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Amplitude monitoring of the β Cephei star 16 Lacertae

J.P. Sareyan[1], **J. Chauville**[2], **E. Chapellier**[1], **and M. Alvarez**[3]

[1] Observatoire de la Côte d'Azur, Dept. Fresnel, B.P.229, F-06003 Nice Cedex, France
[2] Observatoire de Meudon, URA 335 du CNRS, F-92195 Meudon Cedex, France
[3] Observatorio Astronomico Nacional, UNAM, Apdo 877, Ensenada, B.C. 22800, Mexico

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Abstract. Based on new observations, it is shown here that the amplitude of one of the three well known and stable short periods in the β Cep variable 16 Lac has changed: while the radial mode $P_1 = 0.16917$ d is near its lower amplitude level and the amplitude variation of the non-radial mode $P_3 = 0.18173$ d is still probably in phase with the orbital period, the amplitude of the NR mode $P_2 = 0.17077$ d has increased progressively by a factor two in the last ten years. The observed phase of P_2 shows that at least for this period, the previous ephemeris is no longer valid. Various hypotheses are proposed to account for the observed amplitudes variations.

Key words: stars: 16 Lac – stars: variable – stars: binaries: close – stars: oscillations

1. Introduction

16 Lacertae (HR 8725 = HD 216916 = EN Lac, B2IV) is one of the best known β Cephei - β Canis Majoris star. It belongs to the Lac OB1 association (distance 600 pc, age 12 to 16×10^6 years, Eggen, 1975). It is a well-detached eclipsing binary of 12.09684 day period (Struve et al., 1952; Pigulski and Jerzykiewicz, 1988), so the components radii and mass ratio are rather well determined, and by a direct method, which is not common in this part of the HR diagram.

The primary, a main sequence star ($M_1 \simeq 10 M_\odot$, $R_1 \simeq 5.5 R_\odot$, $T_{eff} \simeq 22000K$) is the β Cephei type variable, while the secondary ($M_2 \simeq 1.3 M_\odot$, $R_2 \simeq 1.2 R_\odot$) could be a pre-main sequence object (Pigulski and Jerzykiewicz, 1988). The primary's rotation period - 11.7 to 14 days - is very probably synchronized with the orbital period (Balona, 1985, Chapellier et al., 1995, thereafter Paper 1).

Three close frequencies have been detected in the star's photometry (Fitch, 1969, Jarzebowski et al., 1979) and later confirmed (Garrido et al., 1983). There could exist some more frequencies in the star pulsation spectrum, apart from the three main components, but with very small amplitudes (Jerzykiewicz, 1993). Since 40 years (Fitch, 1969), significant variations in the amplitudes of the three periods have been reported. Such variations are of great interest to understand the β Cep pulsation and the physics underlying the mode selection. So 16 Lac deserves continuous attention: we observed it in two campaigns (1987 and 1992), and will continue to monitor it.

2. Observations

The observations have been carried out at the Pico del Veleta Observatory (Granada, Spain) in 1987, during 5 nights, with a 62 cm telescope, a "Geneva" type photometer and two filters (UV #4 and blue #5 in Sareyan et al., 1976); and in 1992 in San Pedro Martir Observatory (Baja California, Mexico) both for 5 nights with a 84 cm telescope (photometer "Cuentapulsos", Johnson's V with a neutral filter, and Stromgren's b), and for 6 nights with a 150 cm telescope and the "Danish" spectrophotometer, i.e. in simultaneous Stromgren's u v b y , b and v channels beeing attenuated by a factor $\simeq 2$ neutral filter, located inside the spectrophotometer (Table 1).

The comparison stars were HR 8766 (2 And, A3Vn) and HR 8708 (A3m+F6V); HR 8733 (B2IV-V) was also added in the observing cycles at San Pedro Martir Observatory. These stars have been checked for constancy within a few millimagnitudes (Sareyan et al., 1994). The Figs. 1 and 2 give examples of observations. All the present data will be sent to the IAU Archives of unpublished observations of variables stars.

The filter #5 mentionned above is close to Stromgrens' b, so that the observations made in these narrow bandpass blue filters can be compared, and the derived amplitudes directly fit together, as already mentionned in Garrido et al.(1983). In order to do so, we applied corrections to the 84 cm telescope b data and to the 150 cm telescope b data (-0.41581 and -0.40427 magnitude, respectively), so that the mean magnitude on the comparison star HR8766 is zero for both instrumental systems. We used here the GBFOM programs described in Sareyan et al. (1992).

Send offprint requests to: J.P.Sareyan

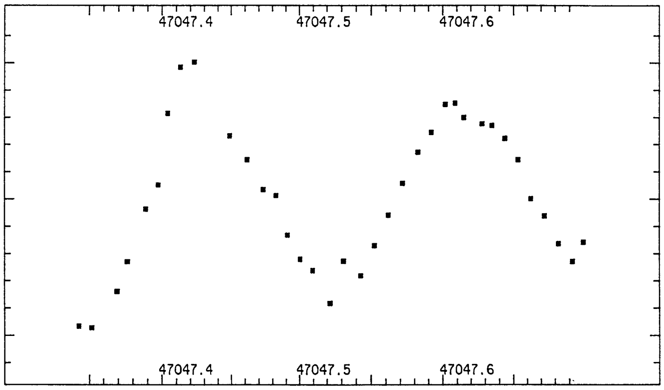

Fig. 1. Example of a blue filter light curve for a single night in 1987 (16Lac - HR8766). Vertical ticks are 5 mmag apart, horizontal scale is HJD - 2400000. Light increases upwards (magnitudes downwards) in the Figs. 1,2,3 of this paper.

Table 1. The observations.

Observatory Telescope, filter	HJD range 2440000 +	hours
Pico del Veleta 62 cm #4,#5	7042.378-.690	7.5
	7045.370-.694	7.8
	7046.377-.693	7.6
	7047.343-.699	8.6
	7048.502-.654	3.7
San Pedro Martir 84 cm b,V	8893.648-.952	7.3
	8894.676-.953	6.7
	8895.649-.947	7.2
	8896.644-.945	7.2
	8897.659-.910	6.0
San Pedro Martir 150 cm u,v,b,y	8898.734-.945	5.0
	8899.635-.946	7.5
	8900.720-.940	5.3
	8901.646-.928	6.8
	8902.648-.920	6.5
	8904.706-.927	5.3

3. Analysis

As the observing runs are too short in 1987 and 1992 to separate the first two periods (P_1 and P_2 have a beat period of about 18 days), we find in the period analysis a mixture - weighted by their respective real amplitudes - of both periods. For example, the PDM analysis (Stellingwerf, 1978) on the 1992 b filter data shows, in the 0.15 - 0.21 d range, periods of 0.1702 and 0.1703 day using respectively the 150 cm telescope data, and all data (i.e. including the 84 cm telescope data as well). As we will see later, the conventional periods P_1 and P_2 weighted by their real amplitudes give a 0.1703 d resulting "mixture". So on our data sample, we have no direct access to an independent determination of P_1 (0.1692d) and P_2 (0.1708d). However, we easily detect on our data the third period P_3 (its beat period with either P_1 or P_2 is under 3 days) at 0.1814 and 0.1818 d (using respectively the PDM analysis method (Stellingwerf, 1978) for the 150 cm telescope, and for the whole data. Breger's "Period" program (1990) finds 0.1815 d).

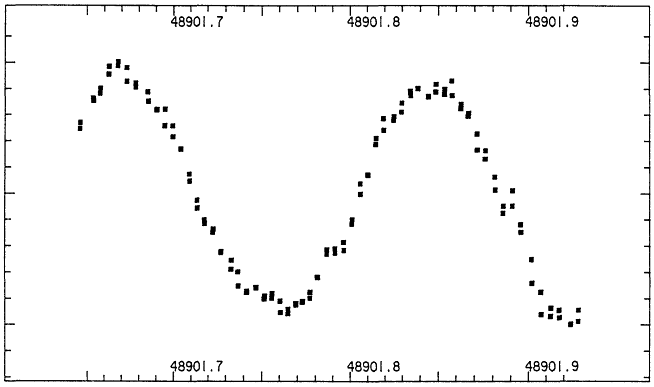

Fig. 2. As Fig. 1 in 1992

Table 2. Amplitudes in #5 or b filter, in millimagnitudes (mmag).

	1987	1992
P_1 = 0.1691678 d	7.8	5.2
P_2 = 0.1707769 d	7.5	11.1
P_3 = 0.1817331 d	13.8	6.2
rms error	3.60	3.75
correlation	0.820	0.806

4. Amplitudes

On the available 1987 and 1992 data we decided to force the long- known three periods, on the basis that they have been stable for 35 years since the first reliable photometric observations, i.e. since the very beginning of the 1950's (Paper 1). So we introduced the most recent and precise determination of these periods (P_1 = 0.1691678 d, P_2 = 0.1707769 d, P_3 = 0.1817331 d, Paper 1) to derive and analyze in our data their respective amplitude variations.

Given the three above periods, we obtain by a least squares fit of sine curves through the 1987 and 1992 data the amplitudes (half variation light range) of Table 2 in the filter b (or its equivalent filter #5), in millimagnitudes (mmag). The Fig. 3 shows the fit obtained for 1992's data.

(NB: All our 1987 and 1992 observations are "out of eclipse", according to the ephemeris given by Pigulski and Jerzykiewicz (1988)).

If we only take into account the "Danish" photometer data of 1992, we obtain amplitudes of 6.3, 9.9 and 6.6 mmag for P_1, P_2 and P_3 (instead of 5.2, 11.1 and 6.2 for the whole 1992 data). These discrepancies - about 1 mmag on the amplitudes - give an order of magnitude of the possible error bars.

Apart from the rms errors quoted in Table 2, we can have an idea of the actual precision on the amplitudes if we look for periods in the data of the second comparison star (HR 8708 - HR 8766): We find 1.5 mmag amplitudes with $\simeq$ 4 mmag rms So we can think the error bar to be at most 2 mmag on the amplitudes

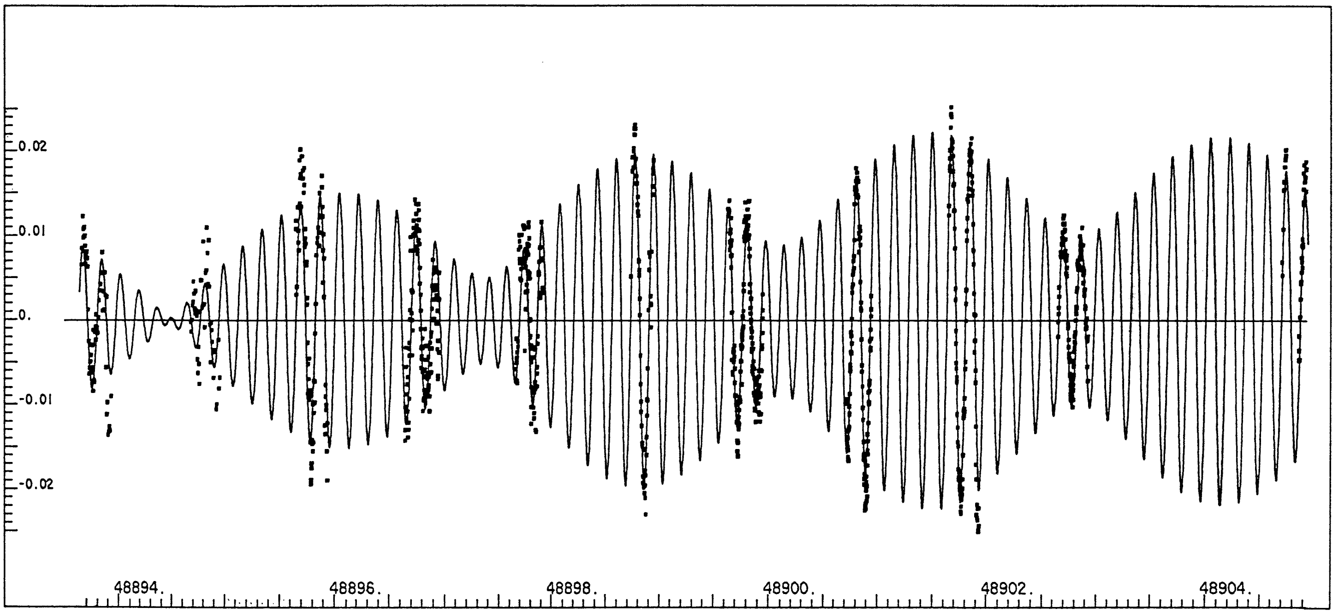

Fig. 3. The whole 1992 campaign in the b filter. Vertical ticks are 1 mmag apart. We superimposed the fit obtained with the three main periods, which leads to the 1992 amplitudes of Table 2.

of Table 2. On the data, one can obtain the color/amplitude ratio between UV (filter u or #4) and visible (filter y for example, or blue #5): (Au - Ay)/Ay. This ratio, as well as that of the amplitudes of radial velocities to magnitudes ΔRV/Δm is an indicator of the pulsation mode, as already shown by several authors.

The color/amplitude ratio for P_1 being somewhat higher than those of P_2 or P_3, one can infer that these pulsations might be of a different kind: P_2 and P_3 are non radial modes, according to Fitch (1969) and Jerzykiewicz (1993). P_2 is very probably a l=2 mode, and P_3 could be a l=1 mode (Paper 1), although this latter mode is rather unusual in β Cep pulsators (Heindericks et al.,1994). Although the precision attained on the color/amplitude ratios is not very high, we obtain here for P_3 ratios (0.41 and 0.55) that are in the same range as previous determinations (0.42 in Jerzykiewicz, 1993, and 0.62 in Paper 1). P_1 is very probably radial and could be the fundamental; Table 3 shows that P_1 and P_2 are unlikely to be the product of a unique mode splitted by rotation ! (Some previous analyzes had attributed NR modes to P_1 and P_2, and a radial mode to P_3: see Balona, 1985, Pigulski and Jerzykiewicz, 1988).

5. Other periods?

It has been mentionned in Paper 1 that on the whole 1950 - 1984 data, only P_2 appeared as a regular sinusoid: P_1 and P_3 show dissymetrical aspects (the light increase of the light curves lasts longer than the light decrease for these periods). A simple test on such discrepancies from regular sinusoidal behavior is to introduce in the analyses a $P_i/2$ period simultaneously with period P_i, and to look for an improvement of the fit of the light curves. We did this for every combination of the three principal periods P_i and their first harmonic $P_i/2$.

On the 1987 data the curve fit of the Table 2 is slightly improved by the introduction of $P_1/2$, but not by $P_2/2$ and/or $P_3/2$. So for these data, only P_1 could be - marginally - different from a sinusoid.

The 1992 data fit is slightly improved by the introduction of $P_2/2$, and we can improve it a little further if $P_1/2$ is also taken into account. $P_3/2$ does not show any significant amplitude improvement and/or rms reduction... So in these data, only P_1 and P_2 could have a shape significantly different from a sinusoid.

So on the whole of our present 1987 and 1992 data, only P_1 can show permanently a light curve different from a simple sinusoid. (P_1 is very probably also the only radial mode).

1. We do not improve significantly the light curve fit by considering the periods (around 0.084-0.088 d) found by Jerzykiewicz (1993). As shown before, the introduction in our data of these low amplitude ($\leq$ 1 mmag) periods (quite close to half the principal three periods !) might slightly improve the light curve fit. However, due to our limited string of observations, we cannot derive definitive conclusions about the likely presence or absence of such frequencies in our data.
2. Jerzykiewicz's (1993) 6.05 d period - or half the orbital period - doesn't give any significant peak and/or data fit improvement in our data.
3. The period P_4 = 0.139 d , claimed by Jerzykiewicz (1993) as a possible overtone of any of the three principal periods can be detected in our 16 Lac - HR 8766 (2 And) data, in 1987 as well as in 1992: It appears with an amplitude around 1.5 mmag. (We obtain, according to the different period finding methods, periods in the 0.127 - 0.146 d range, with

Table 3. Color/amplitude ratio in 1987 and 1992 (uvby data)

	1987			1992				
	A#4	A#5	(A#4-A#5)/A#5	Au	Av	Ab	Ay	(Au-Ay)/Ay
P_1	12.9	7.8	0.65	9.1	6.4	6.3	5.5	0.70
P_2	8.8	7.5	0.17	14.3	10.0	9.9	9.6	0.49
P_3	19.5	13.8	0.41	9.9	6.8	6.6	6.4	0.55

Table 4. Blue amplitudes (mmag), corrected for the variations of HR 8766.

	1987	1992
$P_1 = 0.1691678$	7.1	5.0
$P_2 = 0.1707769$	6.6	11.1
$P_3 = 0.1817331$	14.0	6.2
rms	3.50	3.65
correlation	0.825	0.812

a marked maximum probability around 0.14 d). However a more careful analysis made *between comparison stars* (i.e. the HR 8766 - HR 8733 and HR 8766 - HR 8708 data) shows that the detected 0.139 d period very probably comes from the star HR 8766 (2 And) itself: the two intercomparison light curves show the same phases and similar amplitudes. A paper is being prepared on this star, as a follow up of the present discovery of its photometric variability.

If we substract this 0.139 d period with its amplitudes (respectively 1.5 and 1.3 mmag in 1987 and 1992), we obtain Table 4 for the amplitudes of the three classical periods in 16 Lac. These amplitudes are not significantly different from those of Table 2 (a 0.3 to 0.4 mmag difference on the average !): the variations of HR 8766 do not play any role on the conclusions that we will derive on the amplitudes of 16 Lac, up to a confidence level better than 2 mmag.

6. Light amplitudes

When compared to previous amplitudes, the actual 1987 and 1992 determinations show an increase in the amplitude of P_2 (which was at its minimum around 1980). So our 1992 observations show for the first time P_2 to have an amplitude higher than P_1 since 16 Lac was known as a light variable.

The amplitude of P_1 is still low since 1980-1984 (around 6 mmag on the average) and is in our 1987-1992 data clearly lower than that of P_2, while P_3 amplitude "seems erratic" as usual (see Fig. 3 in Paper 1).

It has been already pointed out that the amplitudes of P_1 and P_2 were much higher around 1950 and have been decreasing *together* at similar rates since then. They also were very probably at a lower level at the beginning of this century (i.e. in 1912-1914: Paper 1).

The actual increase of the amplitude of P_2 means that something has happened that provides in this non radial pulsation mode more energy than a decade ago. In comparison the decrease, or stability, of the amplitude of P_1 at a rather low level shows that this (very probable) radial mode keeps some energy to continue, but is not favorized as it used to be 40 years ago. Is there a one century period in the excitation of this (P_1) radial mode, or only a time constant of several decades? Only future observations will tell us...

The behavior of P_3 seems to be totally independant from P_1 and P_2. The amplitude of P_3 may vary from 15.5 mmag to almost zero (1.5 mmag) in a time scale of months as happened in 1951.

But if we analyze further these P_3 amplitudes, they appear in the past and in our data to be distributed around two values, each one with a rather small rms error: 6 measurements with a mean value at 5.0 mmag (rms error = 1.8 mmag), 7 measurements with a mean value at 12.5 mmag (rms error = 1.7 mmag). The average value is 9.1 mmag, but with a very large rms error (4.2 mmag). This might be the signature of an oscillation (on a sinusoidal time dependant phenomenon, the probability is maximum for the values to be most of the time near their extrema).

On our longest run (1992), if we substract P_1 and P_2 sine functions, we can obtain the P_3 one, night by night for the 11 nights of observation. These 11 data points, as expected, do not present any probability peak in the (orbital) 12 d range. If plotted in phase with the ephemeris of the orbital motion (Pigulski and Jerzykiewicz, 1988), the resulting variation could be represented by a least square sine function with P_3 period (Fig.4). This "best fit" sinusoid has an amplitude of 1.2 mmag and its mean is 6.7 mmag. The correlation is rather low, as the extreme observed values (second and eleventh nights: JD 2448894 and 904 respectively) are those with less data. However this sinusoid, which average value is similar to that of Paper 1, shows a maximum value at HJD 2448903.206, i.e. at phase 0.15 after the calculated periastron. This phase is determined with a rather low precision. Due to the actual amplitudes of P_3, which is no longer the principal period, this result is not contradictory with the previous 0.25 value, itself also determined with rather low precision (Paper 1).

7. Phases of the different periods

When we compare the light maxima derived from our period analysis with the ephemeris published in Paper 1, we obtain

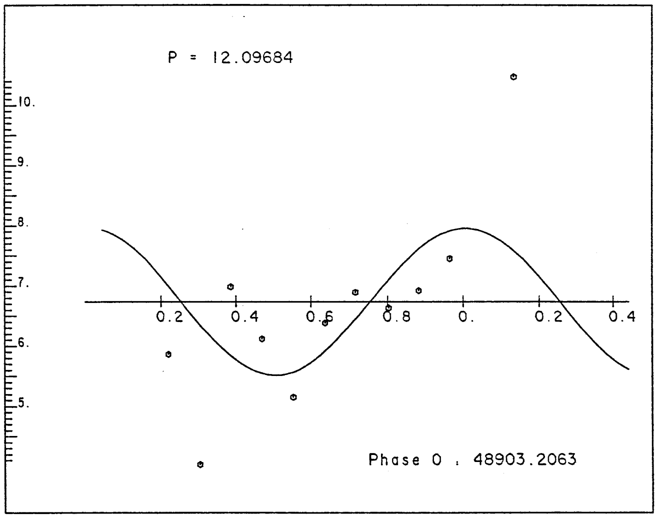

Fig. 4. Amplitude of the period P_3 alone (in mmag) as a function of the orbital phase (least square sinusoidal fit)

Table 5. (O-C) phases

	1987	1992
$P_1 = 0.1691678$	- 0.13	- 0.21
$P_2 = 0.1707769$	+ 0.35	+ 0.29
$P_3 = 0.1817331$	- 0.05	+ 0.02

the phases of Table 5. If these 1950-1984 ephemeris and their error bars are to be trusted, the eventual errors made on the periods themselves and/or on the times of light maxima can be evaluated from these rms errors, i.e. 0.003, 0.20 and 0.28 in phase respectively for P_1, P_2 and P_3.

We can see there that P_3 is still perfectly in phase with the ephemeris, which could be a further confirmation that its amplitude could be modulated by the orbit, the pulsation being "forced" into a more stable value than P_2 and P_1's by the regularity of the orbital period.

On the contrary the two first pulsation modes P_1 and P_2 are clearly not in phase with the previous ephemeris: The discrepancies observed for these two modes in 1987 and 1992 are about 10 times those observed in the 1950 - 1984 range ! They are much larger than any likely error: the precision obtained on the light curves and on the ephemeris fit shows that only a small fraction of such discrepancies could be due to the too short time basis of the observations in 1987 and 1992. If we assume that only these periods did vary, we would obtain respectively 0.1691675 and 0.1707776 d for P_1 and P_2. This means that the amplitude increase observed on P_2 could be related to an eventual increase of the period value, which occurred between 1984 and 1987, from 0.1707769 to 0.1707776 d at least (0.1707776 is a lower value assuming that the increase occurred in 1984). The discrepancies between the 1950-1984 ephemeris and the actual 1987-1992 phases could be due

to period - or phases - variations of opposite sign in P_1 and P_2 between 1984 and 1987, or

to a total extinction of these two modes, followed by a new growth of one or several modes, whose period(s) would show up in our data as an unresolved peak between 0.16917 and 0.17078 d.

Only new observations carried out over more than 18 days would allow one to know.

8. About energy transfer

Fitch (1969) and Paper 1 propose, in opposition to Garrido (1983), that there is a coupling between the orbital period and the three pulsation frequencies. It has been shown also that there is no energy transfer between these three pulsation modes (Chapellier,1986), when their amplitudes vary. This is especially evident in the P_3 amplitude variations that occurred in 1951 - a factor 10 in two weeks -, as no correlated contemporaneous energy transfer appeared in P_1 and/or P_2. Here, in 1987 and 1992, we obtain

Energy = $\sqrt{\Sigma(amplitude)_i^2}$ = 17.5 and 13.7 (mmag) respectively (or 35 and 27.5 mmag, according to Chapellier's notation based on the light variation *ranges*). E being proportional to the total energy available in the short periods of amplitudes A_i. So, in the visible and near UV part of the spectrum, the total energy output involved in the star short period variations does vary.

9. Looking for explanations

Although the long term energy variations in the visible are rather small compared to the total stellar output (from about 3 to about 1% in decades), one can wonder where this energy variation can be redistributed:

1. In other parts of the spectrum?
2. In unknown modes or different time constant variations (for example shorter than 0.01 d time constants would hardly be noticed the way we actually do differential photometry)?
3. In photospheric or "atmospheric" activity, or to some alteration in the actual structure of the more superficial layers of the star?
4. In tidal coupling that would reduce the rotation speed of the primary? (the time scales and amount of energy transfered would not allow an easy detection in the frequency couplings).
   According to Waelkens and Rufener (1983), tidal interaction damps the pulsation phenomenon in βCep variables, as could be the case for the three shortest orbital period known in such stars (i.e. αVir, βCep, ... , and 16 Lac). This could be an explanation of P_1 and P_2 behavior in 16 Lac. However as it is a slow rotator, its amplitudes are not likely to be damped completely by rotation: as pointed out by Jakate (1979) the fastest rotators among the βCep variables have the smallest amplitudes.

An exclusion between pulsation and "elliptical" (i.e. geometric) variations can explain the decrease of P_1, as non spherical perturbations of the star should damp its radial modes (a limit case being that of αVir, which rotation probably finally got synchronized with its binary orbit). Accordingly, if energy is still available in 16 Lac to feed pulsation, it should appear better in non radial modes (P_2 for example).

A good test of such an explanation would be to monitor carefully the 6.05 d period detected by Jerzykiewicz (eventually a semi-orbital period) and see if there is any correlation between its amplitude and that of P_1 and P_2. One should remember here that any such "elliptical" variation would be mixed with the primary's light reflexion onto the secondary (there is about an 8 magnitudes difference between components !).

As pointed out in Paper 1, the P_3 amplitudes could still be phase-locked with the orbit, the maxima occuring about a fifth of the orbital period after the periastron. At that phase, if the primary is somewhat ellipsoidal, it should also present a maximum apparent surface.

10. Conclusion

We detect here a significant increase of the amplitude of P_2, one of the non-radial modes in 16 Lac. For the first time since precise photometry is being achieved, this amplitude is greater than that of P_1, which underwent a slow amplitude decrease in the past decades and still is at a low level. P_1 and P_2 are not in a good agreement with their previous ephemeris: the value of the periods could have changed by a small but significant amount or/and their maximum light epoch has to be shifted: the ephemeris calculated from the 1950's to 1984 cannot represent our 1987-1992 P_1 and P_2 data with the same precision as before.

We confirm here that P_1 is probably of a different nature from P_2 and P_3, and likely a radial mode with, in our 1987-1992 data, a possible dissymetric light curve.

All other previous low amplitude periods appear as non-existent or marginal in our observations. The period 0.139 d belongs to the principal comparison star, with a very low (under 2 mmag) amplitude.

The amplitudes of P_3 are still in phase with the orbital period, or in phase with the rotation as they are very probably synchronized, but further studies have to confirm this behavior, as it is based until now on rather low correlations.

It is shown here that the total pulsational energy available in the visible part of the spectrum does vary: at least in the 0.15 - 0.20 d range, there is no redistribution of the pulsation energy between the different modes.

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