Spectroscopic diagnostics of pulsation in rotating stars

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A new bright $\beta$ Cephei star: $\beta$ Lupi

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Abstract

We present time series of high resolution spectra of the bright B2 III star $\beta$ Lup. The spectra show multi-periodic variations of the SiIII $\lambda$4567 and $\lambda$4574 line profiles, in the form of features which move from the blue to the red across the rotationally broadened line-profiles, which is typical for high-degree non-radial pulsations. We use Fourier analysis techniques to obtain frequency spectra of the line-profile variability and use phase and amplitude diagrams to analyze the line-profile variations at selected frequencies. The limited time span of 7 days and the observing window of 9 hours per day lead to ambiguities in the determination of the pulsation frequencies, and hamper a solid identification of all pulsation modes. However, for several of the modes in $\beta$ Lup we are able to estimate an $\ell$-value. We conclude that $\beta$ Lup exhibits multiple non-radial pulsations. Taking into account its known temperature, luminosity and spectral type, we propose that the star is a new member of the $\beta$ Cephei class variables.

6.1 Introduction

The asteroseismological potential of the $\beta$ Cephei stars has been emphasized in many papers (e.g. Breger 1995, Shibahashi & Aerts 1998, Dziembowski 1998a, 1998b). The multi-periodic line-profile variability found in many of these stars is successfully explained by models of stellar oscillations. The identification of multiple non-radial pulsation modes which penetrate the stellar interior offers the means to test and improve theories of stellar structure and evolution.

Since $\beta$ Lup (HD 132058) is of spectral type B2 III, it was included as a candidate in a number of studies to search for new $\beta$ Cephei variables among bright early-B stars.
Chapter 6. A new bright β Cephei star: β Lupi

However, several photometric campaigns did not reveal variability in β Lup (Percy 1974, Jerzykiewicz & Sterken 1977, Shobbrook 1978). Levato et al. (1987) concluded from their spectroscopic survey that β Lup is probably a radial-velocity variable.

De Geus et al. (1989) derived log $T_{\text{eff}}$=4.34, log $g$=3.76, and log $L/L_\odot$=4.0 for β Lup. These values place β Lup inside the small domain of the Hertzsprung-Russell diagram where β Cephei stars are predicted to be pulsationally unstable (Dziembowski & Pamyatnykh 1994, Pamyatnykh 1998).

Brown & Verschueren (1997) determined a projected rotational velocity $V_{\text{smi}}$ of $92 \pm 6$ km s$^{-1}$ for β Lup, using an artificially broadened sharp-lined template spectrum matching the observed FWHM of weak metal lines.

In Section 6.2 we describe the acquisition and reduction of the data on which our spectral study of β Lup is based. The analysis is described in Section 6.3. We analyse the equivalent width (EW) and radial velocity variations in Section 6.3.1. In Sections 6.3.2 and 6.3.3 we determine the strongest apparent frequencies from Fourier analyses of the intensity variations in the line profiles. We use two different methods to analyse the intensity variations at each position in the line-profile: Fourier transforms and single-sinusoid fits. With these techniques we create diagnostic diagrams (Sect.6.3.4) in an effort to retrieve the $\ell$-values of the non-radial pulsation modes in β Lup (Sect.6.4). Our conclusions are summarized in Section 6.5.

6.2 The observations and data reduction

We obtained 82 high-resolution spectra (spectral resolution R=65000) at the ESO La Silla CAT telescope equipped with the CES spectrograph, over a period of 7 nights in May/June 1998. The spectral range of 19.5 Å, projected by the ESO Very Long Camera on about 2600 useful columns of ESO CCD #38 covers two lines of a SiIII triplet (SiIII λ4567.8 and SiIII λ4574.8). Exposure times were typically 15 minutes and were kept shorter than 20 minutes, resulting in S/N ratios of the reduced spectra between 650 and 1200.

The spectra were reduced using standard packages in IRAF. Wavelength calibration was done with ThAr spectra. We used the CCD overscan region to determine the bias level. CCD pixel-to-pixel variations were removed by flat fielding with dome flats. Bad columns were removed by linear interpolation of pixel intensities in adjacent columns. One-dimensional spectra were extracted after subtracting a global fit to background and scattered light. All spectra were shifted to, and acquisition times were transformed to the heliocentric frame. We normalized the spectra by fitting a cubic spline with typically 5 segments to the regions in between the obvious absorption lines in the extracted spectra.

6.3 The analysis

In contrast to the very small photometric variability ($\Delta V<0.005$; see Shobbrook 1978) our high-resolution spectra reveal a complex pattern of variability in the observed line
Fig. 6.1. A single night of spectra over the full recorded wavelength range. Spectra are offset according to acquisition time. The moving features in the line-profiles suggest multiple non-radial pulsation modes. All obvious modes seem to have high $\ell$ values.
profiles. The two lines show a parallel behavior, as expected. The spectra show several simultaneous quasi-absorption and quasi-emission features that move from the blue to the red across the line profiles. These moving features vary in number and strength which we interpret as the presence of multiple sources of variability that act cooperatively and destructively in an alternating fashion. One night of data is shown in Fig. 6.1. Our working hypothesis is that several non-radial pulsation modes of high degree are present in β Lup.

6.3.1 Equivalent width and radial velocity variations

We calculated the equivalent width (EW) and radial velocity (RV) of the line profiles as defined in Chapter 2. The integration domains were based on where the average of all line profiles reaches the continuum; we kept the integration domains as narrow as possible to minimize the contribution of continuum noise.

Since the two lines in our spectra are part of the same triplet, only variations measured consistently in both lines can be attributed to intrinsic changes in the star. Changes in only one of the two lines are most likely due to imperfections in the data acquisition and reduction process. We find small variations of the EW. The measured EW variations of both line profiles do not seem to be correlated. We therefore do not attribute these variations to intrinsic changes in β Lup.

We find small variations of the RV, with a high degree of similarity between both lines. This confirms the conclusion of Levato et al. (1987) that β Lup is a radial-velocity variable. The measured changes remain smaller than 5 km/s, which is of the order of the projected slit width. We applied a Fourier analysis to the measured RV variations and find ambiguities in the results for both lines, i.e. the frequency spectra calculated from the RV variations of the two lines turn out to be somewhat different. The peaks appear at frequencies that differ ~1 d⁻¹ between the two lines, which is most likely caused by the one-day aliasing effect. We also applied the Phase Dispersion Minimalisation (PDM) technique (Schellingwerf 1978) to the RV variations, using 5 PDM bins ($N_b=5$) and 2 PDM covers ($N_c=2$), which gives the same frequencies as the Fourier analysis. For both line profiles we find power around 0.37, 1.37 and 2.37 d⁻¹ and around 1.05, 2.05 and 3.05 d⁻¹. We conclude that our 82 spectra are not sufficient to determine the correct period(s) of the RV variations without ambiguities.

6.3.2 Variability across the line profiles

To find the frequencies of the moving features in the line profiles we analysed the time series with the method described by Gies & Kullavanijaya (1988) and Chapter 2. The method is based on the Doppler imaging principle (Vogt et al. 1987), in which one assumes a mapping of photospheric features (e.g. local velocity, brightness or EW variations) onto line profiles which are Doppler broadened by the rotation of the star. The two rotationally broadened line-profiles in our spectra are covered by approximately 350 wavelength bins each. From a Fourier transform applied to all wavelength bins we obtain the power of variability as a function of frequency (periodogram), for all
6.3. The analysis

Fig. 6.2. Top: CLEANed Fourier periodogram of all β Lup spectra. For each wavelength bin (horizontal axis) a Fourier analysis of all the spectra is performed. The power resulting from the Fourier analysis is plotted as a grey-value as a function of temporal frequency (vertical axis). Grey-scale cuts: 0–4·10⁻⁷. Bottom: Mean of all spectra
positions in the line profiles. The Fourier analysis also provides information about the phase change of the periodic variations across the line profiles.

The shortest time span between subsequent exposures corresponds to a Nyquist frequency of ~ 57 d\(^{-1}\). The length of the data set is such that the HWHM of the main power peak in the window function is 0.076 d\(^{-1}\). For each wavelength bin in the spectra we analysed the variable signal: we computed the Fourier components for frequencies between 0 and 50 d\(^{-1}\) with a frequency spacing of 0.01 d\(^{-1}\). We used a CLEAN algorithm (Roberts et al. 1987) in order to remove the temporal window function, due to incomplete temporal sampling of the variational signal, from the Fourier transform of each wavelength bin. We used 400 iterations with a gain of 0.2. The resulting periodogram is displayed in Figure 6.2.

The periodogram in Fig. 6.2 is, at first sight, not in agreement with theoretical periodograms. What we would have expected is that each non-radial pulsation mode gives rise to power at frequency\(^1\) \(f_i = f_* + |m|\Omega\), consistently present at all positions in the line profile (see Chapter 2 and Chapter 3). Although we recognize clear traces of such power distributions (e.g. at ~ 3.3 and ~ 4.3 d\(^{-1}\)) the power in our periodogram appears as 'patches' at certain positions in the line-profile instead of a continuous distribution across the complete line profile. Theoretical periodograms are however calculated for ideal datasets with an almost perfect sampling and in absence of noise. If the variations measured in \(\beta\) Lup are indeed caused by non-radial pulsation modes then the power between the patches is most likely missing due to our limited coverage with gaps of 15 hours per day, in combination with the noise in the spectra.

6.3.3 The frequency spectrum

We present summed power spectra for both line profiles in Fig. 6.3. These power spectra reveal several peaks in the range between 0 and 8 d\(^{-1}\). The summed power spectra of both line profiles are consistent to a high degree, but small differences appear at ~ 2.1 and ~ 4.8 d\(^{-1}\). The detected frequencies are listed in Table 6.1. Within the HWHM of the central peak in the window function we find the same frequencies for both lines. In the rest of this Chapter we will refer to the detected peaks by the frequency found for the stronger \(\lambda 4567\) line profile.

Power at one-day aliases

We suspect that many of the peaks are caused by the one-day aliasing effect, most notably part of the peaks found at 3.34, 4.32 and 5.30 d\(^{-1}\) and those at 2.98 and 3.94 d\(^{-1}\). This would indicate that CLEAN is not able to fully remove the window function. All above-mentioned frequencies would then be related to only two real frequencies in \(\beta\) Lup. The limited time span of the dataset makes our frequencies too inaccurate to exclude that these peaks are aliases. As a test we prewhitened the dataset with each of

\(^1\)If the line-profile amplitudes are large enough, and at least partly caused by surface-velocity fields, harmonic power at frequency \(2f_* + 2|m|\Omega\) is also expected, as well as some leakage of power to the sum and beat frequencies in case of multiple modes.
Fig. 6.3. Summed Fourier spectra. The power (i.e. the square of half the amplitude) in the two-dimensional periodogram has been summed over the two line profiles. The dotted thin lines indicate the frequencies for which we constructed IPS diagrams. The short vertical lines near the top of the panels indicate frequencies for which we were able to construct at least one reasonably useful IPS phase diagram; the thick vertical lines indicate the three detected pulsation modes. For clarity we applied offsets in the plots. **Top:** The summed power of the SiIII 4567 and SiIII 4574 line profiles, in arbitrary units. **Bottom:** For the 4567 profile the three diagrams show the CLEANed Fourier spectrum, the CLEANED Fourier spectrum after prewhitening at 4.32 d\(^{-1}\), and the CLEANED Fourier spectrum after prewhitening at 4.32 d\(^{-1}\) and 2.32 d\(^{-1}\). We show the interesting range between 1.5 and 8.5 d\(^{-1}\).
Table 6.1. All frequencies between 0 and 8 d\(^{-1}\) with significant power in the summed Fourier transforms of the SiIII \(\lambda 4567\) and \(\lambda 4574\) line profiles. For the \(\lambda 4567\) line profile, the second column lists the frequency in d\(^{-1}\) whereas the first gives the order of appearance from the strongest (1) to the weakest (14) peak. The maximum blue-to-red phase differences \(\Delta \Psi\), measured from the IPS diagnostics for the Fourier transform (label FT) and for the sinusoid fit (label SF) are in columns 3 and 4, in units of \(\pi\). Lower limits are indicated by a plus symbol. The fractional \(\ell\) values corresponding to the measured values for \(\Delta \Psi\), are in columns 5 and 6. The results for the \(\lambda 4574\) line profile are in columns 7 to 12. Column 13 lists the final \(\ell\) value when taking all four amplitude and phase diagrams into careful consideration. Comments are in the rightmost column: 1. useless IPS diagnostics; 2. possible one-day alias; 3. inconsistencies between both lines; 4. inconsistencies between both methods; 5. only lower limits could be obtained; 6. After prewhitening at 4.32 d\(^{-1}\); 7. After prewhitening at 2.32 d\(^{-1}\).

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6.3. The analysis

the first four above mentioned frequencies: we find that prewhitening at a single frequency does not remove all four peaks from the periodogram. However, prewhitening at 4.32 d\(^{-1}\) does successfully remove much of the power at 3.34, 4.32 and 5.30 d\(^{-1}\), which indicates that 4.32 d\(^{-1}\) is a true apparent frequency of β Lup. We find that the removal of the four peaks at 5.30, 4.32, 3.34, and 2.31 is most successfully accomplished by successively prewhitening at 4.32 and 2.32 d\(^{-1}\). The bottom panel of Figure 6.3 displays the summed Fourier spectra before and after subsequently prewhitening at 4.32 d\(^{-1}\) and 2.32 d\(^{-1}\).

Power at sum and/or beat frequencies

We suspect that two of the detected peaks are caused by the beating of stronger frequencies. The peak at 6.08 d\(^{-1}\) appears at the sum frequency of 1.74 and 4.32 d\(^{-1}\). Similarly, the peak at 7.09 d\(^{-1}\) is probably the result of the strong variations at 1.74 and 5.30 d\(^{-1}\).

6.3.4 IPS amplitude and phase diagrams

The results described in the previous sections made clear that the obtained periodogram and the summed power spectra deviate strongly from the ideal case. At all detected frequencies the power distribution over the line profile seems incomplete. We suspect that many of the detected frequencies in the power spectrum are false. These false peaks are caused by one-day aliasing and by beating between strong frequencies. In this section we investigate the nature of the line-profile variations, for each of the detected frequencies.

In Chapter 2 we described a method for the analysis of non-radial pulsations in rotating stars. The method is based on the IPS (Intensity Period Search) diagnostic which consists of two diagrams, the amplitude and the phase diagram, which represent the line-profile variations caused by each individual pulsation mode.

The two diagrams are each related to distinct properties of the pulsation mode. The amplitude diagram contains information on mode parameters like \(k, i, V_{\text{max}}, \Omega/\omega^{(0)}, W, (\delta T/T)_{\text{max}}, \alpha_{\text{w}}, \) and \(\chi^{\text{ma}}\) (see Chapter 2 and 5) for the meaning of these symbols). The phase diagram is representative of the pulsation index \(\ell\) (and \(|m|\) if a harmonic is measured as well). In Chapter 3 we established a unique relation between the measured phase diagram and the \(\ell\)-value of the responsible pulsation mode.

Here we use two different techniques to calculate IPS diagnostics. We use the Fourier transform from Section 6.3.2 to investigate the amplitude and phase behavior across the line profile. For seven of the frequencies in Table 6.1 we plot the amplitudes and phases at each position in the line profile (Figs. 6.4 and 6.5).

We create a second series of diagnostics by fitting a sinusoid with fixed frequency to the intensity variation at each position in the line profiles. We perform fits of the function

\[
I(\lambda, t) = A_i(\lambda) \sin (ft + \Psi_i(\lambda))
\]
Fig. 6.4. IPS diagnostics for the variations found in the λ4567 line-profile at frequencies 4.32, 3.34 and 5.30 d⁻¹. The panels of the left column show the diagnostics for λ4567, and the right column is for the λ4574 line profile. Each diagnostic consists of two diagrams: the top diagram displays the amplitude distribution $A_\lambda (\lambda)$ in units of $d_{\text{mean}}$ and the bottom diagram shows the phase distribution $\Psi_\lambda (\lambda)$, as a function of wavelength $\lambda$. The wavelengths corresponding to $-V_c \sin i$ and $V_c \sin i$ are indicated by the marks on the bottom axis of the phase diagrams. We present the amplitudes in units of $d_{\text{mean}}$, which is the maximum absorption depth of the mean line-profile, to allow a better comparison with theoretical models. For the λ4567 and λ4574 lines we respectively find $d_{\text{mean}}=0.061$ and $d_{\text{mean}}=0.043$ in continuum units. For the region in which we find significant amplitude the diagrams are drawn with a solid line. Outside this region a dotted line is used to plot the diagrams. The positions of the phase diagram at which we measure $\Delta \Psi_\lambda$ are indicated by a small box. The IPS diagrams resulting from our single-sinusoid fits are drawn as the thickest line. For the IPS diagnostic from the CLEANed Fourier transform we used a thin line.
6.3. The analysis

Fig. 6.5. Similar to Fig. 6.4. For the frequencies 1.74 and 3.94 d\(^{-1}\) we plot the results of both the \(\lambda4567\) line profile (left) and the \(\lambda4574\) (right) profile. Only one half of the phase diagram can be used for these frequencies, leading to lower limits for \(\Delta\Psi\). The position at which we cut off the diagram is indicated by an open circle instead of a square symbol. For 2.98 and 2.32 d\(^{-1}\) we only show the diagrams from the \(\lambda4567\) line profile. Note that the latter two were obtained after prewhitening the data (see Table 6.1)
to the intensity variations, for each of the frequencies \( f_i \) listed in Table 6.1. The free parameters in the fit are the amplitude \( A_i(\lambda) \) and the phase \( \Psi_i(\lambda) \). The IPS diagnostics are then created by plotting \( A_i(\lambda) \) and \( \Psi_i(\lambda) \) across the line profile. The advantage of this second approach is that the resulting amplitude diagrams turn out to be somewhat more continuous and that the corresponding phase diagrams appear more monotonic.

As mentioned before, many of the detected frequencies are caused by aliasing and beating effects. Up to this point it is not possible to distinguish the true frequencies from the artifacts. However, this does not prevent the application of the above mode-analysis techniques for each detected frequency. Whether or not the considered frequency is a true apparent frequency, the IPS diagnostics give insight in the nature of the detection. A phase diagram that is monotonically decreasing indicates bumps that move across the line profile. On the other hand, a phase diagram with irregular phase reversals where the corresponding amplitude is significant is not compatible with non-radial pulsation models, ruling out a detection of a pulsation mode at that frequency. It is therefore useful to investigate the IPS diagnostics for all 14 frequencies in Table 6.1.

We applied the two techniques to both of the line-profiles which leads to 4 IPS diagnostics for each of the 14 frequencies. In some cases we find differences between the two methods. In other cases we find differences between the two line profiles. We designate a diagnostic as useless if we find irregular changes of the phase diagram at positions where the corresponding amplitude is missing (the phase diagram is undefined at these positions). Such diagnostics are useless because they can neither confirm nor reject the possibility of non-radial pulsations; our dataset is not sufficient for these frequencies. The IPS diagnostics for some of the frequencies are shown in Figs. 6.4 and 6.5.

Note that the amplitudes from the Fourier transform are systematically lower than those from the fit methods. This is caused by the CLEAN algorithm which not only removes the window function from the periodogram but also some of the power at the real frequencies; in addition, CLEAN may cause power to leak to one-day aliases.

### 6.4 Mode identification

We derive \( \ell \)-values from all useful diagnostics. We measure the maximum blue-to-red phase difference \( \Delta \Psi \) from the phase diagrams which leads to an \( \ell \) value for each of the detected frequencies. We measure \( \Delta \Psi \) as the maximum phase difference found over the region in the line profile where we find significant amplitudes. For instructive examples of how we measure \( \Delta \Psi \) from the phase diagram we refer to Figure 3.2. In the diagrams of Figs. 6.4 and 6.5 we used square symbols to indicate the positions between which we read off \( \Delta \Psi \). The measured values for \( \Delta \Psi \) are tabulated in Table 6.1.

In principle, the region in which the diagrams are defined should span at least the range between \(-V_\perp \sin i\) and \(+V_\perp \sin i\). For the cases in which the amplitude diagram extends over a smaller region, we can only derive a lower limit for \( \Delta \Psi \) and \( \ell \). In a few cases (the diagrams for 1.74 and 3.94 d\(^{-1}\)) we find amplitude and/or phase diagrams which extend across only one half of the line profile, which also gives rise to lower
6.4. Mode identification

limits. Since this is the case for all four diagrams at these two frequencies, we can only derive a lower limit for $\ell$ for these cases. Lower limits are indicated by the plus symbols in Table 6.1.

6.4.1 Determination of $\ell$ values

To estimate the pulsation index $\ell$ from the maximum blue-to-red phase difference $\Delta \Psi$ we use the relations given by Equation 3.8 and Table 3.2. For the present analysis we chose to use the entry for modes with $|m| > 2$ which gives an 79% certainty of retrieving the correct value of $\ell \pm 1$. This gives the relation

$$\ell = 0.227 + \frac{1.082}{\pi} |\Delta \Psi|.$$ (6.2)

The derived $\ell$-values from each of the two methods and for both line profiles are listed in Table 6.1. In the table we list a final $\ell$-value or a range of $\ell$-values for all frequencies for which we obtained convincing IPS diagnostics. The $\ell$-values based on partial diagrams, i.e. the lower limits, are marked with a plus symbol. The $\ell$-values obtained from diagnostics for which we find inconsistencies between both lines and/or methods are given between brackets.

6.4.2 Discussion

For a large fraction of the detected frequencies (1.74, 2.98, 3.34, 3.94, 4.32, 5.30, 6.08, 7.09) we find useful IPS diagnostics that have similar characteristics as IPS diagnostics from non-radial pulsation models. A few of the useful IPS diagrams turn out to be incompatible with non-radial pulsations (0.31, 0.75, 1.21 d\(^{-1}\)). For some of the detected frequencies (6.55 and 7.68 d\(^{-1}\)) the IPS diagnostics show signs of a pulsation mode but the data set is not sufficient to create useful IPS diagrams, which prevents a confirmation or rejection of a pulsation mode for these frequencies.

The case of 2.32 d\(^{-1}\) does not lead to conclusive results. Fig. 6.3 shows that the amount of power measured at this frequency is different for the two line profiles. The power at 2.32 d\(^{-1}\) might be caused by one-day aliasing, which would group it together with 3.34, 4.32 and 5.30 d\(^{-1}\). After prewhitening the data with 4.32 d\(^{-1}\) we find useful IPS diagrams for the $\lambda 4567$ line only. The phase diagram clearly indicates that the variability at 2.32 d\(^{-1}\) is characterized by bumps moving across the line profile, which indicates its possible relation to a pulsation mode. In the next subsection we will demonstrate that the variation at 2.32 d\(^{-1}\) give an important contribution to the observed line-profile variability. However, the origin of the peak at 2.32 d\(^{-1}\) remains unclear.

From summed Fourier transforms we have selected the 14 strongest frequencies for detailed analysis (Sect. 6.3.3). Based on frequency considerations alone we could already identify some of these frequencies as false. We suspect that the apparent peaks in the Fourier spectra at {3.34, 4.32, 5.30} d\(^{-1}\) and {2.98, 3.94} d\(^{-1}\) are the result of only
Fig. 6.6. Best four subsequent nights of the observed time-series of the $\lambda_{4567}$ line profile. **Bottom:** Gray scale representation of residual spectra (mean subtracted). Intensities less than average are indicated black; bright regions in the profile are indicated by lighter shades. We used gray-scale cuts $-0.01,+0.01$. Note the absence of large bumps in the last shown night: only a bump in the blue wing of the line profiles is visible. Such behavior can be explained by the cancellation between different pulsation modes with comparable $\ell$-values. **Middle:** Overplot of residuals. This panel shows that most variability is present at the wings of the line-profile. **Top:** Mean of all line-profiles, including those from the other nights.
Fig. 6.7. Reconstruction of the data from three frequencies. We used three of the IPS diagrams, obtained with the sinusoid-fit technique at the frequencies 1.74, 3.94 and 4.32d$^{-1}$, to reconstruct the data. Note that the reconstruction is not created from theoretical IPS diagrams but from the IPS diagrams that we derived from the data.
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Fig. 6.8. Similar to Fig. 6.7 but for four frequencies. We included the IPS diagrams at 2.32d$^{-1}$ as well. This figure illustrates that the obvious line-profile variations are well represented by these four IPS diagrams, but that a detailed reconstruction requires more included modes. Note that the reconstruction is not created from theoretical IPS diagrams but from the IPS diagrams that we derived from the data.
two intrinsic frequencies in $\beta$ Lup; power has leaked to one-day aliases due to the large daily gaps in the dataset (see Sect.6.3.3). Secondly, we interpret the peaks at 6.08 and 7.09 $d^{-1}$ as the result of beating effects between stronger frequencies (see Sect.6.3.3).

We conclude from the remaining set of frequencies (1.74, {2.98, 3.94}, {3.34, 4.32, 5.30}) that at least three non-radial pulsation modes are present in $\beta$ Lup. Taking into account the errors in our $\ell$-determination we find:

\[ \ell \in \{5,6,7,8\}, \text{ with } f_i \in \{3.34,4.32,5.30\} \text{ } d^{-1} \]

\[ \ell > 5, \text{ with } f_i \in \{2.98,3.94\} \text{ } d^{-1} \]

\[ \ell > 4, \text{ with } f_i = 1.74 \text{ } d^{-1} \]

6.4.3 Reconstruction

We analysed the variability of the spectral line-profiles of $\beta$ Lup making use of IPS diagnostics for each of the apparent frequencies. We attributed some of these frequencies to one-day aliasing and beating effects. We were able to identify three pulsation modes. To see to what extent these identified modes contribute to the observed line-profile variations we reconstruct the dataset from the IPS diagnostics of these three modes. We use the amplitude and phase information to sum sinusoids with frequencies 1.74, 3.94 and 4.32 $d^{-1}$ to each position of the average spectrum. It turns out that the three identified modes do not satisfactorily reproduce the data. We find that the variability at 2.32$d^{-1}$ is also needed to reproduce the most obvious line-profile variations.

We show data and reconstruction during the best four subsequent nights in Figures 6.6, 6.7 and 6.8. These figures show that the variations at the above mentioned frequencies can explain much of the observed variations. As some of the observed features are still missing in the reconstruction, we consider it likely that more pulsation modes are needed to explain the detailed behavior of $\beta$ Lup.

6.5 Conclusions

We summarize the main conclusions of this Chapter:

1. We discovered complex multi-periodic line-profile variations in $\beta$ Lup, with apparent pulsation periods of three to more than ten hours.

2. We analysed the intensity variations across the line profile and found variational power at a number of frequencies. We suspect many of these to be the result of one-day aliasing and beating effects.

3. The most plausible explanation for the results of our analysis is that $\beta$ Lup exhibits non-radial pulsations. The concept of multiple non-radial pulsation modes provides a natural explanation for the multiperiodic behavior of the line profiles as well as for the time scales.
4. As the known fundamental stellar parameters put the star inside the \( \beta \) Cephei instability strip, we classify \( \beta \) Lup as a new bright member of the \( \beta \) Cephei class variables.

5. For three of the pulsation modes in \( \beta \) Lup we are able to derive \( \ell \)-values, or lower limits of \( \ell \). We tentatively conclude that some of the other frequencies are caused by additional pulsation modes. All identified modes have \( \ell \geq 5 \).

6. The limited time span of 7 days and the observing window of only 9 hours per day lead to ambiguities in the determination of the pulsation frequencies, and hamper a solid identification of all pulsation modes. Determination of the important parameters for all suspected modes requires a dedicated observing campaign with a longer total time span and a more complete daily coverage.

7. The high \( \ell \)-values of all detected pulsation modes in \( \beta \) Lup explain the absence of large photometric variations and the relatively small variations in EW and RV. Most of the presently known \( \beta \) Cephei stars where discovered either photometrically or with EW and RV measurements from low-resolution spectroscopy. It is likely that most of the \( \beta \) Cephei variables that exhibit modes of only high order are still not discovered. We believe that the history of discovering \( \beta \) Cephei variables has caused a bias, leading to an over-sampling of cases with pulsation modes of low \( \ell \). It is therefore desirable to search for new \( \beta \) Cephei stars by means of high-resolution spectroscopy. Such surveys would not only lead to newly discovered variables, but would improve the statistics of the \( \beta \) Cephei stars as well.
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