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The observational status of the Slowly Pulsating B star ι Herculis*

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Abstract. New spectroscopic and photometric measurements are presented concerning the SPB binary star ι Her. Our observations are spread over 10 years, and consist of 10 spectroscopic nights in 1985, 7 spectroscopic nights and 22 photometric nights in 1987, and 15 spectroscopic nights in 1995. In addition, we analysed the photometric observations provided by Hipparcos (1990–1993) as well as all published radial velocities. We used all the spectroscopic data to refine the binary ephemeris. It was therefore possible to study the pulsation variability properly.

Despite our large data set, only one frequency has been clearly established: $\nu_1 = 0.28671$ c.d^{-1}, for which an ephemeris is provided. Three other frequencies are detected: $\nu_2 = 0.43$ c.d^{-1}, $\nu_3 = 0.77$ c.d^{-1} and $\nu_4 = 0.2483$ c.d^{-1}. The ν_2 frequency is present in most data sets, ν_4 is detected only in Hipparcos data (longtime basis of homogeneous data set), while ν_3 is detected in only one data set.

The precision on the value of ν_1 allowed us to estimate the phase-lag between photometric and spectroscopic variations for the first time in an SPB star. The lag of the photometric maxima with respect to those of velocity is around 0.64 period i.e., significantly different from what is measured in the classes of variable stars surrounding the SPB stars.

The pulsation amplitude has varied in a complex way during the last 10 years. It has increased during the 3 years of photometric observations by Hipparcos, while a decrease by a factor 2 was observed in spectroscopic data between 1985 and 1995.

Periodograms of both photometric and spectroscopic variations show faint peaks in the [6;8] c.d^{-1} and [15;25] c.d^{-1} frequency regions. However, one of our data sets, providing a good precision on the velocity variations, shows a rather flat periodogram after 5 c.d^{-1}, with no detectable peak having an amplitude above 0.05 km s^{-1}. Therefore, these relatively high frequencies may have a transient nature. Although ι Her is one of the best observed SPB star, its variability behaviour is still uncertain, and long term monitoring is needed.

Key words: stars: binaries: spectroscopic – stars: individual: ι Her – stars: oscillations – stars: variables: general

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* Partially based on observations obtained at the Observatoire de Haute Provence

1. Introduction

Slowly Pulsating B stars were named from Waelkens (1991) who detected, in mid-B stars, multiperiodic photometric variations (on time-scales of tens of hours) attributed to non-radial g-modes. This is confirmed by the models where the stars are destabilized by a κ-mechanism originating in the iron opacity bump (see e.g. Dziembowski et al. 1993). But two problems still remain. First, only a few modes are detected in SPB stars, whereas numerous modes are excited in the models. The study of an SPB star observed over a long time range should provide a good test about mode detection but also on the long-term stability of the pulsations. Second, some of the hotter SPB stars seem to present an additional shorter time-scale variability that may be explained in terms of p-modes which are an observational characteristic of β Cephei stars. Actually, the hotter SPB stars may also belong to the cooler part of the β Cephei stars instability strip.

The SPB star ι Herculis (HR 6588, V = 3.80, B3 IV) is a good candidate with respect to these two points: it has a long story of both photometric and spectroscopic variability, and is among the hottest SPB stars. Up to now, many detected frequencies have been reported in the literature, in the range 0.76–34 c.d^{-1}. Smith (1978) found profile variations that were fitted with at least 3 different frequencies (1.7, 2.4 and probably 4.8 c.d^{-1}) with amplitude changing on a time scale of months, and thus classified the star in the 53 Per group. Smith (1981) also analysed six weak absorption lines in the range $\lambda\lambda$ 4127–4132 and found variations by a factor of 3 in frequencies between one and a few cycles per day. As these lines are very sensitive to temperature changes, he associated these variations with nonradial pulsations. Line profiles variations were also reported by Le Contel et al. (1987). While large variations in one night were observed in photometry by Warman (unpublished, cited by Smith 1981), nothing seemed to appear, at least within 1–2 hundredth of a magnitude, in the data set of Seeds (1971). During the preparation of an ultraviolet atlas of ι Her (Upson & Rogerson 1980) Rogerson (1984) discovered a larger than expected scatter in the radial velocity of this star, identified as a two-frequency variation of 0.66 and 0.62 c.d^{-1}. Recently, a spectroscopic study (Mathias & Waelkens 1995, hereafter Paper I) showed that the usual low frequencies reported for this star in the literature could not explain the variations of the radial velocity curves, and that two main frequencies were detected in the data, around 0.3 and

0.7 c.d^{-1}. Finally, Mulliss (1996)[1] presented, from 58 spectra, radial velocity variations spanning about 400 nights. He detected the frequencies given by Rogerson (1984) and reported a new frequency (1.25 c.d^{-1}). Mulliss (1996) also pointed out that other frequencies should be present.

In addition to these typical SPBs frequencies, higher ones are often detected in ι Her. First, Gonzalez-Bedolla (1981) measured a 16 c.d^{-1} frequency in his photometric data. Later, Chapellier et al. (1987) detected β Cephei-type frequencies in their data sets (7 or 8 c.d^{-1} in photometry, and 8.5 c.d^{-1} in spectroscopy) during a few days in 1981 and 1983. A higher frequency, of the order of 20 c.d^{-1}, was also present in the data of Paper I. This was attributed to p-modes on the basis of the location of ι Her in the HR diagram. The conclusion of Paper I was that such "hybrid" stars would be of particular interest for the knowledge of the stellar structure, since both upper (via acoustic modes) and inner (via gravity modes) parts of the star could be simultaneously studied.

In addition to this complicated pulsation pattern, Kodaira (1971) and Abt & Levy (1978) deduced from their data analysis that ι Her was a component of a binary system, with an orbital period around 113 d.

The aim of this paper is to improve our understanding of this star using new and published spectroscopic and photometric data (described in Sect. 2). We first refined the binary elements (Sect. 3) in order to remove the orbital motion before studying the pulsational behaviour of ι Her. Then the power spectrum of the variations is analysed in Sect. 4, and discussed in Sect. 5. Finally, some conclusions are given in Sect. 6.

2. Observations and data reductions

2.1. Spectroscopy

A first series of 127 spectra was obtained during 10 consecutive nights (from July 22 to July 31, 1985) at the Observatoire de Haute-Provence with the 1.93 m telescope and the TGR spectrograph. Two spectral regions were selected, one around the Si III triplet $\lambda\lambda$ 4552, 4567, 4574, and the other around the He I $\lambda\lambda$ 5876 line, each region being observed for 5 nights. The resolving power was very high, above 80 000, and the average exposure time was around 30 minutes, leading to a signal-to-noise ratio of the order of 25. Preliminary results are presented in Le Contel et al. (1987), and the associated radial velocity curves are represented in Fig. 1.

Another series of spectra has been obtained at the Coudé focus of the 1.93 m telescope at the Observatoire de Haute-Provence in 1987. About 60 spectra distributed over 7 consecutive nights (from July 8 to July 14, 1987) were performed with the ISIS fiber fed spectrograph equipped with a 512 pixels CCD. The dispersion was about 8 Å.mm^{-1} in a domain centered on the He I $\lambda\lambda$ 4437 line. A thorium hollow cathode was used for wavelength calibrations and a tungsten lamp for flat field corrections. Final spectra, reduced to the continuum, were filtered with a polynomial function, the resolving power being around 10 000. The heliocentric radial velocities were derived from the average of the measurements of the following 5 lines: He I $\lambda\lambda$ 4387, 4437, 4471, O II $\lambda\lambda$ 4414 and Mg II $\lambda\lambda$ 4481.

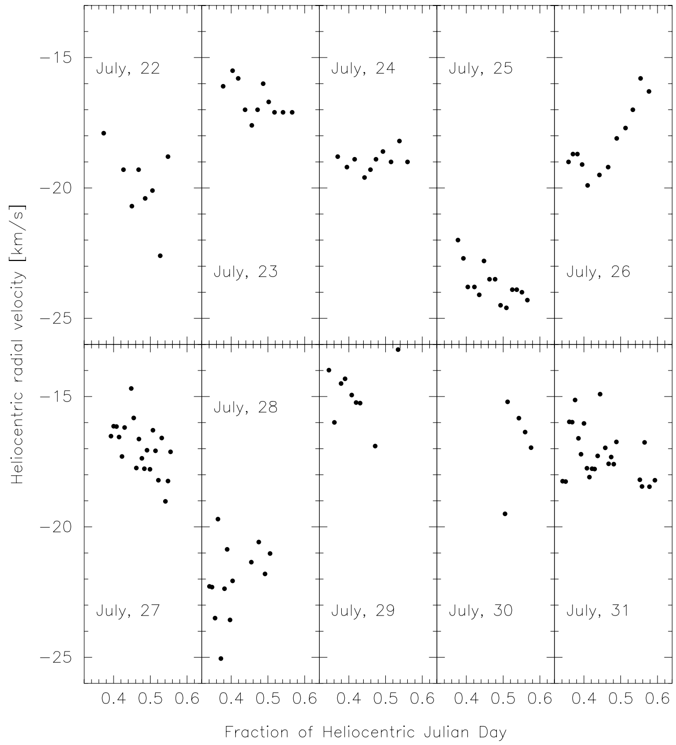

Fig. 1. Heliocentric radial velocity curves obtained in 1985. The five first nights concern the Si III $\lambda\lambda$ 4552 line, while the five last nights concern the He I $\lambda\lambda$ 5876 line

The relative stability of the instrumentation was checked on the RV standard γ Equ, measuring the Mg II doublet. The heliocentric radial velocity of this star was observed constant within ± 1 km s^{-1}. The deduced radial velocity curves are represented in Fig. 2 The velocity curves show night-to-night variations in a range of 8 km s^{-1}, but it is difficult to measure more than a global tendency during a given night.

More recent observations were obtained in 1995 with the spectrograph AURELIE (Gillet et al. 1994), at the Coudé focus of the 1.52 m telescope of the Observatoire de Haute-Provence. The detector was a mono-dimensional CCD. The data were obtained during 10 nearly consecutive nights between May 19 and May 30. The spectral range was centered around the Si III triplet $\lambda\lambda$ 4552, 4567, 4574. The resolving power was around 60 000. To ensure a signal-to-noise ratio above 200, the average exposure time was around 20 min. More than 180 spectra were obtained. The reduction processes are the same as the observations used in Paper I. The corresponding velocity curves are represented in Fig. 3. The radial velocity was computed using the Si III $\lambda\lambda$ 4567 line. The Si III $\lambda\lambda$ 4552 line is blended with S II line while the Si III $\lambda\lambda$ 4574 line is relatively faint. The total velocity amplitude varies within a window of approximately 5 km s^{-1} wide. The amplitude recorded during one individual night never exceeds 2.2 km s^{-1} (May 28$^{\text{th}}$). Note that the in-

[1] document available at http://ardbeg.astro.utoledo.edu/ritter/cmulliss.ps

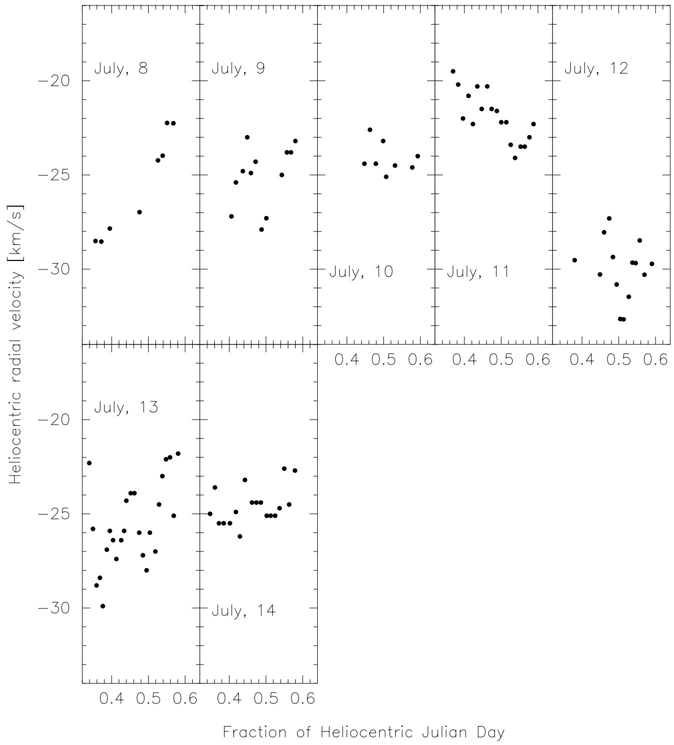

Fig. 2. Heliocentric radial velocity curves obtained in 1987. They are computed as the average of 5 lines (see text)

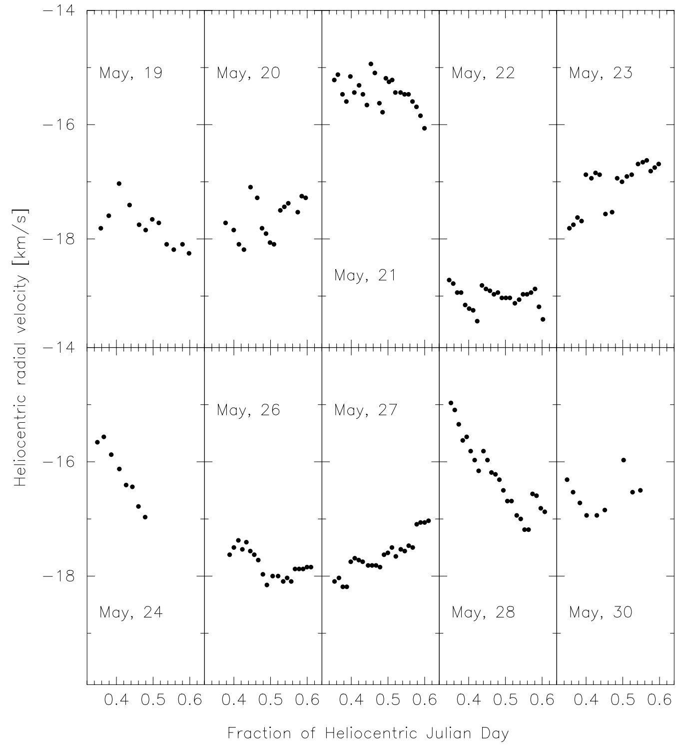

Fig. 3. Heliocentric radial velocity curves obtained in 1995 with AURELIE. The small jumps in velocity (one or two tenth of $\mathrm{km\,s^{-1}}$) approximately each hour are due to a pixel drift

ternal precision is better than that concerning the 1987 data. However, the velocity jumps noticed on the curves are not real, but due to a pixel drift.

In addition, ι Her was observed (May 17 to May 21, 1995) with the cross-dispersed spectrograph ELODIE (Baranne et al. 1996) at the Cassegrain focus of the 1.93 m telescope of the Observatoire de Haute-Provence. The detector was a 1024×1024 elements CCD. For the whole visible range, the resolving power was about 40 000. To obtain a signal-to-noise ratio around 200, the typical exposure time was around 5 min. The spectra were reduced with the INTER-TACOS software (Baranne et al. 1996) which takes care of the offset and flat-field pixel-to-pixel corrections, as well as the wavelength calibration in the heliocentric frame. To ensure a good internal precision ($< 0.1\,\mathrm{km\,s^{-1}}$), the stellar and thorium lamp spectra were obtained concurrently. The velocities were deduced from the correlation peak obtained from more than 220 spectral lines. Fig. 4 represents the corresponding radial velocity curves. The radial velocity ranges between -19.0 and -15.6 $\mathrm{km\,s^{-1}}$. As can be noted, the dispersion is very small.

2.2. Photometry

Our observations were obtained in 1987, from two 8 hour separated observatories: Sierra Nevada in Spain and San Pedro Màrtir in México. The v filter of Strömgren's system was used. The star HD 161569 (B9.5 V, V=6.6) was taken as a comparison and HR 6509 (A4 V, V=5.8) as a check star. No significant variations within 0.003 magnitudes were found in the differences between comparison and check stars during all the campaign.

Due to a probable instability of the instrument together with poor weather conditions, the San Pedro Màrtir observations were not considered further in this paper. In Spain, observations were collected during the second half of July and the first half of August (15 nights spanning 28 days). The observations of the 10 best nights are presented in Fig. 5. The total amplitude is about 0.028 mag, and night-to-night variations are present.

Finally, we also used Hipparcos data (ESA 1997) which consist of two sets (105 measurements each), corresponding respectively to filters B_T and V_T. The measurements are spread over about 1 000 days. Depending on the considered filter, the total amplitude range is 0.046 or 0.033 mag.

3. Determination of the orbital elements

Since the velocity amplitude of the orbital motion is comparable to that of the pulsation motion, it is necessary to remove the orbital component from the total variation before the pulsation motion analysis. We first considered the orbital ephemerides provided in the literature by successively Kodaira (1971), Abt & Levy (1978) and Mulliss (1996). However, mainly due to a bad phase coverage and because pulsations were involved, a clear dispersion appears between these ephemerides, in particular concerning the eccentricity ($e = 0.43$ for Abt & Levy (1978) and $e = 0.38$ for Mulliss (1996)). This parameter is very important since it determines the shape of the orbital velocity

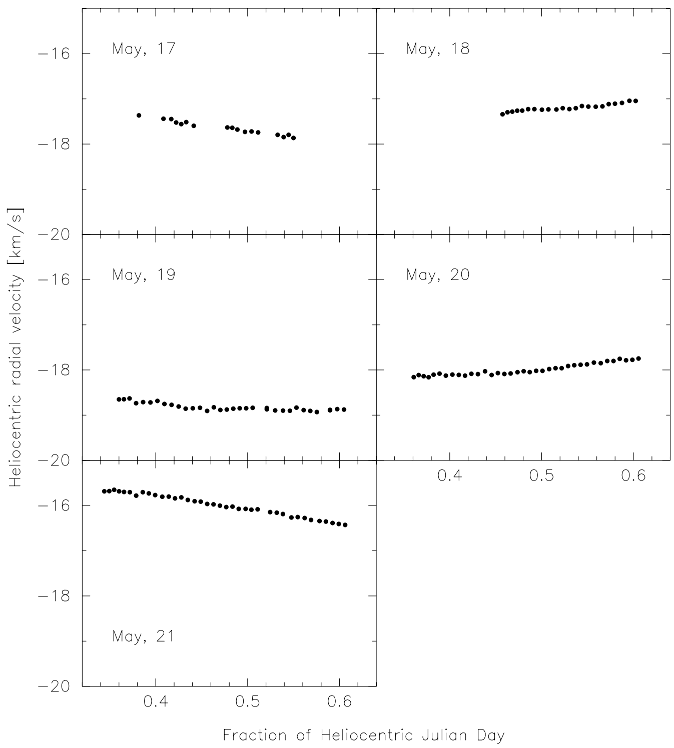

Fig. 4. Heliocentric radial velocity curves obtained in 1995 with ELODIE

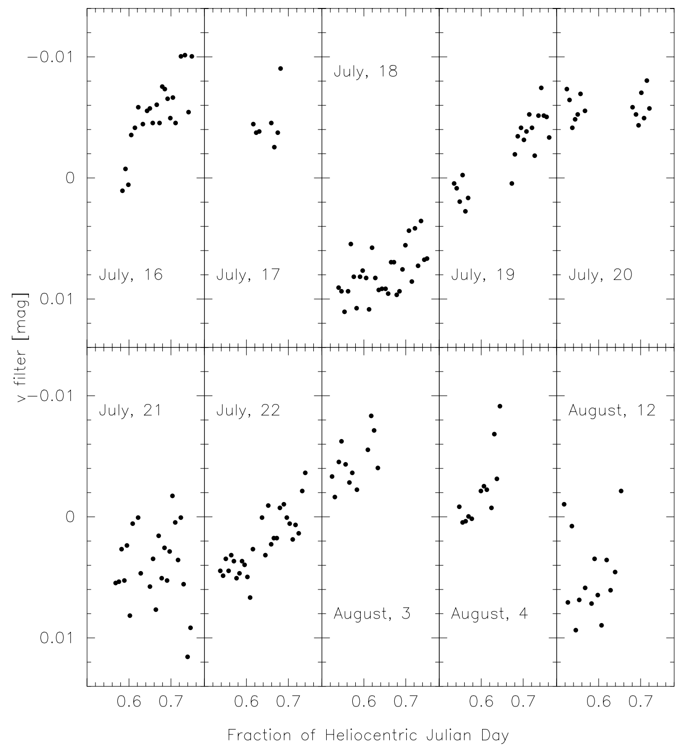

Fig. 5. Best photometric data obtained in 1987 in the Sierra Nevada Observatory

curve to remove from our data. We thus decided to use all previous spectroscopic data available in the literature to compute a new ephemeris. In order to reduce the effect of the pulsation component, we considered only the average velocity of a given night if more than one observation was obtained during that night. The more scattered data are those of Kodaira (1971). This may be due to the low dispersion used (20 Å.mm^{-1}), and to the measured lines (Balmer lines, certainly blended, subject to Stark effect and having wide profiles). Nevertheless, because his data were well distributed during his observing run, we took them into account with the exception of 4 points, which were too far away from any other observation. The parameters of the binary system were thus determined using 133 data points, representing the average of 1002 measurements. They are given in Table 1. Assuming a mass of 7 $M_\odot$ for the primary, the mass function provided here implies an upper limit of 0.4 $M_\odot$ for the companion. This result agrees with the white dwarf usually suspected (Peters & Aller 1970). The binary orbit together with the data (each night being averaged) are represented in Fig. 6.

Our orbital elements differ significantly from those given by Abt & Levy (1978); for instance, our period and eccentricity are out from their proposed range. Conversely, our elements are more or less within the error bars given by Mulliss (1996), except the eccentricity and the orbital amplitude which are respectively significantly larger and lower. Note that our time basis is much more important than Mulliss's one (1996): about 58 years compared to a bit more than 1 year. It is also larger than that of Abt & Levy (1978), who used only about 100 data spread over 38 years. This explains why our confidence level is rather

Table 1. Parameters of the binary orbit. P is the orbital period, γ is the center-of-mass velocity, K is the orbital velocity amplitude, T is the epoch of periastron passage, e is the eccentricity, ω is the longitude of periastron, $a\sin i$ is the projection of the semi-major axis and $f(m)$ is the mass function

$P = 112.825 \pm 0.008\,\mathrm{d}$
$\gamma = -19.9 \pm 0.2\,\mathrm{km\,s^{-1}}$
$K = 5.7 \pm 0.4\,\mathrm{km\,s^{-1}}$
$T = 2449709.46 \pm 1.38\,\mathrm{d}$
$e = 0.55 \pm 0.04$
$\omega = 210^\circ \pm 7^\circ$
$a\sin i = (7.4 \pm 0.8)\,10^6\,\mathrm{km}$
$f(m) = 0.0013 \pm 0.0004\,\mathrm{M_\odot}$

high. These new elements were used to subtract the orbital motion from the different velocity sets considered in the following sections.

4. Frequency analysis

4.1. Low frequencies

Three different methods, adapted to unequally spaced data, were used to perform the frequency analysis: Fourier, CLEAN (Roberts et al. 1987) and PDM algorithms (Stellingwerf 1978). Only the Fourier searches (Breger 1990) are presented; the PDM method confirms this analysis, while the CLEAN method leads to doubtful results in some cases.

We first concentrated on typical SPBs behaviour i.e., we looked for frequencies in the range [0;5] c.d^{-1}. However, be-

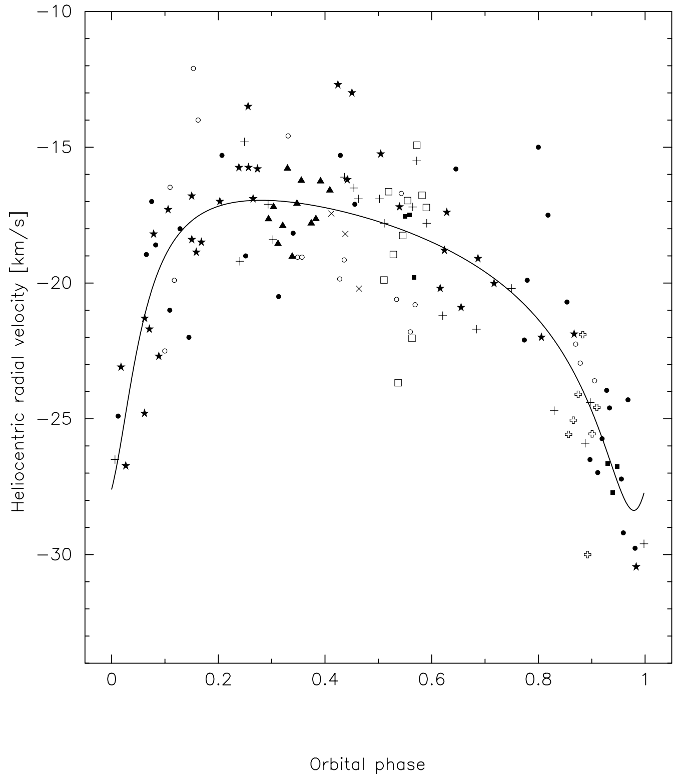

Fig. 6. Plot of the orbital radial velocity curve together with different data sets: Petrie & Petrie (1939): black dots; Kodaira (1971): circles; Abt & Levy (1978): crosses; Chapellier et al. (1987): ×; Le Contel et al. (1987): open squares; 1987 data (this paper): open crosses; Paper I: black squares; Mulliss (1996): black stars; 1995 data (this paper): black triangles

cause no significant peak is present above 2 c.d^{-1}, and for clarity, we presented only periodograms in the [0;2] c.d^{-1} frequency range (Fig. 7). Once the main frequency peak was detected, a sinusoid was fitted to the different data sets. It appeared that sometimes the maximum amplitudes (and the minimum residuals) did not correspond to the main peak. In this case, we retained only the frequency provided by the sine-fit (i.e., having the minimum residuals). A summary of this analysis is given in Table 2. A frequency around 0.29 c.d^{-1} is common to all our observation series. Paper I was the only previous study to report such a frequency. We thus decided to perform the same analysis on different data sets available in the literature:

- the 408 radial velocities of Paper I
- the 58 radial velocity measurements of Mulliss (1996) scattered over one year. The considered line is S II ($\lambda\lambda 5454$), for which the measurements are the most numerous
- the Hipparcos data, which consist of 105 observations recorded through both B_T and V_T filters (close to Johnson B and V)
- the 161 UV radial velocities obtained from a scan of Rogerson's (1984) observations.

Results are listed in Table 2. The previously noted frequency around 0.29 c.d^{-1} appears also in Paper I and Hipparcos data.

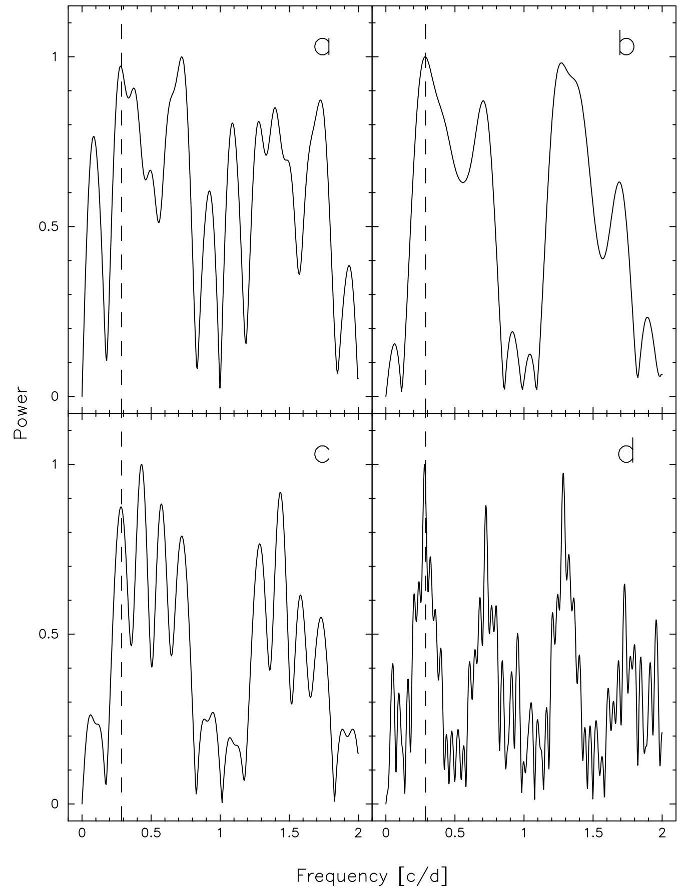

Fig. 7a–d. Fourier periodograms corresponding to different data sets. Power is normalized to unity. a: 1985 spectroscopic data. b: 1987 spectroscopic data. c: 1995 spectroscopic data (AURELIE). d: 1987 photometric data. The vertical dashed line represents the position of the ν_1 frequency (see text)

In Mulliss's data (1996), the 1.287 c.d^{-1} detected frequency can be interpreted as a 1 day alias of the 0.29 c.d^{-1} frequency. As for the 0.76 c.d^{-1} frequency detected in Rogerson's (1984) data, it will be discussed below. Therefore, we can retain a main frequency around 0.29 c.d^{-1} present in both photometric and spectroscopic observations. Hipparcos provides the most precise value: $\nu_1 = 0.28677$ c.d^{-1}, because its measurements are spread over a large time range and have the better distribution (in particular no alias). However, since the very wide observing window leads to a Fourier periodogram with many peaks, it is the CLEAN result that is represented on Fig. 8.

The ν_1 frequency is not detected in Rogerson's (1984) observations while the periodograms, obtained from the 3 different methods cited above show a main peak at 0.766 c.d^{-1}, associated with an amplitude of 1.92 km s^{-1}. A prewhitening of Rogerson's data with this frequency leads to a second one at 0.47 c.d^{-1}, with an amplitude of 0.99 km s^{-1}. In order to improve this result, we computed a sine-fit with these two frequencies as starting values. However our analysis diverged.

The algorithm used by Rogerson in a similar analysis, with the same two frequencies (0.766 and 0.47 c.d^{-1}) as starting val-

Table 2. Results of the frequency analysis concerning different data sets. Epoch is related to the observation campaigns [years], columns "Nights" and "Ranges" represent respectively the number of nights (when meaningful) and the total range (in nights) of the observations, while N is the number of observations in the considered data set. Then ν_m and a_m represent respectively the main detected frequency [c.d^{-1}] and its amplitude [km s^{-1} in the first part of the table, mmag in the second part]. Finally, in the last column the reference from which the data sets have been obtained is given.

Epoch	Nights	Ranges	N	ν_m	a_m	Reference
1979		4	161	0.7644	1.92	Rogerson (1984)
1985	10	10	127	0.28192	2.78	this paper
1987	7	7	103	0.2895	2.78	this paper
1991–1992		398	58	1.2872	1.30	Mulliss (1996)
1993	6	46	408	0.2890	1.19	Mathias & Waelkens (1995)
1995	4	5	148	0.3086	1.42	this paper (ELODIE)
1995	11	10	183	0.2952	1.27	this paper (AURELIE)
1987	15	37	198	0.2792	6.3	this paper (Grenade)
1990–1993		1191	105	0.286753	11.6	Hipparcos B_T
1990–1993		1191	105	0.286785	9.9	Hipparcos V_T

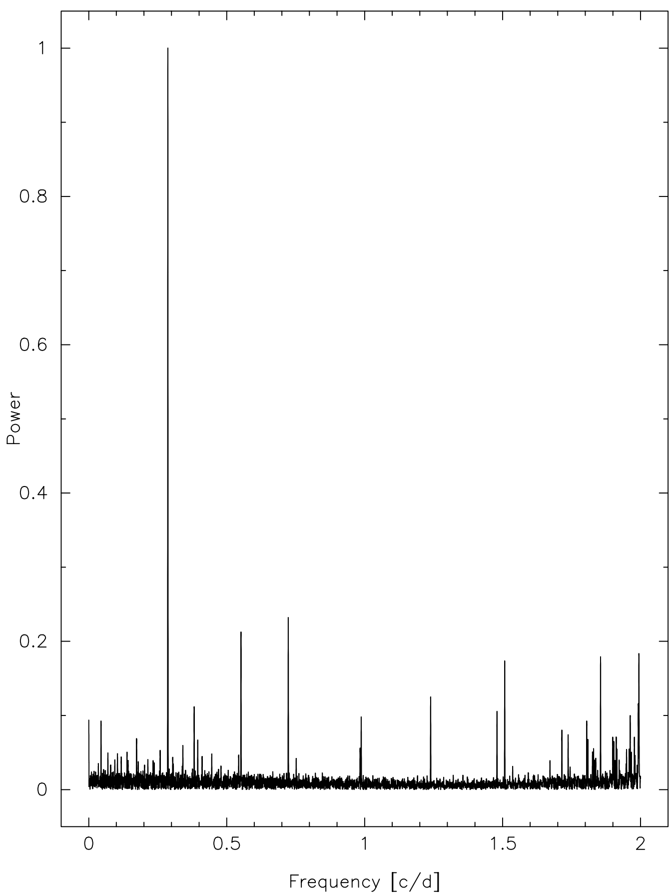

Fig. 8. Periodogram corresponding to the B_T Hipparcos filter. For clarity, only the CLEAN periodogram is represented. The gain used is 0.5, and 100 iterations were performed. Power is normalized to unity. The maximum peak corresponds to the ν_1 frequency (see text)

ues, converged to the 0.618 and 0.660 c.d^{-1} frequencies. We do not agree with these values, because the corresponding beat-period is 24 d, a value much larger than the narrow observing window that spans only 3.6 d. There is also a significant gap between the starting and the final solution. Finally, the corresponding amplitudes are of the order of 10 km s^{-1}, a factor 5 times greater than the values obtained for the starting frequencies. Unfortunately, only the 0.618 and 0.660 c.d^{-1} frequencies are mentioned in Rogerson's abstract and thus became the only cited result. Our interpretation is that the UV variations are best explained by the 0.77 and 0.47 c.d^{-1} frequencies.

From Fig. 7, it is obvious that additional frequencies are present in the different data sets. As can be seen in Table 3, the variance associated with the ν_1 frequency ranks from 19 (Mulliss 1996) to 87 % (Paper I) of the total variance, with a mean value of 56 %. Therefore, other frequencies must be present.

A frequency analysis similar to that conducted above was then undertaken on each data set prewhitened with the "Hipparcos" ν_1 frequency. The corresponding periodograms are presented in Fig. 9, and results are given in Table 3. The situation is less clear than that concerning the ν_1 frequency, with now the presence of 3 frequencies that will be discussed below.

First, a frequency around $\nu_2 = 0.43$ c.d^{-1} is detected in 1985, 1987 and 1995 AURELIE observations with variances ranking from 40 to 77 % in the residuals of ν_1. This ν_2 frequency is identified in the periodograms represented in Fig. 9. Although it has a slightly larger value, the 0.47 c.d^{-1} frequency detected in Rogerson's data (1984) may also be interpreted as the signature of ν_2. Conversely, ν_2 is detected in neither Mulliss's (1996) nor in Paper I data, where its corresponding variance ranks from only 3 to 19 % of the variance. In photometric data, the ν_2 frequency accounts for between 4 and 16 % of the variance (for Hipparcos and Grenade data, respectively). It should be noted that the amplitudes ratios a_2/a_1 are clearly lower in photometry than in spectroscopy (average value of respectively 0.34 and 0.77): this is why the second frequency is more difficult to detect in photometric data.

The $\nu_3 = 0.77$ c.d^{-1} frequency is detected only in Rogerson's data where it accounts for 56 % of the variance. Its non-detection in all the other data sets may be due either to prewhitening or to decreasing amplitude: First, the 0.5 c.d^{-1} alias of the main frequency ν_1 is close to ν_3, and prewhitening the data set

Table 3. Results of the frequency analysis concerning the different data sets prewhitened with $\nu_1 = 0.28677$ c.d^{-1}. Epoch is related to the observation campaigns [years], a_1 represents the amplitude associated with ν_1 [km s^{-1} in the first part, mmag in the second part of the table], while V_1 is the percentage of the variance that ν_1 accounts for. Then, ν_s and a_s represent respectively the main detected secondary frequency together with its amplitude and its variance percentage V_s. Finally, in the last column the reference from which the data sets have been obtained is given.

Epoch	a_1	V_1	ν_s	a_s	V_s	Reference
1985	2.76	41	0.4040	1.99	41	this paper
1987	2.77	45	0.4330	1.91	41	this paper
1991–1992	1.06	19	1.6995	1.49	40	Mulliss (1996)
1993	1.18	56	1.6566	0.91	69	Mathias & Waelkens (1995)
1995	1.36	87				this paper (ELODIE[a])
1995	1.08	48	0.4421	0.96	77	this paper (AURELIE)
1987	6.4	70	1.392	2.1	25	this paper (Grenade)
1990–1993	11.6	62	0.248324	4.1	20	Hipparcos B_T
1990–1993	9.9	75	0.248331	2.9	25	Hipparcos V_T

[a] The frequency analysis did not converge towards any secondary frequency ν_s

with ν_1 reduces the amplitude corresponding to ν_3 below the detection threshold. Second, the amplitude associated with ν_3 may have decreased (the other considered data sets are obtained later). This phenomenon has been observed for the SPB star 53 Per (Chapellier et al. 1998) and is noted for ι Her itself (see Sect. 5.1.3).

Two data sets (Mulliss 1996 and Paper I) present a frequency around 1.7 c.d^{-1}. At least three interpretations may be done: a one-day alias of the linear combination $\nu_1 + \nu_2$, a one-day alias of the $\nu_3 = 0.76$ c.d^{-1} detected in Rogerson's data (1984) or a non-real frequency since both data sets concerned here have a very bad time coverage: 58 measurements scattered over one year for Mulliss, and 408 measurements concerning 2 series of 3 consecutive nights separated by more than a month (Paper I). Thus, it seems safer to discard this frequency from the results of the present study.

Finally, Hipparcos data show, in both filters, a second frequency: $\nu_4 = 0.2483$ c.d^{-1}. Unfortunately, this frequency is too close to ν_1 to be detected in any other data set, much shorter than the beat period between ν_1 and ν_4 (26 d). Only Mulliss (1996) had a sufficient time basis, but his data are not numerous enough.

4.2. High frequencies

As said in Sect. 1, frequencies larger than those recorded above have also been detected both in photometry and spectroscopy, ranging from 2.4 to 34.3 c.d^{-1}. We call them high frequency as they seem to correspond to different modes. As a matter of fact, more than one cycle can be observed within a given night. Table 4 summarizes the different results. Excepting the time scales provided by line profile studies (Smith 1981), the

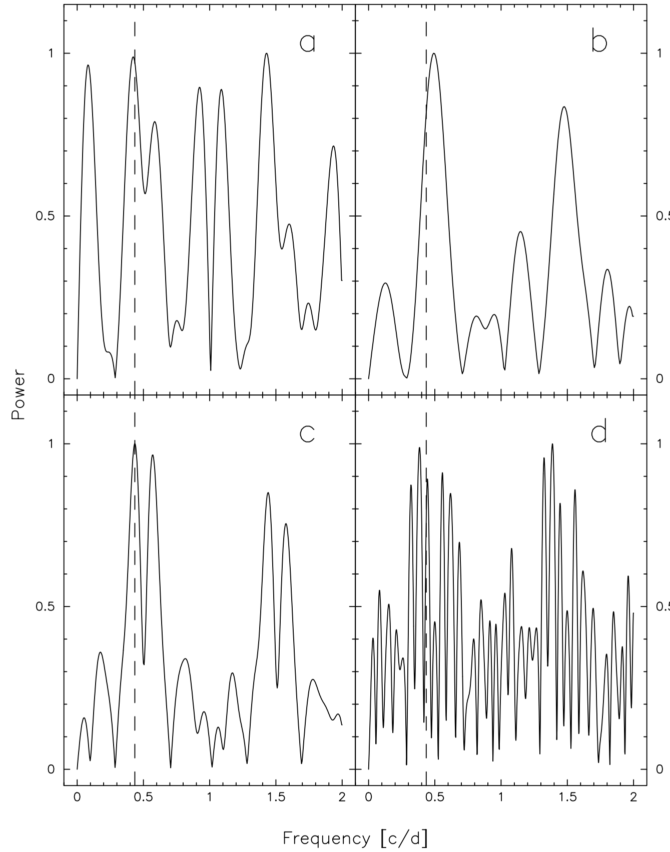

Fig. 9a–d. Same as Fig. 7 after prewhitening with the ν_1 frequency. The vertical dashed lines represent the position of the $\nu_2 = 0.43$ c.d^{-1} frequency (see text)

previous detected frequencies lie in two regions: [7;8.5] c.d^{-1} and [16;24] c.d^{-1}.

We reanalysed the different data sets mentioned in the previous section. The measures were first prewhitened with the ν_1 and ν_2 frequencies. A frequency analysis was then undertaken in the range [0;30] c.d^{-1}. Results for different data sets are presented in Fig. 10. The main peaks are still in the [0;3] c.d^{-1} frequency range, and represent non-detected frequencies of SPBs type, but also linear combinations and harmonics of the ν_1 and ν_2 frequencies.

However, most of the data sets present peaks in the [6;8] c.d^{-1} frequency range (especially in the spectroscopic data obtained in 1987, 1993 and 1995 (with AURELIE)), with corresponding amplitudes between 0.15 and 0.30 km s^{-1}. In addition, spectroscopic data obtained in 1985, 1987 and 1993 present peaks, close to the detection threshold, in the [15;25] c.d^{-1} frequency range. Results concerning the high frequency part of the AURELIE 1995 data spectrum should be treated with caution since pixel drifts occurred, especially considering the ELODIE data obtained at nearly the same epoch (see below).

In Paper I, the authors detected in their 1993 radial velocity data a high frequency, around 20 c.d^{-1}, associated with an amplitude of about 1 km s^{-1}. The correlation mode of ELODIE provides an internal precision better than 0.1 km s^{-1}. It is there-

Table 4. The different high frequencies mentioned in the literature. Epoch is related to the observation campaigns [years]; then are given the frequency scale of the variations [c.d^{-1}], the peak-to-peak amplitude, the used method and the reference of the concerned study.

Epoch	Frequency	Amplitude	Method	Reference
1936	7.1	20 %	intensity ratio	Edwards (1937)
1937–1939	16.	20 %	intensity ratio	Petrie & Petrie (1939)[a]
1937–1939	16.	1. km s^{-1}	radial velocity	Petrie & Petrie (1939)[a]
1976–1977	1.7, 2.4, 4.8		line profile variations	Smith (1978)
1979	34.3 to a few c.d^{-1}		line profile variations	Smith (1981)
1979	17.1	0.03 mag	photometry	Warman (unpublished)
1979	16.1	0.03 mag	V photometry	Gonzalez-Bedolla (1981)
1983	7.0 or 8.1	0.015 mag	UV photometry	Chapellier et al. (1987)
1983	8.5	1.4 km s^{-1}	spectroscopy	Chapellier et al. (1987)
1993	16. – 24.	0.8 km s^{-1}	radial velocity	Paper I

[a] Note that these authors ruled out such a frequency. What we report here is the apparent time scale of the considered variations they published

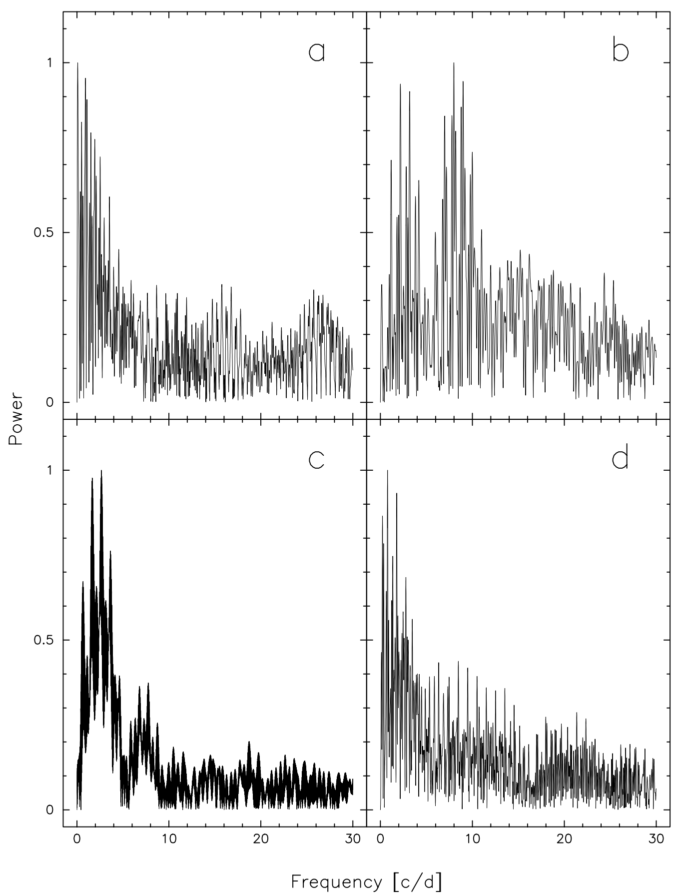

Fig. 10a–d. Fourier periodogram corresponding to different data sets. Power is normalized to unity. a: 1985 spectroscopic data. b: 1987 spectroscopic data. c: 1993 spectroscopic data (Paper I). d: 1995 spectroscopic data (AURELIE)

fore possible to detect the small variation mentioned in Paper I. As can be seen in Fig. 4, the dispersion is very small, and obviously the short time-scale periodicity mentioned in Paper I is not present. A frequency analysis performed on these data shows a very flat power spectrum above a 5 c.d^{-1} frequency. Therefore, no high frequency was present in the pulsation of ι Her during the 1995 observing campaign.

5. Discussion

5.1. The SPBs behaviour

With its B3 IV spectral type, ι Her lies in the SPBs instability trip (e.g. Gautschy & Saio 1996). Several other observed SPBs characteristics, as listed by North & Paltani (1994), confirm this statement. First, the presence and stability over a time scale of years of at least three frequencies is pointed out: ν_1 and ν_4 in between 1990–1993 (Hipparcos), ν_1 and ν_2 in 1985–1987. Second, the amplitude in the Hipparcos B_T filter is larger than that measured in the V_T filter, while no significant phase lag is observed between the two. Finally, the 4 proposed frequencies are in the range of observational and theoretical criteria. Thus, the present study confirms that ι Her should be classified as an SPB star variable.

5.1.1. Ephemeris

From above, Hipparcos data provide a good value of the main frequency: $\nu_1 = 0.28677$ c.d^{-1}. Using it as a starting value, an ephemeris has been computed for all spectroscopic observations between 1983 and 1995:

$$T_{v_{\max}}(E) = 244900.4831 + 3.48781 \; E$$
$$\pm \quad 0.3651 \quad 0.00029$$

where $T_{v_{\max}}(E)$ is the calculated date of heliocentric radial velocity maxima after E cycles. $P = 3.48781$ d is the resulting period, corresponding to the more precise value of $\nu_1 = 0.28671$ c.d^{-1} This new value of ν_1 is very close to that obtained with Hipparcos, being within the error bars. Table 5 gives the mean value of the radial velocity maxima epoch for each observation sets, and the difference $O - C$ between $T_{v_{\max}}$ and the maximum computed with the ephemeris. The ephemeris fits reasonably well all the spectroscopic observations, with a 0.50 d rms. It is compatible with all photometric observations, since the date of mean luminosity maxima of the 1987 observations and the Hipparcos ones are separated by 488.978 cycles, which implies a 3.48765 d (0.28673 c.d^{-1}) photometric period.

Table 5. Epoch of observed heliocentric radial velocity maxima and $O-C$ values [d] computed for each spectroscopic data sets

$T_{v_{\max}}$	$O-C$	References
2445474.9053	0.0800	Chapellier et al. (1987)
2446274.0875	0.5537	Le Contel et al. (1987)
2446987.8835	-0.6513	this paper
2449119.1953	-0.3914	Mathias & Waelkens (1995)
2449548.5529	-0.0344	Mulliss (1996)
2449862.8191	0.3289	this paper

5.1.2. The phase-lag

The phase-lag, defined as the difference between the epoch of maximum luminosity and that of maximum radial velocity, has been computed with two different methods using the period given by the ephemeris:

- comparison of mean luminosity maxima epoch with the ephemeris given above. This method leads, for the Spain and both Hipparcos data sets, to a phase-lag of respectively 0.659, 0.639 and 0.634 P, where P is the main pulsation period
- comparison of the nearly simultaneous spectroscopic and photometric data obtained in 1987. The phase-lag here is 0.845 P

It should be noted that the second method is not as accurate as the first one since we added uncertainties on each maxima determination. Therefore, and because Hipparcos data are the most suitable for SPB stars, the phase-lag value must be around 0.64 P for ι Her. This value, the first one obtained for an SPB star, differs significantly from reported values concerning pulsating stars on each side of the SPBs instability strip: 0.25 P for the β Cephei stars, and 0.5 P for the classical instability strip. However, other observations, involving simultaneous photometric and spectroscopic data, are needed to confirm this result.

5.1.3. The amplitudes

The pulsation amplitudes show important variations during the last 10 years. In spectroscopic data, the amplitude associated with the ν_1 frequency has dropped from 2.76 km s^{-1} in 1985–1987 to 1.08–1.36 km s^{-1} in 1993–1995 (Table 3). The same phenomenon occurred to the amplitude associated with the ν_2 frequency which has decreased by a factor of 2 during the same epoch.

However, this result should be treated with caution, since both the lines used to derive the velocity and the resolution of the different data sets are not the same. In particular, the larger dispersion noted in the 80's data may be enhanced as a bias in the corresponding amplitude.

Because the photometric data concern different filters, nothing can be said over the 1987–1993 period. However, due to their long time basis, a crude study of the Hipparcos data was undertaken. The data corresponding to each filter were binned with 15 points in each subset. Then, a sine-fit using the ν_1 frequency

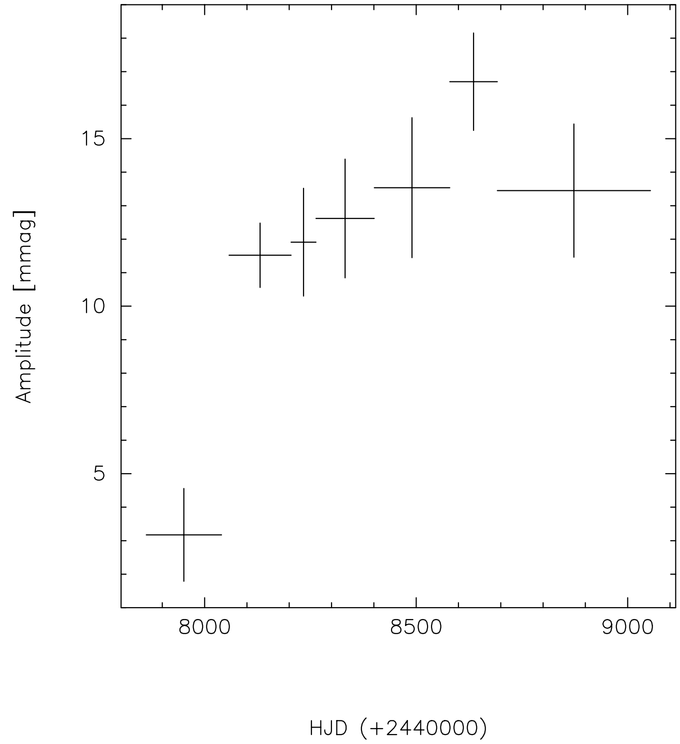

Fig. 11. Evolution of the amplitude of the sine-fit computed with the ν_1 frequency in the B_T Hipparcos filter. Horizontal bars represent the window containing the 15 points, while vertical bars represent the $1-\sigma$ error on the amplitude value

was computed on each subset, providing the evolution of the photometric amplitude with time. The general observed trend is an *increase* of the photometric amplitude (Fig. 11), in both filters.

Thus it appears that the amplitude associated with ν_1 shows opposite variations on time-scale of years. However, observations are neither homogeneous enough nor well spread in time to follow the amplitude evolution over 10 years.

A similar phenomenon has also been observed for the SPB star 53 Per. For this latter, the amplitude associated with one of the two main frequencies increases regularly while the other remains constant (Chapellier et al. 1998). This phenomenon could be quite frequent among the SPB stars, since it is detected in the two best monitored stars of this class.

Furthermore, the amplitude ratios $(2K/\Delta m)$ associated with ν_1 and ν_2 are very different. Using the 1987 data, the values 950 and 430 km s^{-1}.mag^{-1} are respectively obtained. A plausible interpretation is that the two modes have a different ℓ degree, as mentioned, for β Cephei stars, by Cugier et al. (1994).

5.2. The short time scale behaviour

The [6–8] c.d^{-1} frequency range can be related to p-modes of a typical β Cephei star with a low mass (Chapellier et al. 1987). Using the available measures of ι Her in the Genova photometric system together with the adequate calibration (North & Nicolet 1990), the parameters of the star are

$(\log L/L_{\odot}, \log T_{\rm eff})$=$(3.26, 4.24)$. Thus, from these parameters ι Her lies within the SPBs instability strip and just below the tip of the β Cep instability strip as shown by Pamyatnykh (1999). However, Dziembowski et al. 1993 and Gautschy & Saio (1996) ruled out, in this HR diagram region, the existence of p-modes due to a too rapid variation of the lagrangian pressure perturbation within the driving zone: they are only excited in the more luminous stars. Following these studies, only high-order g-modes should be excited in a 7 $M_{\odot}$ (and below) B-star. Hence, the detection of high frequencies in such a low mass star is puzzling. But as shown by Pamyatnykh (1999), the extension of the instability strip for these stars depends mainly on metallicity but also on the overshooting, which causes the effective red-edge of the β Cephei stars to be cooler.

Conversely, the high frequencies, in the [15–25] c.d^{-1} range, are still not understood. Obviously, more observations are needed to confirm their reality.

Another interesting point is the apparent instability of these high frequencies motions. This variability may be due to a transient phenomenon. Such an hypothesis, concerning the β-Cephei pulsation type, has already been invoked for the B2.5 IV star 53 Psc, where a relatively large frequency (10.4 c.d^{-1}) has sometimes been detected (Jerzykiewicz & Sterken 1990).

6. Conclusions

- The analysis of all the data provided by the literature allowed the computation of new binary elements, with a larger eccentricity compared to previous results.
- By subtracting the orbital motion from the observed velocity we could study the "pure" pulsation motion. The observed maximum night-to-night variation is about 8 km s^{-1}. However, within a night, the amplitude is much smaller.
- One SPBs frequency is clearly established: $\nu_1 = 0.28671$ c.d^{-1}. Another frequency is detected in Hipparcos data around $\nu_4 = 0.2483$ c.d^{-1}. A frequency $\nu_2 = 0.43$ c.d^{-1} is present in most spectroscopic data sets, but is very faint in photometric ones. Finally, a frequency $\nu_3 = 0.766$ c.d^{-1} is present in only one data set (Rogerson 1984). The frequency around 1.7 c.d^{-1} is more doubtful since it can be a one-day alias of ν_3 or $\nu_1 + \nu_2$. Obviously, other frequencies are present, but we failed in measuring them.
- Amplitude variations are detected along the 10 years of the observations. The typical time-scale is of the order of years. This phenomenon is similar to the one reported concerning the SPB star 53 Per (Chapellier et al., 1998).
- For the first time, the phase-lag is measured for an SPB star. It is found to be around 0.64 P for ι Her. This represents a new constraint for theoretical models.
- We failed in detecting the high frequencies (around 20 c.d^{-1}) reported earlier (e.g. Paper I). New, long term observations are needed to confirm the reality of this particular behaviour. On the contrary, power is present in the [6;8] c.d^{-1} range in the frequency spectrum of some data sets, corresponding to β Cephei type variation. It seems that the short time scale has a transient nature. No convincing explanation could be given. As both β Cephei and SPBs typical time scales are observed, and since ι Her is located in the HR diagram within the SPBs instability trip and close to the β Cephei one, we propose that it be classified as a "hybrid" star.

Considering their typical low frequencies, together with the many modes potentially excited, SPB stars are difficult to monitor. Although the star ι Her is one of the best observed, its behaviour remains still uncertain. Is ι Her a typical SPB star in its large time scale behaviour? If yes, very long term monitoring is needed to understand both the atmospheric motions and the internal structure of these stars.

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