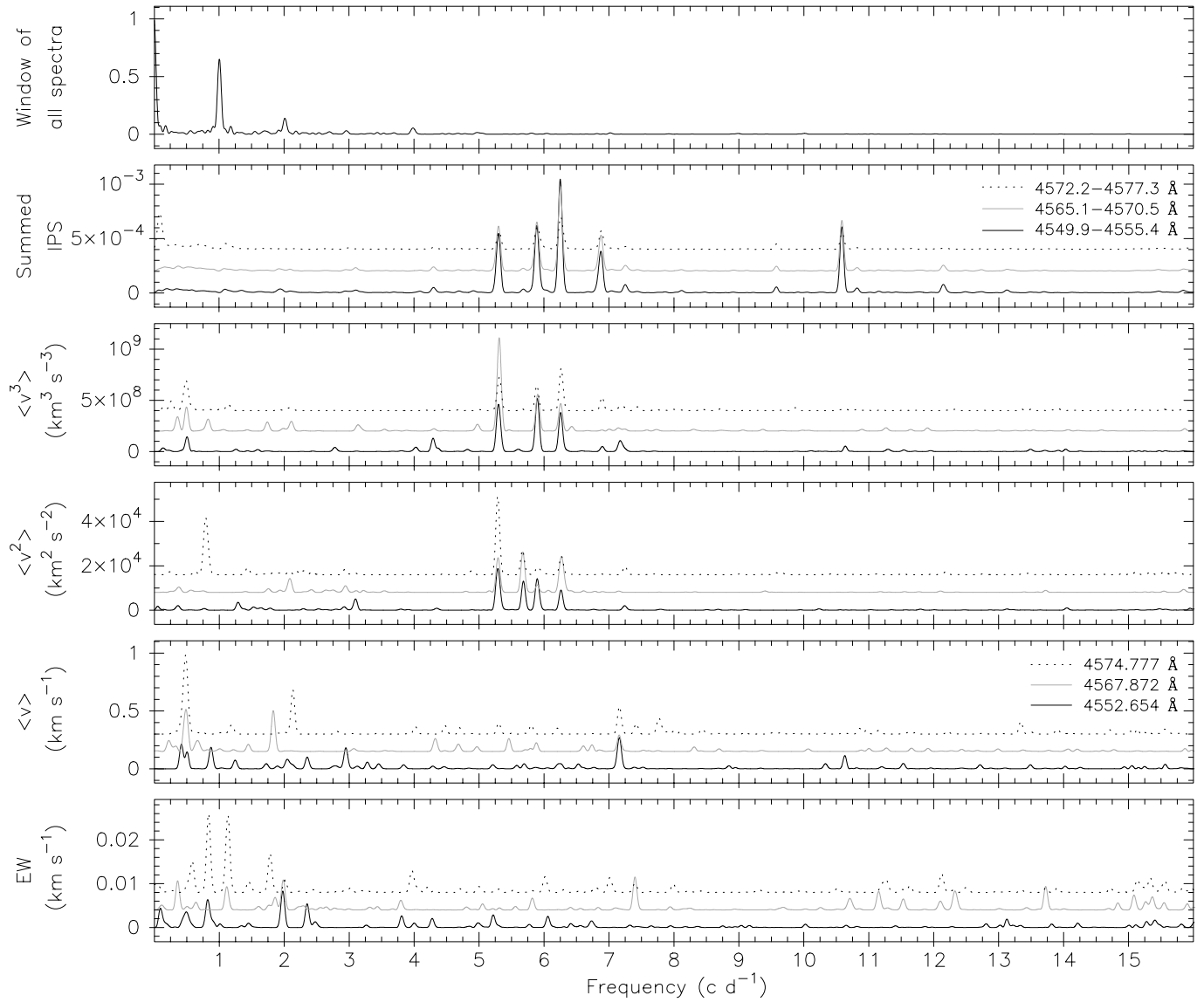


Fig. 6. The CLEANed periodograms of the equivalent width and the first three velocity moments for the three lines in the Si III-triplet. The periodograms of the individual Si III-lines are shifted upwards with respect to each other. The second panel from above gives the summed two-dimensional periodograms for these lines. The top panel gives the window function of the data.

5.1.2. Intensity variations across the profiles

For each wavelength bin in the line-profiles we analysed the varying intensity levels in the way introduced by Gies & Kullavaniyaya (1988).

We used the same CLEAN parameters as for the analysis of the moments. In Fig. 9 we plot the result for the 4553 Å line. In this two-dimensional periodogram, the complex pattern of bumps moving across the line-profile has been resolved into distinct prominent peaks of power in the periodogram which extend from the blue to the red wings of the line-profile. The two-dimensional CLEANed periodogram is summed for the three Si III-lines over the profile to give a one-dimensional periodogram. We summed over the domain defined by the averaged integration limits as used for the calculation of the moments.

The results are plotted in the second panel from the top of Fig. 6. The agreement between the three lines is remarkable. The most prominent peaks are listed in Table 6.

Since the variations corresponding to P_{super} and P_{rot} , as seen by Harmanec (1999), are most probably caused by sub-features passing across the line-profiles, we need to complement our frequency analysis for each wavelength bin in the line-profiles with the use of the PDM-method. We used the same binstructure as above: $(N_{\text{bin}}, N_{\text{cover}}) = (70, 5)$. The frequency resolution was again enhanced to 0.0001 c d^{-1} . The results for the 4553 Å line are shown in Fig. 10.

Again, we find many local minima in the θ -statistics. The deepest minimum corresponds to a period $P_{\text{min}} \simeq 2^{\text{d}}55$, which is slightly longer than P_{rot} . As an example, we plot in Fig. 11 the phase curves of the residual central line depths (I_c) of the

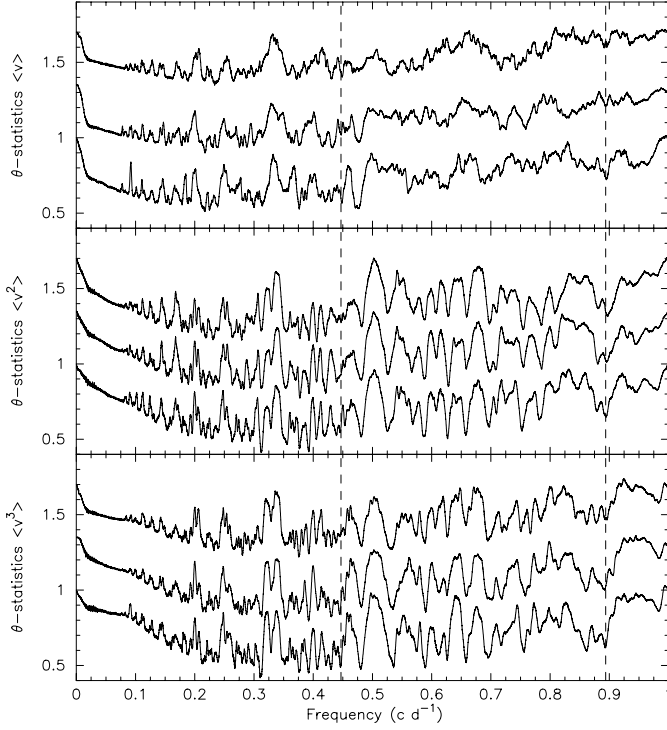


Fig. 7. The θ -statistics of $\langle v \rangle$ (top), $\langle v^2 \rangle$ (middle) and $\langle v^3 \rangle$ (bottom) of the three Si III lines (4553 Å bottom, 4568 Å middle, 4575 Å top). The dashed lines indicate the “super” period $P_{\text{super}} \equiv 1.^{\text{d}}11878$ (right) and with the “rotational” period $P_{\text{rot}} \equiv 2.^{\text{d}}23756$ (left) (Harmanec 1999).

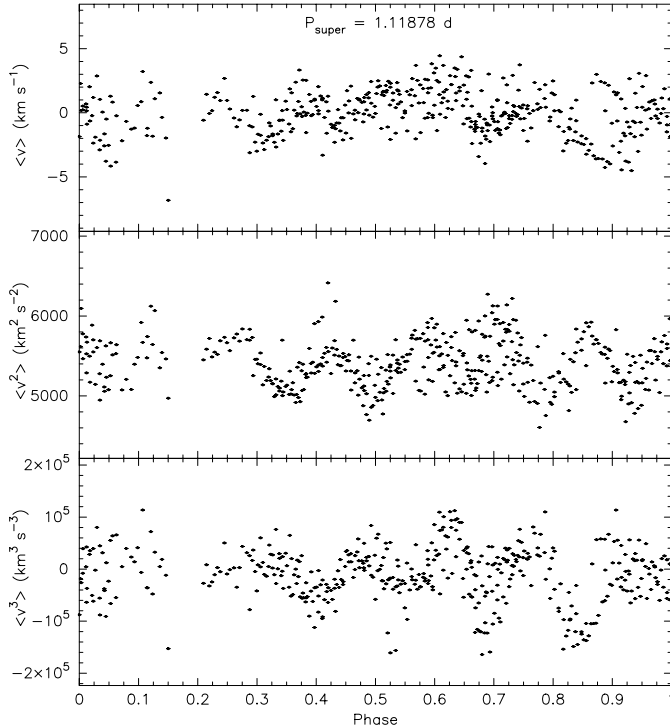


Fig. 8. A phase plot of $\langle v \rangle$ (top), $\langle v^2 \rangle$ (middle) and $\langle v^3 \rangle$ (bottom) of the 4553 Å line with the “super” period P_{super} .

Table 5. Frequencies found by performing a frequency analysis on the velocity moments of ε Per. We list the coinciding MPS peaks for the first three velocity moments. Their position in the list of the highest peaks is indicated between brackets. Below every column, the total variance reduction (f.v.: fraction of the variance) in the data using the listed common frequencies is given. The last column denotes the ratio of the “super” period $P_{\text{super}} \equiv 1.^{\text{d}}11878$ (Harmanec 1999) to the corresponding period P : $m \simeq P_{\text{super}}/P$.

COINCIDING $\langle v \rangle$ PEAKS			
4553 Å	4568 Å	4575 Å	m
(5) 0.505 c d ⁻¹	(1) 0.485 c d ⁻¹	(1) 0.480 c d ⁻¹	0.6
(1) 7.155 c d ⁻¹	(3) 7.150 c d ⁻¹	(3) 7.160 c d ⁻¹	8.0
↓	↓	↓	
f.v. 17.5%	f.v. 19.3%	f.v. 18.8%	
COINCIDING $\langle v^2 \rangle$ PEAKS			
4553 Å	4568 Å	4575 Å	m
(1) 5.285 c d ⁻¹	(3) 5.290 c d ⁻¹	(1) 5.285 c d ⁻¹	5.9
(3) 5.680 c d ⁻¹	(1) 5.670 c d ⁻¹	(3) 5.670 c d ⁻¹	6.3
(2) 5.890 c d ⁻¹	(5) 5.895 c d ⁻¹	(6) 5.900 c d ⁻¹	6.6
(4) 6.255 c d ⁻¹	(2) 6.260 c d ⁻¹	(4) 6.265 c d ⁻¹	7.0
↓	↓	↓	
f.v. 53.2%	f.v. 45.4%	f.v. 42.9%	
COINCIDING $\langle v^3 \rangle$ PEAKS			
4553 Å	4568 Å	4575 Å	m
(2) 5.295 c d ⁻¹	(1) 5.305 c d ⁻¹	(2) 5.310 c d ⁻¹	5.9
(1) 5.895 c d ⁻¹	(2) 5.900 c d ⁻¹	(4) 5.890 c d ⁻¹	6.6
(3) 6.250 c d ⁻¹	(3) 6.255 c d ⁻¹	(1) 6.265 c d ⁻¹	7.0
(4) 0.505 c d ⁻¹	(4) 0.495 c d ⁻¹	(3) 0.485 c d ⁻¹	0.6
↓	↓	↓	
f.v. 61.7%	f.v. 52.7%	f.v. 47.6%	

Table 6. Highest IPS peaks as summed over narrow moment domains. The last column denotes the ratio of the “super” period $P_{\text{super}} \equiv 1.^{\text{d}}11878$ (Harmanec 1999) to the corresponding period P : $m \simeq P_{\text{super}}/P$.

COINCIDING IPS PEAKS			
4553 Å	4568 Å	4575 Å	m
(4) 5.300 c d ⁻¹	(4) 5.300 c d ⁻¹	(5) 5.310 c d ⁻¹	5.9
(2) 5.890 c d ⁻¹	(3) 5.890 c d ⁻¹	(3) 5.895 c d ⁻¹	6.6
(1) 6.250 c d ⁻¹	(1) 6.250 c d ⁻¹	(2) 6.260 c d ⁻¹	7.0
(5) 6.875 c d ⁻¹	(5) 6.875 c d ⁻¹	(4) 6.885 c d ⁻¹	7.7
(3) 10.585 c d ⁻¹	(2) 10.585 c d ⁻¹	(6) 10.590 c d ⁻¹	11.8

4553 Å profile, folded with P_{min} , P_{super} and P_{rot} . Comparing the middle panel with the upper panel of Fig. 3 of Harmanec (1999), we conclude that P_{super} occurs in our data at the same level as in Harmanec’s data, but our phase plot is not symmetric around 0 as was the case for Harmanec’s analysis.

5.1.3. Conclusions

The resulting periods from the CLEAN-analyses are very similar, but not identical, to those reported by Gies et al. (1999). Our

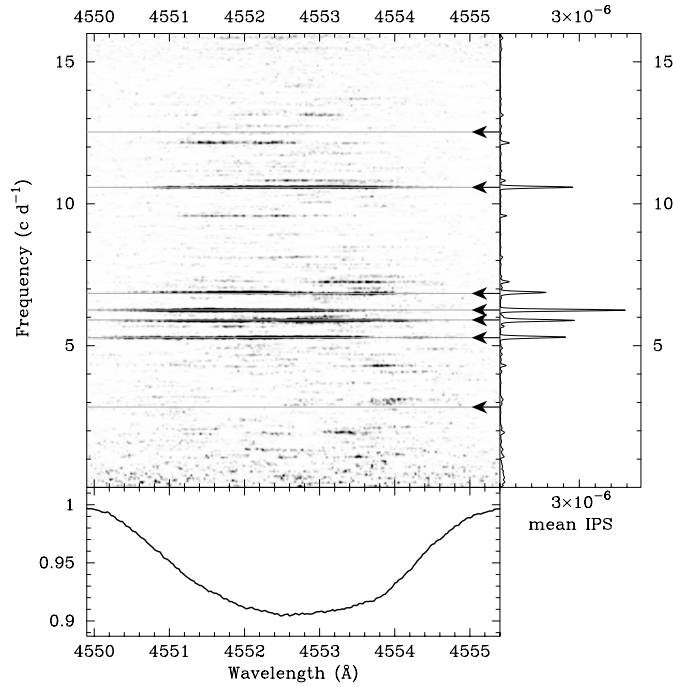


Fig. 9. Two-dimensional CLEANed periodograms of the intensity variations as a function of position in the 4553 Å profile, using 400 iterations with a gain of 0.2. The arrows indicate the frequencies compiled by Gies et al. (1999). The bottom panel gives the averaged line-profile. The right panel gives the CLEANed powerspectrum averaged over the wavelength bins.

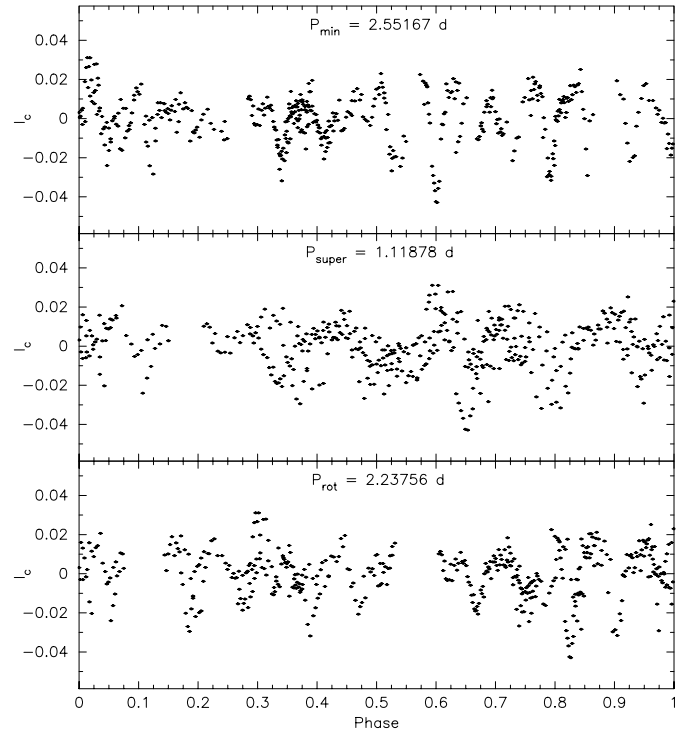


Fig. 11. A phase plot for the residual central line depths (I_c) of the 4553 Å profile folded with the period $P_{\min}$ corresponding with the deepest minimum in the θ -statistics (top), with the “super” period P_{super} (middle) and with the “rotational” period P_{rot} (bottom).

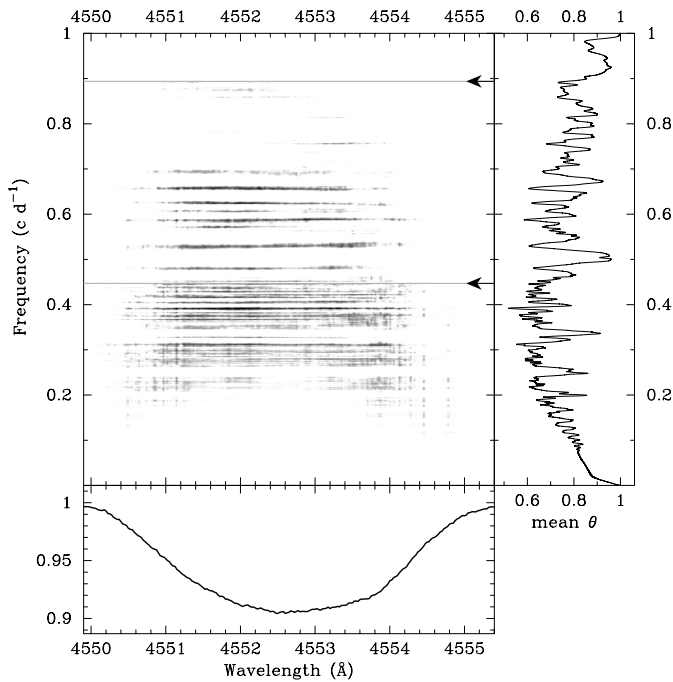


Fig. 10. Two-dimensional PDM θ -statistics of the intensity variations as a function of position in the 4553 Å profile. The arrows indicate the “super” period P_{super} and the “rotational” period P_{rot} (Harmanec 1999). The bottom panel gives the averaged line-profile. The right panel gives the θ -statistics averaged over the wavelength bins.

data is taken over a longer time base, resulting in a higher frequency resolution in our periodograms. We find no evidence of the new frequency of 2.84 c d^{-1} reported by Gies et al. (1999). On the other hand, we do find a frequency of 5.675 c d^{-1} in the second moment, which is about twice the value reported by Gies et al. (1999). Also, we do not find strong evidence for power at the frequency 12.5 c d^{-1} , a frequency that Telting & Schrijvers (1997) found in the data of Gies & Kullavanijaya (1988) and which they identified as the harmonic of the signal at frequency 6.25 c d^{-1} . In the first moment $\langle v \rangle$, two new candidate frequencies show up: 7.155 c d^{-1} and one near 0.500 c d^{-1} .

When we conduct a PDM-analysis which allows exotic phase curves, we do find indications in our spectroscopic data in favour of the “super” period P_{super} , as induced by Harmanec (1999). The phase plots of the higher order moments $\langle v^2 \rangle$ and $\langle v^3 \rangle$ (see middle and bottom panel of Fig. 8 for 4553 Å), and of the residual central line depths (I_c) of the line-profiles (see middle panel of Fig. 11 for 4553 Å) also indicate variations with P_{super} . The first moment $\langle v \rangle$ is the only data set in which we do not find indications for P_{super} , nor for the frequencies proposed by Gies et al. (1999). Note that the frequency 7.155 c d^{-1} we find in $\langle v \rangle$ corresponds to the period $0^{\text{d}}13976$, which is yet another integer submultiple of P_{super} : $1^{\text{d}}11878/8 = 0^{\text{d}}1398475$. At present, it is not clear to us if the frequencies found with CLEAN can give rise to a beat-period of $1^{\text{d}}118$. Neither can we decide that P_{super} is the (only) physical frequency active in ε Per.

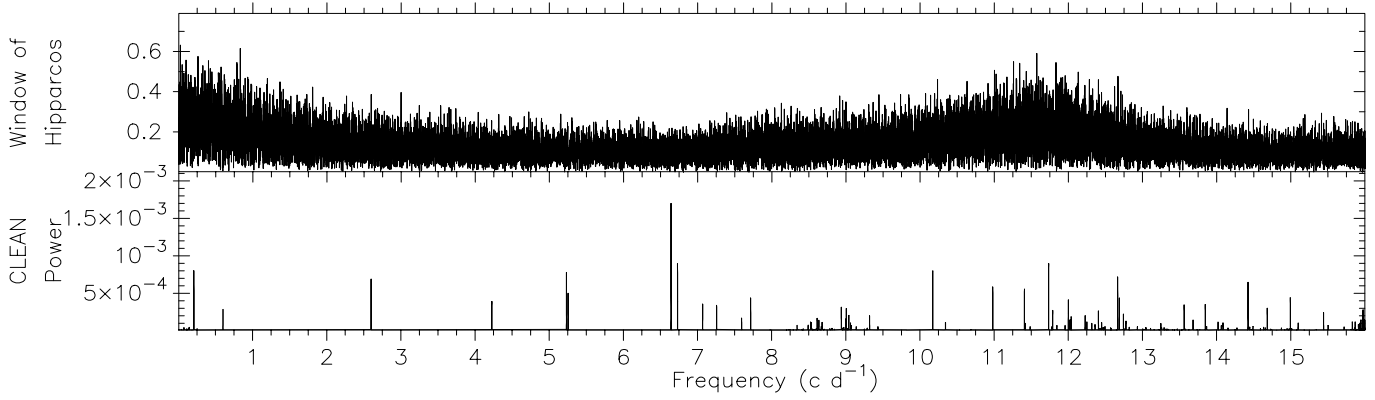


Fig. 12. The CLEANed periodogram of the Hipparcos photometry. The top panel gives the window function of the data.

5.2. Hipparcos Photometry

Hipparcos has observed ε Per during its mission. It is worthwhile to analyse the H_p magnitudes because they are accurate for bright stars and the data have a long time base (1123 days). Previous studies of Hipparcos data have led to the clear detection of variability (see e.g. Eyer & Grenon 1997), even in the case of short-period variables such as δ Scuti stars (Eyer & Grenon, 1998). Moreover, few photometric studies of ε Per are published and only one of them has resulted in the detection of a period that is compatible with the spectroscopic behaviour (Smith et al. 1987).

We retained the 53 Hipparcos data points with quality label 0. Identifying frequencies from this dataset spanning about 1000 days has to be done with care. The window function of the Hipparcos data is shown in the upper panel of Fig. 12. The HWHM of the central peak is 0.00065 c d^{-1} . Again, the “true” error must be lower, so the frequency analysis was done with a frequency resolution of 10^{-4} c d^{-1} .

The CLEAN runs that we performed gave different best frequencies, depending on the value of the gain and the number of iterations. Each time, we obtain a complicated spectrum of possible frequencies with a low amplitude. As an example, the power spectrum for a gain of 0.2 and 400 iterations is shown in the lower panel of Fig. 12. For three of the peaks in the power-spectrum reaching 3 mmag, the corresponding frequencies, the variance reduction in the data, and the amplitude for a mono-periodic fit are listed in Table 7. A triperiodic model with these frequencies reduces 59% of the variance in the Hipparcos photometry.

Finally, we performed a regression analysis by considering frequencies in the range $[2, 11] \text{ c d}^{-1}$. The frequencies that reduce more than 30% of the variance are listed in the middle panel of Table 7. All three together, they reduce 51% of the variance in the data. We also performed some regression analyses for a biperiodic model. We fitted biperiodic sinusoids with the first and second frequency respectively in the range of: firstly $[5, 7] \text{ c d}^{-1}$ and $[10, 12] \text{ c d}^{-1}$ (all IPS frequencies are accounted for), and secondly $[5, 6] \text{ c d}^{-1}$ and $[6, 7] \text{ c d}^{-1}$ (all MPS frequencies are accounted for). The two best pairs of frequencies are listed in the bottom part of Table 7. As best combination, we re-

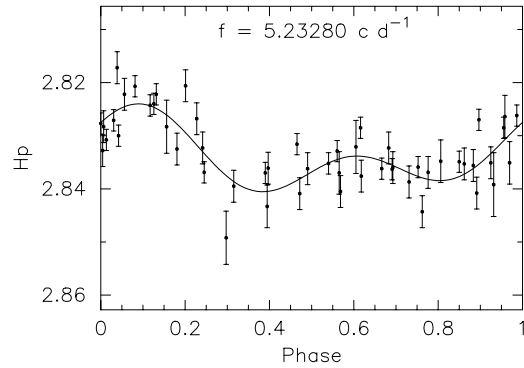


Fig. 13. A phase plot for the Hipparcos data of ε Per for the frequency 5.23280 c d^{-1} and its first harmonic.

Table 7. The frequencies found in the Hipparcos photometry with different frequency analysis methods, together with their corresponding amplitude A and variance reduction (f.v.). Top: three of the highest peaks in the periodogram of a CLEAN-analysis for a gain of 0.2 and 400 iterations. Middle: three best frequencies that sort from a regression analysis in the frequency interval $[2, 11] \text{ c d}^{-1}$. Bottom: the two best pairs of frequencies found from a biperiodic regression analysis with search ranges of $[5, 7] \text{ c d}^{-1}$ and $[10, 12] \text{ c d}^{-1}$, and of $[5, 6] \text{ c d}^{-1}$ and $[6, 7] \text{ c d}^{-1}$ for respectively the first and second frequency.

Frequency	A (mmag)	f.v.	Method
5.2329 c d^{-1}	48(10)	32%	CLEAN
6.6433 c d^{-1}	55(11)	37%	CLEAN
11.7350 c d^{-1}	51(10)	33%	CLEAN
3.4951 c d^{-1}	54(11)	33%	mono regr.
5.2328 c d^{-1}	50(10)	33%	mono regr.
6.6433 c d^{-1}	55(11)	37%	mono regr.
5.2328 c d^{-1}	51(8)		
10.4655 c d^{-1}	50(9)	60%	biper.regr.
6.7433 c d^{-1}	47(8)		
11.7579 c d^{-1}	57(9)	60%	biper.regr.

cover 5.2328 c d^{-1} and its first harmonic, which reduce 60% of the variance in the Hipparcos data. A phase plot for this solution is shown in Fig. 13.

It was already clear from previous studies that ε Per's photometric behaviour is complicated. Smith et al. (1987), however, were able to detect the frequency 6.25 c d^{-1} with an amplitude of 4 mmag in their B and V data, which are spread over 6 days. This frequency does not show up in our frequency analyses, although we find a very small peak at 6.2176 c d^{-1} in one of the CLEAN periodograms. To compare our result with Smith et al.'s, we also performed a regression analysis for the interval $[6.2, 6.3] \text{ c d}^{-1}$. A local maximum of 17% variance reduction is found for the frequency 6.2569 c d^{-1} , and a fit that includes the first harmonic of this frequency reduces 22%. This result is clearly worse than the one based on the frequency 5.2328 c d^{-1} . A comparison of the phase diagram shown in Fig. 13 with the light curves given by Smith et al. (1987, their Fig. 15) shows that our solution gives a better fit to the data (the scale in Fig. 13 was taken the same as the one used in Smith et al. to allow a fair comparison). Moreover, our solution is based on data spread over a much longer timescale and of better quality.

We conclude that we find evidence for the presence of the frequency 5.2328 c d^{-1} and its first harmonic in the Hipparcos data. A similar conclusion was drawn by Harmanec (1999), who gives 5.23265 c d^{-1} as a possible frequency. The photometric variability of ε Per is well-described, but not completely explained, by the model that we propose in Fig. 13. The scatter in the phase diagram is (still) comparable to the amplitude of the periodic observation. It is very probable that additional frequencies determine the variability. There is currently no photometric data set that allows a better determination of the photometric frequencies.

6. Discussion

We were able to perform an analysis of the line-profile behaviour of ε Per on high-quality data that fully cover the orbital period of the star. The orbital solution that we find for the binary is in full agreement with the one proposed earlier by Tarasov et al. (1995) and leads to more accurate orbital parameters once the orbital period is fixed to the value derived by Tarasov et al. Our data does not offer a stringent test for the proposition by Tarasov et al. that the binary ε Per moves in a wide orbit with a yet unknown third star and a period of 4156 days.

The line profile variability of the star is very complex, as was already shown in previous recent studies. When using the CLEAN-algorithm, our extensive data set reveals the same frequencies as those already reported in the literature (e.g. Gies et al. 1999). When using the PDM-method with an appropriate binstructure to allow complicated phase curves, we find some indications for the presence of the “super” period $P_{\text{super}} \equiv 1^{\text{d}}.11878$, as introduced by Harmanec (1999), but many other periods are at the same level of detection. Harmanec already pointed out that some of the frequencies found in previous studies can be described as integer submultiples of this P_{super} . This is also true for one of the frequencies found in the first velocity moment $\langle v \rangle$, 7.155 c d^{-1} . At this point of our study, we can not exclude that all the frequencies found with CLEAN are a consequence of phase locking.

Our interpretation of the physical origin of the complex line-profile variability in terms of i) corotating circumstellar structures above the stellar photosphere, ii) multiperiodic non-radial pulsation will hopefully shed new light in this discussion. We will publish our findings in a separate paper once the analyses will be finished.

Aerts et al. (1998) have found evidence for a change in the frequency spectrum of β Cru as a function of the orbital phase. Although this important observational finding needs further verification, it shows that the tidal forces can play an important role in the line-profile behaviour of stars with an eccentric orbit. We have tried to search for the same effect in ε Per, but the short orbital period in combination with the complicated frequency pattern makes it difficult to draw conclusions. We grouped the data of the three nights around apastron (19–21/10/1996) and those around periastron (26–28/10/1996) and compared their CLEAN spectra of the first moment. We find a different structure in the periodogram, with evidence for the frequency 6.25 c d^{-1} at apastron and 6.87 c d^{-1} at periastron. These two frequencies also appear from the frequency analyses of the moments and of the intensity variations. Besides a different order of appearance of the frequencies, we also find a different amplitude for each of them. It is tempting to interpret these different main frequencies and their amplitudes as being due to a difference in tidal effects in peri- and apastron (Fitch 1967, 1969). This, however, would be too speculative since performing a frequency analysis night per night also leads to a different dominant frequency for the separate nights. Moreover, successive nights near apastron also reveal a clearly different line-profile behaviour (see Fig. 1). We thus conclude that it is not possible to derive any information on the importance of tidal effects for the line-profile variations in ε Per.

Acknowledgements. P. De Cat acknowledges the financial support of the Belgian Fund for Joint Basic Research, Project No. G.0398.98. We thank the referee, Dr. Petr Harmanec, for his very careful reading of our manuscript and for the numerous helpful comments that helped to improve the quality of the paper.

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