An asteroseismic study of the β Cephei star 12 Lacertae: multisite spectroscopic observations, mode identification and seismic modelling

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ABSTRACT

We present the results of a spectroscopic multisite campaign for the β Cephei star 12 (DD) Lacertae. Our study is based on more than thousand high-resolution high S/N spectra gathered with eight different telescopes in a time span of 11 months. In addition, we make use of numerous archival spectroscopic measurements. We confirm 10 independent frequencies recently discovered from photometry, as well as harmonics and combination frequencies. In particular, the slowly pulsating B-stars (SPB)-like g-mode with frequency 0.3428 d$^{-1}$ reported before is detected in our spectroscopy. We identify the four main modes as $(\ell_1, m_1) = (1, 1), (\ell_2, m_2) = (0, 0), (\ell_3, m_3) = (1, 0)$ and $(\ell_4, m_4) = (2, 1)$ for $f_1 = 5.178 964$ d$^{-1}, f_2 = 5.334 224$ d$^{-1}, f_3 = 5.066 316$ d$^{-1}$ and $f_4 = 5.490 133$ d$^{-1}$, respectively. Our seismic modelling shows that $f_2$ is likely the radial first overtone and that the core overshooting parameter $\alpha_{ov}$ is lower than 0.4 local pressure scale heights.

Key words: stars: individual: 12 Lac – stars: interiors – stars: oscillations.

1 INTRODUCTION

12 (DD) Lacertae (12 Lac) is one of the best observed β Cephei stars, a class of variable early B-type stars whose light and radial velocity changes are due to gravity and pressure-mode pulsations of low radial order (Stankov & Handler 2005). The variability of 12 Lac has been known for one century during which the star has been extensively studied. We refer to Handler et al. (2006) for a very detailed summary of the work accomplished in the past.

Despite the numerous earlier studies, safe mode identification of the observed modes was not achieved until recently. Thanks to an intensive photometric multisite campaign, Handler et al. (2006) unambiguously identified the $\ell$ values of the five modes with the highest photometric amplitudes. In addition, they found constraints on $\ell$ for the six other independent modes detected in their data set. Their $\ell$-identifications ruled out the assumption previously adopted for stellar modelling (e.g. Dziembowski & Jerzykiewicz 1999) that three of the strongest modes, almost equidistant, belong to the same multiplet. Indeed, these three modes are actually associated to three different values of the degree $\ell$.

Obviously, reliable empirical mode identification was indispensable before any attempt of in-depth seismic modelling of 12 Lac. To complement the photometric results, a spectroscopic multisite...
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2 OBSERVATIONS AND DATA REDUCTION

The data originate from a spectroscopic multisite campaign dedicated to our studied star. In addition, we added the 903 spectra of Mathias et al. (1994), which allowed us to increase the time span and, thus, to achieve a better frequency accuracy. In total, 1820 observations were gathered using nine different small- to medium-sized telescopes spread over the northern continents. Table 1 summarizes the logbook of our spectroscopic data. The resolution ($\lambda/\Delta\lambda$) of the instruments ranged from 30 000 to 80 000 and the average signal-to-noise (S/N) ratio near 4500 Å between 180 and 380.

Table 1. Log of our spectroscopic multisite campaign. The Julian Dates are given in days, $\Delta T$ denotes the time-span expressed in days, $N$ is the number of spectra and S/N denotes the average signal-to-noise ratio for each observatory measured at the continuum between 4500 and 4551 Å.

| Observatory (Name of the instrument; resolution) | Longitude | Latitude | Telescope | Julian Date Beginning | Julian Date End | $\Delta T$ | $N$ | S/N |
|-----------------------------------------------|-----------|----------|-----------|---------------------|----------------|----------|-----|-----|
| 2003–2004                                      | 2895 2900 | 6 105    |          |         |                |          |     |     |
| Apache Point Observatory (ARC; 31500)           | −105°49′ | +32°46′  | 3.5-m    | 2927    | 2928           | 2        | 93  | 300 |
| Bohyunsan Astronomical Observatory  (BOES; 30000) | +128°58′ | +36°09′  | 1.9-m    | 3109    | 3109           | 1        | 27  | 180 |
| Dominion Astrophysical Observatory (45000)      | −123°25′ | +48°31′  | 1.2-m    | 2858    | 2859           | 2        | 66  | 250 |
| McDonald Observatory (Sandiford; 60000)         | −104°01′ | +30°40′  | 2.1-m    | 2893    | 2901           | 9        | 210 | 380 |
| Nordic Optical Telescope (SOFIN; 80000)          | −17°53′  | +28°45′  | 2.6-m    | 2947    | 2951           | 5        | 32  | 370 |
| Okayama Astrophysical Observatory (HIDES; 685000)| +133°35′ | +34°34′  | 1.88-m   | 3201    | 3202           | 2        | 7   | 180 |
| Thüringer Landessternwarte Tautenburg (67000)     | +11°42′  | +50°58′  | 2-m      | 2863    | 2869           | 7        | 103 | 240 |
| 1990–1992                                      | 2886 2895 | 6 109    |          |         |                |          |     |     |
| Observatoire de Haute-Provence (AURELIE; 42000)  | +5°42′   | +43°55′  | 1.52-m   | 8135    | 8135           | 1        | 70  | 220 |
| Total                                          | 82 1820  |          |          |         |                |          |     |     |

All data were subjected to the normal reduction process, which consists of debiasing, background subtraction, flat-fielding and wavelength calibration. Finally, the heliocentric corrections were computed, and all spectra were normalized to the continuum by fitting a cubic spline function.

For our study, we considered the Si $\text{m\,\,} i$ triplet around 4567 Å because its characteristics simplify the modelling of the line-profile variations, which we use for mode identification. Indeed, these silicon lines are sufficiently strong without being much affected by blending. Moreover, they are dominated by temperature broadening, such that the intrinsic profile can simply be modelled with a Gaussian. Finally, they are not too sensitive to temperature variations (see De Ridder et al. 2002; Aerts & De Cat 2003), so that neglecting them remains justified.

The similar average radial velocity of about $-15$ km s$^{-1}$ for 1990–1992, 2003–2004 and earlier measurements (e.g. Wilson 1953) definitely excludes the possibility of 12 Lac being a spectroscopic binary. Besides the pulsation effect, the different centroids are due to the different zero points of the different telescopes. Before extracting the pulsation information from the whole data set, it is necessary to correct for this effect. The spectra were shifted in such a way that the constant of a least-squares sine fit using the first three dominant modes is put to the same value for each observatory.

In Fig. 1, we superimpose the average profiles of the Si $\text{m\,\,} i$ $\lambda$4553 Å line computed for each observatory separately, after correction for the different zero points. We note that the centroid of the lines are in good agreement but not exactly at the same position. Larger differences can be seen for the width and the depth of the lines. Such deviant average profiles are due to the limited time spread of the observations together with the multiperiodic character of the star.
The average profiles of the Si\(\text{III}\)\(\lambda\)4553 Å line from each observatory. The dashed line shows the average profile from the BAO observatory. This profile deviates from all the others because the relatively small number of spectra implies that the beat cycle is not well covered (see Table 1).

Figure 2. The Si\(\text{III}\) line profiles of one night (JD 2452898) taken with the McDonald telescope. The arrow indicates the flux scale of one spectrum.

In the case of a similar spectroscopic multisite campaign devoted to \(\nu\) Eridani, Aerts et al. (2004) observed similar differences, which are not caused by instrumental and/or S/N ratio effects.

Fig. 2 displays the large and complex radial-velocity variations of 12 Lac. The plotted spectra were taken with the McDonald telescope during only one night. In Fig. 3, we show the radial velocities for the densest part of the multisite campaign (2003 August 7 to 2003 November 17). A clear beating pattern is seen.

3 FREQUENCY ANALYSIS

We performed a frequency analysis on the first three velocity moments \(\langle v^1 \rangle\), \(\langle v^2 \rangle\) and \(\langle v^3 \rangle\) (see Aerts, de Pauw & Waelkens 1992, for a definition of the moments of a line profile) of the Si\(\text{III}\)\(\lambda\)4553 Å line by means of the program Period04 (Lenz & Breger 2005). For some \(\beta\) Cephei stars (see Telting, Aerts & Mathias 1997; Schrijvers, Telting & Aerts 2004; Briquet et al. 2005), a two-dimensional (2D) frequency analysis on the spectral lines led to additional frequencies compared to a one-dimensional (1D) frequency search in the moments. For 12 Lac 1D analysis on \(\langle v^2 \rangle\) and \(\langle v^3 \rangle\) did not reveal additional independent periodicities compared to those present in the first moment. We also do not find additional frequencies in the 2D frequency analysis. The 2D analysis is more sensitive to the detection of high-degree modes than a 1D analysis, so here we have already an indication that the frequencies are low-degree modes.

In what follows, we only describe our frequency analysis on \(\langle v^1 \rangle\), which is the radial velocity from which the fitted averaged radial velocity is subtracted.

The frequencies were determined with the standard method of pre-whitening the data. In addition, we made use of a procedure available in Period04 which allows to improve the detected frequency from non-linear least-squares fitting with the maxima in the Fourier transform as starting values. At each step of pre-whitening, we subtracted a theoretical multisine fit with the amplitudes, phases and also optimized frequencies that yielded the smallest residual variance. All peaks exceeding an amplitude S/N ratio above 4 in the Fourier periodogram (Breger et al. 1993, 1999) were retained. The noise level was calculated from the average amplitude, computed from the residuals, in a 2 d\(^{-1}\) interval centred on the frequency of interest.

The detected frequencies are listed in Table 2 and the Fourier periodograms are shown in Fig. 4. Our frequency analysis reaffirms the presence of the already well-known five main frequencies (Mathias et al. 1994) together with the new independent signals and combination frequencies discovered by Handler et al. (2006). We note that one additional independent frequency \(f_p = 5.309\) 12 d\(^{-1}\) was found by the latter authors and not by us. An important result is that we clearly recover the low-frequency signal possibly originating from a \(g\)-mode. Such a SPB-like oscillation does not seem to be uncommon among \(\beta\) Cephei stars. For instance, it was also
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Table 2. Frequencies and radial velocity amplitudes of the first moment of the Si\( \text{\textsc{iii}} \) \( \lambda 4553 \) Å line together with their S/N ratio (we refer to the text for explanation). Error estimates (Montgomery & O’Donoghue 1999) for the independent frequencies range from \( \pm 0.000002 \) \( \text{d}^{-1} \) for \( f_1 \) to \( \pm 0.00002 \) \( \text{d}^{-1} \) for \( f_9 \). The error on the amplitude is 0.01 km s\(^{-1}\).

| ID | Frequency \((\text{d}^{-1})\) | Amplitude in \( \langle v\rangle \) \((\text{km s}^{-1})\) | S/N |
|----|------------------|------------------|-----|
| \( f_1 \) | 5.178964 | 59.941713 | 14.50 | 99.6 |
| \( f_2 \) | 5.334224 | 61.738704 | 7.70 | 52.2 |
| \( f_3 \) | 5.066316 | 58.637917 | 6.26 | 42.7 |
| \( f_4 \) | 5.490133 | 63.543206 | 2.61 | 17.5 |
| \( f_5 \) | 0.342841 | 3.968067 | 1.34 | 7.1 |
| \( f_6 \) | 4.241787 | 49.09475 | 0.91 | 6.7 |
| \( f_7 \) | 5.218075 | 60.394387 | 0.84 | 5.8 |
| \( f_8 \) | 6.702318 | 77.573125 | 0.62 | 4.4 |
| \( f_9 \) | 7.407162 | 85.731042 | 0.67 | 4.9 |
| \( 2f_1 \) | 10.35814 | 119.88590 | 0.63 | 4.5 |
| \( f_2 + f_3 \) | 10.40056 | 120.37693 | 0.72 | 3.8 |
| \( f_1 + f_2 \) | 10.51319 | 121.68044 | 2.59 | 19.7 |
| \( 2f_1 + f_3 \) | 15.42400 | 178.51860 | 0.72 | 6.6 |
| \( f_1 + f_2 + f_3 \) | 15.57950 | 180.31838 | 0.71 | 6.4 |

observed in 19 Mon (Balona et al. 2002), in \( \nu \) Eridani (Handler et al. 2004), in \( \delta \) Ceti (Aerts et al. 2006) and in V1449 Aql (Briquet et al., in preparation). We also point out that such hybrid SPB-\( \beta \) Cep pulsators are theoretically predicted for hotter stars than previously thought (Miglio, Montalb\'an & Dupret 2007 versus Pamyatnykh 1999).

The equivalent width (EW) of the silicon line of 12 Lac clearly varies with the two dominant modes \( f_1 \) and \( f_2 \). The sum frequency \( f_1 + f_2 \) is even present. Fig. 5 represents phase diagrams for both

Figure 5. Phase diagrams of the equivalent width of the Si\( \text{\textsc{iii}} \) \( \lambda 4553 \) Å line, for \( f_1 \) (top panel), and for \( f_2 \) (bottom panel) after pre-whitening with \( f_1 \).

Figure 4. Amplitude spectra of 12 Lac computed from the first moment of the Si\( \text{\textsc{iii}} \) \( \lambda 4553 \) Å line. The uppermost panel shows the spectral window of the data. All subsequent panels show the periodograms in different stages of pre-whitening. The significance limit in red is calculated according to four times the noise over a 2 \( \text{d}^{-1} \)-range around the significant frequency.
4 MODE IDENTIFICATION

4.1 The methods used

We used two different and independent methods to identify the modes, namely the method (Briquet & Aerts 2003) and of the Fourier parameter fit method (FPF method; Zima 2006).

The basic principles of both methods are the following. With the moment method, the wavenumbers \((\ell, m)\) and the other continuous velocity parameters are determined in such a way that the theoretically computed first three moment variations of a line profile best fit the observed ones. In the FPF method, for every detected pulsation frequency, the zero point, amplitude and phase are computed for every wavelength bin across the profile by a multiperiodic least-square fit of a rotational mode of lower amplitude (see next section). For the four strongest modes, the frequency values derived from our spectroscopic measurements are exactly the same, within the errors, as the photometric ones by Handler et al. (2006). For the modes with radial velocity amplitudes typically lower than 1 km \(s^{-1}\), there are differences between values derived from both kinds of data, which might have some influence on the mode identification outcome. Because the number of observations as well as the time span of the data sets in the literature are much larger than the dedicated spectroscopic ones, the literature frequency values are expected to be more accurate and hence we adopt them.

4.2 Derivation of the wavenumbers

For the FPF method, a sophisticated theoretical formalism for the modelling of the displacement field is used and includes, for instance, first-order effects of the Coriolis force as well as temperature variations of the stellar atmosphere. We refer to Zima (2006, 2008) for details on the computation of the synthetic line-profile variations. The fixed parameters are the mass and the radius. When taking into account temperature effects, the effective temperature \(T_{\text{eff}}\) and the log of the gravity \(\log g\) have also to be fixed. For 12 Lac, we adopted the values \(M = 13.5 \, M_\odot\) (Handler et al. 2006), \(R = 6.9 \, R_\odot\) (Handler et al. 2006), \(T_{\text{eff}} = 24,500 \pm 1000\, K\) (Morel et al. 2006), \(\log g = 3.65 \pm 0.15\) (Morel et al. 2006). We note that the mode identification results are robust when using different values for these parameters, within the errors.

In a first step, we identified the three main modes \((f_{1,3,4})\) by fitting mono-mode Fourier parameters, which are computed from synthetic line profiles evenly sampled over one pulsation cycle (for more explanations see Zima 2006). Moreover, we neglected the EW variations of the spectral line due to temperature variations. In order to restrict the parameter space, we estimate roughly the values of the projected rotational velocity \(v \sin i\), the width of the intrinsic Gaussian profile \(\sigma\), and the EW from a least-squares fit of a rotationally broadened synthetic profile to the zero-point profile. This gives only a crude estimate of these three parameters, because the pulsational broadening is ignored in this fit, but it serves the purpose of defining our appropriate grid. Moreover \(v \sin i\) will be overestimated. When taken into account the pulsational broadening caused by the four main modes, we acquire \(v \sin i\) of 36.7 km \(s^{-1}\) (see Fig. 6). A genetic optimization with the following free parameters was afterwards adopted: \(\ell \in [0, 4]\) with a step of 1, \(m \in [-\ell, \ell]\) with a step of 1, the surface velocity amplitude \(a \in [10, 110] \, km \, s^{-1}\) with a step of 1 \(km \, s^{-1}\), the stellar inclination angle \(i \in [5, 85]\) with a step of 5°, \(v \sin i \in [20, 48] \, km \, s^{-1}\) with a step of 0.5 km \(s^{-1}\) and \(\sigma \in [10, 30] \, km \, s^{-1}\) with a step of 0.1 km \(s^{-1}\). We fixed \(f_{2}\) as a radial mode and only fitted the continuous parameters for that mode.

In Table 3, the five best solutions from a fit to the Fourier parameters are listed for each frequency. The 95 per cent-confidence limit of \(\chi^2\) is 1.15. The most probable solutions are \((\ell_1, m_1) = (1, 1), (\ell_3, m_3) = (1, 0)\) and \((\ell_4, m_4) = (2, 1)\) (where a positive \(m\) value denotes a prograde mode). We point out that the agreement between theory and observations is not perfect. More precisely, the observed asymmetry with respect to the centroid of the amplitudes across the line of the dominant modes is not completely reproduced by our model. Such an asymmetry can be caused by EW variations of the intrinsic line profile due to local temperature variations (Schrijvers 2005; Mazumdar et al. 2006). Mode identification results have been obtained with the software package FAMIAS\(^1\) (Zima 2008).

In what follows, we present in detail our mode identification by the FPF method. The moment method gave compatible results, but did not give additional constraints on the \((\ell, m)\) than the ones we present here. Both techniques found the same \(m\) values for the three main modes, giving us much confidence in our outcome. For the fourth mode, the moment method derived the sign of \(m\) in agreement with the FPF method, which could further constrain its value.

\(^{1}\) FAMIAS has been developed in the framework of the FP6 European Coordination Action HELAS – http://www.helas-eu.org/.
& Telting 1999). We considered EW variations in our fitting procedure but we did not obtain an improved solution compared to the case of a constant EW.

In a second step, we attempted to improve the solutions by simultaneously fitting the four main modes and using all the original data points. This however was computationally not possible. To restrict the computation time, we took a subset of our complete time series. Our subset resulted in 388 spectra with a time span of 4 months. We also fixed the wave numbers according to our mono-mode fit described above. We succeeded in improving the surface velocity amplitudes together with the inclination, \( v \sin i \) and the width of the intrinsic profile. The \( \chi^2 \) values are lower than in the mono-mode fit and we are able to reproduce part of the asymmetry in the amplitude across the line as explained above (see Table 4). Fig. 7 illustrates the best models for the amplitude and phase across the line profile for the four main modes.

### Table 3. Mode parameters derived from the FPF mono-mode method.

For each pulsation mode, the five best solutions are shown together with the second best \((\ell, m)\) identifications. For \( f_s \), we list the different solutions for \( m, a_s \) is the surface velocity amplitude \((\text{km s}^{-1})\); \( i \) is the stellar inclination angle in degrees; \( v \sin i \) is the projected rotational velocity, \( \sigma \) is the width of the intrinsic profile, both expressed in \( \text{km s}^{-1} \). Due to spherical symmetry, we have not indicated the inclination angle for radial modes. The 95 per cent significance limit is at \( \chi^2 = 1.31 \).

| \( \chi^2 \) | \( \ell \) | \( m \) | \( a_s \) | \( i \) | \( v \sin i \) | \( \sigma \) |
|---|---|---|---|---|---|---|
| 15.29 | 1 | 1 | 68.7 | 74.6 | 46.47 | 21.00 |
| 15.50 | 1 | 1 | 85.0 | 38.15 | 27.82 | 21.64 |
| 15.31 | 1 | 1 | 48.2 | 72.1 | 43.72 | 25.00 |
| 15.32 | 1 | 1 | 72.3 | 51.4 | 26.83 | 25.00 |
| 15.33 | 1 | 1 | 50.9 | 59.2 | 42.00 | 26.66 |
| 31.62 | 1 | 0 | 68.4 | 41.2 | 30.79 | 26.66 |

| \( \chi^2 \) | \( \ell \) | \( m \) | \( a_s \) | \( i \) | \( v \sin i \) | \( \sigma \) |
|---|---|---|---|---|---|---|
| 12.36 | 0 | 0 | 41.6 | 43.65 | 25.17 | 7.73 |
| 12.83 | 0 | 0 | 37.0 | – | 36.66 | 28.11 |
| 13.07 | 0 | 0 | 42.6 | 43.33 | 25.00 | 7.77 |
| 13.53 | 0 | 0 | 33.4 | 40.47 | 26.41 | 7.79 |
| 13.68 | 0 | 0 | 33.3 | – | 44.0 | 24.70 |

Finally, we tried to identify the other low-amplitude modes with the same methodology and by imposing the wavenumbers \((\ell, m)\) deduced for the four main modes. Unfortunately, we could not obtain additional conclusions. Our failure is not very surprising since these modes have amplitudes lower or of the same order as the harmonics and combination frequencies also present in the signal while non-linear terms are not taken into account in our line-profile modelling. Fig. 8 depicts the amplitude and phase across the line for these low-amplitude modes. Despite the fact that the phase across the profile is well determined for these modes and seems to point to axisymmetric or prograde modes, the \( \chi^2 \) values between the different options were not discriminative, so we do not use that information in the following.

### Table 4. Mode parameters derived from the FPF method through a simultaneous fit of the four main modes.

We used the same methodology and by imposing the wavenumbers \((\ell, m)\) deduced for the four main modes. Unfortunately, we could not obtain additional conclusions. Our failure is not very surprising since these modes have amplitudes lower or of the same order as the harmonics and combination frequencies also present in the signal while non-linear terms are not taken into account in our line-profile modelling. Fig. 8 depicts the amplitude and phase across the line for these low-amplitude modes. Despite the fact that the phase across the profile is well determined for these modes and seems to point to axisymmetric or prograde modes, the \( \chi^2 \) values between the different options were not discriminative, so we do not use that information in the following.

### 4.3 Derivation of the surface equatorial rotational velocity and the inclination

From mode identification, we can also estimate the inclination, \( v \sin i \) and the equatorial rotational velocity \( v_{eq} \). By using \( \chi^2 \) as a weight, we can construct histograms for \( i, v \sin i \) and \( v_{eq} \).
Figure 7. Observed Fourier parameters (black points with error bars) across the line profile together with the best fit for the four identified modes (full line). The amplitudes are expressed in units of continuum and the phases in 2π radians.

we display these histograms. They are computed by considering all the solutions of the FPF method with the correct wavenumbers of the four dominant modes through a simultaneous fit, and by giving each parameter \((i, v \sin i, v_{eq})\) its appropriate weight

\[ w_k = \chi^2_0/\chi^2_k, \]

where \(\chi^2_0\) is the \(\chi^2\) value for the best solution. By calculating a weighted mean and standard deviation of the data, we get \(i = 48 \pm 2^\circ, v \sin i = 36 \pm 2\, \text{km s}^{-1}\) and \(v_{eq} = 49 \pm 3\, \text{km s}^{-1}\). This leads to a surface rotational frequency between 0.11
Figure 8. Observed Fourier parameters (black points with error bars) across the line for the detected pulsation frequencies ($f_{p,5-9}$). The amplitudes are expressed in units of continuum and the phase in $2\pi$ radians.

Table 5. Final results for the mode identification of 12 Lac from our spectroscopic analysis together with the results from the photometric amplitude ratios (Handler et al. 2006).

| ID  | Frequency (d$^{-1}$) | $\ell$ | $m$ |
|-----|---------------------|-------|-----|
|     | Spectr. | Phot. |
| $f_1$ | 5.178 964 | 1     | 1   |
| $f_2$ | 5.334 224 | 0     | 0   |
| $f_3$ | 5.066 316 | 1     | 0   |
| $f_4$ | 5.490 133 | 2     | 2   |
| $f_5$ | 5.342 841 | 1.2, 4 |
| $f_6$ | 5.218 075 | 2     | 0, 1, 2 |
| $f_7$ | 6.702 318 | 1     | -   |
| $f_8$ | 7.407 162 | 1, 2  |
| $f_9$ | 5.845 11  | 1, 2  |
| $f_9$ | 5.309 12  | 1, 2  |

and 0.12 d$^{-1}$ for the appropriate stellar models in Table 6, which will be discussed further on. In the same way, we constructed these histograms with the solutions from the multimode fit of the moment method. However, the moment method did not have the ability to limit the range for $i$ and, by implication, leads to a less trustworthy estimate of $v_{\infty}$. The reason for this is probably that the moment method is based on integrated quantities over the line profile, while in the FPF method we use all the information across the line profile as a whole, which is more sensitive to the position of the nodal lines across the stellar surface and thus to the stellar inclination.

5 Modelling

In this section, we check if state-of-the-art stellar models with standard physics can account for the observed frequency spectrum together with the derived wavenumbers ($\ell$, $m$) for our studied star. By doing so, we can constrain 12 Lac’s model parameters, which are the mass, the central hydrogen abundance and the core convective overshooting parameter. Such asteroseismic constraints have recently been derived for a few $\beta$ Cephei stars: 16 Lac (Thoul et al. 2003), V836 Cen (Aerts et al. 2003; Dupret et al. 2004), v Eri (Ausseloos et al. 2004; Pamyatnykh, Handler & Dziembowski 2004; Dziembowski & Pamyatnykh 2008), $\delta$ Ceti (Aerts et al. 2006), $\beta$ CMa (Mazumdar et al. 2007), $\theta$ Oph (Brillet et al. 2007). Finally, Ausseloos (2005) and, more recently, Dziembowski & Pamyatnykh (2008) already made a comparison with stellar models for 12 Lac.
Our choice for the metal mixture and the opacities is justified by the following arguments. First, Morel et al. (2006) found that the abundances of He, C, N, O, Mg, Al, Si, S and Fe are, within the errors, in good agreement with the solar values derived from time-dependent, three-dimensional hydrodynamical models of Asplund et al. (2005, and references therein). Second, Amsellos (2005) performed a preliminary seismic study of 12 Lac and was confronted with the problem that, when using OPAL opacities, not all observed pulsation modes can be excited for realistic values of the metallicity and core overshooting parameter. This excitation problem is encountered with the Grevesse, Noels & Sauval (1993) but also with the Asplund et al. (2005) mixture, even for large values of $Z$ (typically larger than 0.016). If we consider values of $Z$ smaller than 0.016, which are more representative of the star, the problem is obviously increased. As discussed in Briquet et al. (2007) for $	heta$ Oph, modes that are stable with OPAL opacities (Rogers & Iglesias 1992; Rogers & Nayfonov 2002) can be predicted to be unstable with OP opacities. The reason is that in a typical B Cephei model, the OP opacity is 25 per cent larger than the one for OPAL in the region where the driving of pulsation modes occurs. We consequently wish to check if the use of OP opacity tables improves the situation in the case of the modelling of 12 Lac. We refer to Miglio et al. (2007) for a detailed discussion on the implication of the adopted opacity tables and metal mixtures on the excitation of pulsation modes in the case of B-type stars.

For each stellar model, we calculated the theoretical frequency spectrum of low-order $p$- and $g$-modes with a degree of the oscillation up to $\ell = 4$ using a standard adiabatic code for non-rotating stellar models (Scuflaire et al. 2008a), which is much faster than a non-adiabatic code but leads to the same theoretical pulsation frequencies within the adopted precision of the fit, which was $10^{-3}$ d$^{-1}$. Once the models fitting the observed modes are selected, we checked the excitation of the pulsation modes with the linear non-adiabatic code MAD developed by Dupret (2001).

### 5.2 Seismic analysis

Besides the pulsation characteristics summarized in Table 5, we also use $T_{\text{eff}}$, $\log g$ and the metallicity $Z$ as additional observational constraints. Geneva photometry of 12 Lac provides $T_{\text{eff}} = 23500 \pm 700$ K and $\log g = 3.4 \pm 0.4$ (Handler et al. 2006). From *International Ultraviolet Explorer (IUE)* spectra, Niemczura & Daszyńska-Daszkiewicz (2005) derived $T_{\text{eff}} = 23600 \pm 1100$ K and $\log g = 3.65 \pm 0.15$. Morel et al. (2006) obtained $T_{\text{eff}} = 24500 \pm 1000$ K and $\log g = 3.65 \pm 0.1$ from optical spectra. Using another method on the same spectra as Morel et al. (2006), Lefever (2008) deduced $T_{\text{eff}} = 24000 \pm 1000$ K and $\log g = 3.60 \pm 0.1$. Morel et al. (2006) also determined a metallicity $Z = 0.0089 \pm 0.0018$.

Stellar models are parametrized by the initial hydrogen abundance $X$, the core convective overshooting parameter $\alpha_{ov}$, the metallicity $Z$ and the mass $M$. We adopted $X = 0.72$ but using a different value for $X$ in a reasonable range does not change the conclusions.

We considered two values for $Z$, i.e. 0.010 and 0.015. The first chosen value corresponds to a metallicity typical of B dwarfs in the solar neighbourhood, also found for 12 Lac within the errors (see above, Morel et al. 2006). The second choice corresponds to the solar composition and the reason for also adopting this value is the following. The star being a relatively slow rotator and its surface convective zone being very thin, diffusion mechanisms can alter the photospheric abundances, leading to $Z$ smaller at the surface compared to the interior of the star. However, since these effects are limited to the very superstellar layers, including a diffusion...
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We refer to Briquet et al. (2007) for a deeper discussion. For simplicity, we computed non-rotating stellar models without taking into account diffusion, but we also considered a $Z$ higher than what is derived from spectra. Several values for $\alpha_{\text{ov}}$ in the range [0.0–0.5] were tested. The reason is that the recent asteroseismic modelling of several $\beta$ Cephei stars (listed above) showed the occurrence of core overshooting with $\alpha_{\text{ov}}$ in the range [0.05–0.25] for all studied stars except $\theta$ Oph for which an even higher value of $\sim$0.45 was determined. Moreover, other works corroborate the necessity to include core overshooting in modelling of massive B-type stars. For instance, Deupree (2000) derived a value of about 0.45 by means of 2D hydrodynamic simulations of zero-age main-sequence convective cores. We also mention that, with his study of 13 detached double-lined eclipsing binaries, Claret (2007) found that models with core overshooting of $\alpha_{\text{ov}} \sim 0.2$ are needed to analyse $\sim$10 M$_\odot$ stars.

The observed radial mode with $f_2 = 5.334 \pm 0.024$ d$^{-1}$ and the $\ell = 1$ zonal mode with $f_3 = 5.066 \pm 0.026$ d$^{-1}$ were selected as the first two frequencies to be confronted with the theoretically predicted frequencies. This was an obvious choice since these are zonal modes ($m = 0$) and thus we do not need any information about the equatorial frequency of rotation to fit them with the model frequencies.

We considered two different scenarios: $f_2$ being either the radial fundamental mode or the first overtone.

The theoretical frequency spectrum with $f_2$ being the radial fundamental mode is globally compatible with the observed frequencies of 12 Lac. However, all such models fail to reproduce the $\ell = 1$ mode with $f_3 = 6.702 \pm 0.028$ d$^{-1}$. If $f_2$ corresponds to a radial fundamental mode, $f_3$ can only be an $\ell = 2$ mode according to theoretical models, while the observed photometric amplitude ratios for this mode point out an $\ell = 1$ (Handler et al. 2006). Unfortunately, we cannot confirm this strong constraint since our spectroscopic mode identification was not conclusive for this mode. However, stellar models with $f_2$ corresponding to the radial first overtone can account for a $\ell = 1$ mode with $f_3$. We consequently favour a radial order $n = 2$ for $f_2$. An additional strong argument to favour $f_2$ as the radial first overtone is the following. The Ledoux rotational splitting is defined by $f_{\text{Ledoux}} = m\beta_{\text{sd}} f_{\text{rot}}$, where $\beta_{\text{sd}}$ is a structure constant depending on the stellar model, and originates from the frequency splitting defined as

$$f_{\text{ov}} = f_0 + m\beta_{\text{sd}} f_{\text{rot}} = v_0 + m \int_0^R K(r) \frac{\Omega(r) \ dr}{2\pi R} \text{, (1)}$$

where $f_{\text{ov}}$ is the cyclic frequency of a mode of azimuthal-order $m$, $\Omega(r)$ is the angular velocity and $K(r)$ is the rotational kernel (for more information, see Scuflaire et al. 2008a). With $f_2$ as fundamental, the difference between the frequency $f_3 = 4.241 \pm 0.027$ d$^{-1}$ and the nearest quadrupole mode (at $\sim$3.8 d$^{-1}$) is too large to be explained by the Ledoux rotational splitting and thus $f_3$ cannot be fitted. With $f_2$ as first overtone, $f_3$ is easily identified as the $g_2$ mode with ($\ell, m$) = (2, 1) as shown below (see also Fig. 11). With $f_2$ being the first overtone, $f_3$ is identified as $p_1$.

The couple ($X, Z$) being fixed, the fitting of two frequencies suffices to derive the stellar age and stellar mass for adopted $\alpha_{\text{ov}}$. The positions in the log($T_{\text{eff}}$)–log $g$ diagram of the models matching $f_2$ and $f_3$ for different values of $\alpha_{\text{ov}}$ are shown in Fig. 10. The corresponding parameters are listed in Table 6 for $Z = 0.015$. The mass decreases when the core overshooting parameter increases. We also note the perfect agreement between the log $g$ of the models and the value deduced from spectroscopic observations. Moreover, the best agreement in $T_{\text{eff}}$ corresponds to models with $\alpha_{\text{ov}}$ between 0.0 and 0.4 and a mass between 10.0 and 14.4 M$_\odot$. Note that a decrease in $Z$ implies an increase in mass and, considering a $Z$ of 0.010 instead of 0.015 increases the mass by 0.5 M$_\odot$ at most.

5.3 Radial order identifications

The frequency $f_1 = 5.178 \pm 0.026$ d$^{-1}$ can only belong to the $p_1$ triplet. The frequency splitting $f_1 - f_2 = 0.1126$ d$^{-1}$. According to the models, $\beta_{\text{sd}} = 0.5$ for this mode. This yields an averaged frequency of rotation $f_{\text{rot}} = (f_1 - f_2)/m\beta_{\text{sd}}$. This averaged rotation frequency leads to a rotational velocity twice as high as the surface value estimated from our spectroscopic observations (with corresponding velocities of 100 versus 49 km s$^{-1}$). We thus confirm that 12 Lac must rotate more rapidly in its inner parts than at the surface, as already emphasized by Dziembowski & Pamyatnykh (2008).

As can be seen in Fig. 11, the ($\ell = 1, p_1$) mode can account for $f_2 = 6.702 \pm 0.028$ d$^{-1}$. The match is not perfect for all models in Table 6. This is probably due to the fact that there can occur small shifts due to rotation. On the other hand, a change in metallicity will also cause a small shift of the theoretical frequencies (see Section 5.5). The frequency $f_3$, $7.407 \pm 0.015$ d$^{-1}$ and $f_2 = 5.845 \pm 0.011$ d$^{-1}$ can only be the ($\ell = 2, p_2$) mode and the ($\ell = 1, p_2$) mode, respectively. Indeed, no theoretical frequency of an $\ell = 1$ zonal mode and an $\ell = 2$ zonal mode is in the vicinity of $f_3$ and $f_2$, respectively. We also note that an $\ell = 0$ radial-mode solution for $f_3$ is excluded (see Table 5).

The frequency $f_3 = 5.309 \pm 0.012$ d$^{-1}$ found in photometry and the frequency $f_4 = 5.490 \pm 0.013$ d$^{-1}$ were both identified as quadrupole modes and can be accounted for by the ($\ell = 2, f$) mode. Indeed, the theoretical Ledoux frequency splitting assuming the averaged internal rotation frequency value $f_{\text{rot}}$ derived from $f_1 - f_3$ ranges in $[0.186-0.190]$ d$^{-1}$ for different overshooting values, which corresponds to the difference between $f_2$ and $f_3$. The frequency $f_3$ thus corresponds to ($\ell, m$) = (2, 0) and $f_4$ to ($\ell, m$) = (2, 1) in accordance with the $m$–identification for $f_4$. Note that the theoretical frequency value for the ($\ell = 2, f$) mode is in best agreement for $\alpha_{\text{ov}} = 0.0$ and is 5.287 d$^{-1}$.

$$f_3 = 4.241 \pm 0.027$$ d$^{-1}$ being a prograde $\ell = 2$ mode, is uniquely identified as the ($\ell = 2, g_2$) mode. The corresponding theoretical zonal mode has a frequency between 4.048 and 4.070 d$^{-1}$ with a Ledoux splitting for that mode ranging between 0.183 and 0.185 d$^{-1}$.

$$f_3 = 5.066 \pm 0.028$$ d$^{-1}$ deduced from $f_{\text{rot}}$ and $\beta_{\text{sd}} = 0.80$. In addition, we thus conclude that $m = 1$ for this mode.
Figure 11. Comparison between the theoretical frequencies \((m = 0, \text{ dots})\) and the observed frequencies (full and dotted lines) labelled with their frequency identifications as listed in Table 5. The full lines correspond to the two axisymmetric modes \(f_2\) and \(f_3\). The top and bottom panels correspond to \(f_2\) as the radial first overtone and the radial fundamental, respectively. The theoretical models are calculated for \(X = 0.72, Z = 0.015\) and \(\alpha_{ov} = 0.0\).

\[ f_6 = 5.218075 \text{ d}^{-1} \] may be either identified as \((\ell = 4, g_2)\) or \((\ell = 4, g_1)\) (see also Fig. 11). The models give \(\beta_{nl} = 0.97\) for this mode. In the first case, the zonal frequency ranges between 4.38 and 4.55 \text{ d}^{-1} with a Ledoux splitting of 0.21-0.22 \text{ d}^{-1} deduced from \(\bar{f}_{rot}\). This corresponds to an \(m\) value of 3 or 4. In the second case, the zonal frequency ranges between 5.57 and 5.70 \text{ d}^{-1} with a Ledoux splitting of 0.20-0.21 \text{ d}^{-1}. This corresponds to an \(m\) value of \(-2\). Finally, nothing can be concluded for \(f_g = 0.342841 \text{ d}^{-1}\) because of the dense theoretical frequency spectrum in the low-frequency range and because of the lack of observed constraints on the wavenumbers of this mode. We additionally note that we cannot definitely exclude this frequency to be linked with the frequency of rotation. For instance, \(f_g/3\) is compatible with our observed surface equatorial rotation frequency. As explained in Briquet et al. (2001, 2004), one way to discriminate between the pulsation and rotation interpretation is to compare the variability of the considered frequency in lines of different chemical elements. Unfortunately, we could not achieve such a test because lines other than Si lines are at our disposal only for two nights of observation. This time span is not long enough to recover such a low frequency value.

### 5.4 Comparison with photometry

We used our best models listed in Table 6 to compare our results with the photometric mode identification of Handler et al. (2006). We computed theoretical photometric amplitude ratios for our three main identified pulsation modes \((f_2, f_3, f_4; f_1 \text{ belongs to } f_3)\) following Dupret et al. (2003). We computed the amplitude ratios for Strömgren \(u\) and \(v\), and for Johnson V. For this computation, we must determine the non-adiabatic pulsation mode parameters \(f_T\) and \(f_g\), where \(f_T\) corresponds to the local effective temperature variation and \(f_g\) corresponds to the local effective gravity variation, both at the level of the photosphere. We used the non-adiabatic code \(\text{MAD}\) (Dupret 2001) to compute these \(f_{T,g}\) parameters for our best seismic models of 12 Lac.

We list the observed and theoretical photometric amplitudes for the three main modes in Table 7. We refer to Fig. 4 of Handler et al. (2006) for the results of the photometric mode identification. For all the models, we observed that the amplitude ratios decrease with decreasing mass. For \(f_2\), we find amplitude ratios for \(u/v\) ranging from 0.68 until 0.64, and for \(V/u\) ranging from 0.51 until 0.56. Thus, we encounter exactly the same problem as Handler et al. (2006), i.e. we could not find a perfect agreement for the observed ratios of \(f_2\). For \(f_3\), we find amplitude ratios for \(u/v\) ranging from 0.84 until 0.73, and for \(V/u\) ranging from 0.74 until 0.67. Our models give amplitude ratios for \(f_4\) for \(u/v\) ranging from 0.90 until 0.83, and for \(V/u\) ranging from 0.84 until 0.78. Our conclusion is that we can reproduce the observed photometric amplitude ratios for

| ID | Frequency \((\text{d}^{-1})\) | \(u/v\) Obs. | \(u/v\) Theory | \(V/u\) Obs. | \(V/u\) Theory |
|----|-------------------------------|--------------|----------------|--------------|----------------|
| \(f_2\) | 5.334224 | 0.529 (7) | 0.64 | 0.456 (7) | 0.56 |
| \(f_3\) | 5.066316 | 0.716 (8) | 0.73 | 0.686 (8) | 0.67 |
| \(f_4\) | 5.490133 | 0.82 (1) | 0.83 | 0.78 (1) | 0.78 |

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the two main modes ($f_1$ and $f_2$) from our best seismic models. Moreover, from this a posteriori consistency check, we favour a the more evolved seismic models, i.e. those with lower mass and higher core overshoot (see Tables 6 and 7).

5.5 Discussion

We have shown that adopting $n = 2$ for the radial mode cannot be excluded as was done by Dziembowski & Pamyatnykh (2008), and, in fact, explains all observed frequencies according to their photometric and spectroscopic mode identification except for $f_g$. The identifications of the radial order together with the additional $\ell$ identifications are summarized in Table 8. A perfect agreement in frequency values is not achieved. One reason might be that slightly different values for $(X, Z)$ than those adopted could lead to a better agreement. Another one may be that small frequency shifts due to rotation may occur as already pointed out by Dziembowski & Pamyatnykh (2008), although the surface equatorial rotation frequency is only a few percent of the measured oscillation frequencies. We found evidence for some degree of differential rotation from the observed splitting between $f_1$ and $f_2$. Using the Ledoux splitting, all the other detected frequencies can be well fitted with one and the same averaged rotation frequency $\bar{f}_{\text{rot}}$ inside the star, where $\bar{f}_{\text{rot}}$ is derived from the model fitting of $f_1$ and $f_2$. In the absence of the observations of multiplets, we do not have enough constraints to derive the internal rotation profile as defined in equation (1) and, consequently, to determine its effects on the frequencies and frequency splittings.

Dziembowski & Pamyatnykh (2008) partly included rotation effects in their modelling and proposed a model with the angular rotation velocity more than four times higher in the centre of the star compared to the surface. They imposed that the radial mode is the fundamental without considering alternative identifications. Consequently, they could not account for an $\ell = 1$ for $f_2$. As our results are the same than theirs under the assumption of the radial fundamental mode, we refer to their paper for the properties of the resulting seismic model in this case without repeating it here (see in particular their fig. 7 and our Fig. 11). Their assumption of non-rigid rotation is based on the fact that $f_g$ cannot be fitted because the closest $\ell = 2$ mode is too far to be explained by the splitting due to a uniform rotation. We recall that, on the contrary, our models reproduce the $\ell = 1$ for $f_2$ and the Ledoux splitting for $\bar{f}_{\text{rot}}$ can explain $f_2$ as the $(\ell, m, n) = (2, 1, -2)$ mode. As additional argument to non-rigid rotation, Dziembowski & Pamyatnykh (2008) stated that their model with uniform rotation has no identification for $f_2$. We can explain it as the $(\ell = 4, g_1)$ mode or the $(\ell = 4, g_2)$ mode in agreement with the photometric $\ell$ identification. Finally, even with a non-uniform rotation, they cannot reproduce $f_3$ appropriately while they used this frequency value to exclude rigid rotation.

Until now, the only convincing proof of non-rigid rotation has been achieved for V836 Cen (Aerts et al. 2003; Dupret et al. 2004) and for \nu Eri (Pamyatnykh et al. 2004; Dziembowski & Pamyatnykh 2008). The only other star with two observed multiplets is \theta Oph for which the observed rotational splittings cannot rule out a rigid rotation model. For 12 Lac, we are able to fit the observed frequency spectrum using non-rotating stellar models and Ledoux splittings based on one consistent value $\bar{f}_{\text{rot}}$ for the averaged internal rotation frequency derived from the splitting between $f_1$ and $f_3$. The deviation from the rotation frequency derived from fitting the splitting $f_1 - f_3$ and from the observed surface rotation frequency points to some degree of non-rigidity. With only two components of one and the same multiplet observed, we are not able to quantify this statement.

Besides our basic stellar modelling, we also checked if non-adiabatic computations are able to reproduce the excitation of the observed frequencies. Indeed, recent works revealed shortcomings in the details of the excitation mechanism for these massive B-type pulsating stars. For instance, for \nu Eri (Ausseloos et al. 2004; Pamyatnykh et al. 2004), the observed lowest $g$-mode and highest $p$-mode frequencies were not predicted to be excited by standard models. The same conclusion is found for 12 Lac. Neither the frequency $f_g$ nor the highest $p$-mode frequencies ($f_2$ and $f_4$) are excited by current models, even with OP opacity tables. Since 1991, the agreement between the non-adiabatic computations for \beta Cephei models and the observations has improved with subsequent update of opacities (see e.g. Miglio 2007; Miglio et al. 2007). Consequently, a most probable explanation for the encountered excitation problem is that the current opacities are still underestimated in the region where the driving of pulsation modes occurs. We refer to Dziembowski & Pamyatnykh (2008) for an additional discussion on this matter.

6 CONCLUSIONS

Our study was based on 1820 ground-based, high-resolution, high S/N ratio, multisite spectroscopic measurements spread over 14 yr. As pointed out in Handler et al. (2006), this effort was necessary to identify the previously unknown azimuthal order of the pulsation modes and thus to be able to perform a detailed seismic modelling of the star. We used the Si IV in 4553 Å line to derive the pulsation characteristics of 12 Lac. In total, we find 10 independent frequencies which were also detected in photometry. Worth mentioning is that we also clearly recover the low-frequency signal. One of our aims was to provide a unique identification of as many modes as possible for 12 Lac. The important result of combining our spectroscopic results with the ones from the intensive photometric campaign (Handler et al. 2006) is the unique identification of both $\ell$ and $m$ of the four highest-amplitude modes.

The definite identification of four of the observed modes together with some constraints of the wavenumbers (either $\ell$ values or sign of $m$) on the other modes allowed us to carry out a detailed seismic modelling, under the assumption of linear oscillation modes. The most significant outcome of our modelling is the fact that there is a strong preference that the observed radial mode ($f_3$) is the radial mode. The definite identification of four of the observed modes together with some constraints of the wavenumbers (either $\ell$ values or sign of $m$) on the other modes allowed us to carry out a detailed seismic modelling, under the assumption of linear oscillation modes. The most significant outcome of our modelling is the fact that there is a strong preference that the observed radial mode ($f_3$) is the radial mode.
first overtone. If \( f_2 \) is taken as the radial fundamental, the frequency spectrum of 12 Lac cannot be reproduced satisfactorily. We do point out that the theory we used, as well as Dziembowski & Pamyatnykh (2008), does not include non-linear effects, while these may be present in 12 Lac (e.g. Mathias, Gillet & Crowe 1992). It remains to be studied how these would effect mode identification and seismic modelling, but given the very moderate effect and the limit to only very few third-order combination frequencies, we do not expect this to alter our conclusions, just as for the case of \( v \) Eri, where a linear theory was also used (Pamyatnykh et al. 2004).

With two state-of-the-art methods, the moment method and the FPF method, we were able to identify the azimuthal order of the four main modes. We could also give a constraint on the azimuthal order of the fifth frequency. Two main frequencies were identified as axisymmetric modes. One of which has an \( \ell \) value of 1 (\( f_1 \)), the other one is a radial mode (\( f_2 \)). The two other main frequencies are identified as (\( \ell_1, m_1 \) = (1, 1) and (\( \ell_4, m_4 \) = (2, 1). The conclusion for the fifth frequency is that the azimuthal order is likely to be positive. In addition, the FPF method could also constrain the inclination, \( i = 48 \pm 2 \degree \), and the surface equatorial rotational velocity, \( v_\text{eq} = 49 \pm 2 \text{ km s}^{-1} \).

The complete frequency spectrum of 12 Lac, except the low frequency, can be fully identified. Our seismic modelling also revealed an excitation problem. Indeed, the range of frequencies theoretically excited is not large enough compared to the observations. This might reflect the fact that opacities are still underestimated in the region where the driving of pulsation modes occurs. This conclusion is valid for both the OPAL and OP opacities.

Finally, our best-fit models indicate that the overshooting parameter \( \alpha_\text{ov} \) has to be lower than 0.4 local pressure scale heights to get the best agreement with physical parameters derived from spectroscopic observations. A more refined seismic modelling requires the computation of a much denser grid of models and will be done in future work.

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