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# Asteroseismology of the $\beta$ Cep star HD 129929⋆

## I. Observations, oscillation frequencies and stellar parameters

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**Abstract.** We have gathered and analysed a timeseries of 1493 high-quality multicolour Geneva photometric data of the B3V $\beta$ Cep star HD 129929. The dataset has a time base of 21.2 years. The occurrence of a beating phenomenon is evident from the data. We find evidence for the presence of at least six frequencies, among which we see components of two frequency multiplets with an average spacing of ~0.0121 c d$^{-1}$ which points towards very slow rotation. This result is in agreement with new spectroscopic data of the star and also with previously taken UV spectra. We provide the amplitudes of the six frequencies in all seven photometric filters. The metal content of the star is $Z = 0.018 \pm 0.004$. All these observational results will be used to perform detailed seismic modelling of this massive star in a subsequent paper.

**Key words.** stars: oscillations – stars: variables: general – stars: individual: HD 129929

### 1. Introduction

The star HD 129929 (spectral type B3V, $V$ mag = 8.1) is quite a peculiar object, as it is situated at intermediate galactic latitude with $b = 20.21°$ (Hill et al. 1974), which is unusual for such a massive object. This is the reason why Rufener (1981) included it in the Geneva database as a standard, which led him to discover its variability.

The parallax of HD 129929 has meanwhile been measured by HIPPARCOS, albeit with a large uncertainty. The measured $\pi = 1.48 \pm 1.03$ corresponds to a distance estimate of some 675 parsec. This value leads to a distance of 233 parsec perpendicular to the Galactic plane, which is less than half the value derived earlier from multicolour photometry by Waelkens & Rufener (1983). HD 129929 is not included in the list of runaway stars composed from HIPPARCOS data (Lindblad et al. 1997). However, the new HIPPARCOS distance estimate requires a mean vertical velocity of "only" 13 km s$^{-1}$ should the star have formed in the galactic plane (where we have used the age estimate of 17 million years recently found by Aerts et al. 2003). We compare this value with our new estimate of the radial velocity of the star in Sect. 2.

Waelkens & Rufener (1983) made the first detailed study of the variability of HD 129929 by means of Geneva photometry and found the star to vary triperiodically with frequencies 6.460965, 6.979940 and 6.449041 c d$^{-1}$. The amplitudes of these three frequencies were found to range between 10 to 18 millimagnitudes. The star was hence classified as a new $\beta$ Cep star. More recently, Heynderickx (1992) also established three frequencies in a more extensive dataset that included the one used by Waelkens & Rufener (1983). However, only two of these are in common with those found by Waelkens & Rufener (1983) and moreover the values he lists are slightly different: 6.98670, 6.45610 and 6.97697 c d$^{-1}$.

With such closely spaced frequencies, HD 129929 is a very interesting massive pulsating star to try and perform seismic modelling, once the frequencies are firmly established and the modes are well identified. This situation now occurs for HD 129929 and the main results of our seismic study based upon the multicolour photometry were summarized recently in Aerts et al. (2003). They established firm evidence of the

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⋆ Based on data gathered with the Swiss 0.7m telescope equipped with the photometer P7 of the Geneva Observatory and with the FEROS spectrograph attached to the ESO 2.2 m telescope, both situated at La Silla in Chile; the reduced photometric multicolour data are provided in Table 1, which is only available in electronic form at the CDS via anonymous ftp to
`cdsarc.u-strasbg.fr (130.79.128.5)` or via
`http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/415/241`

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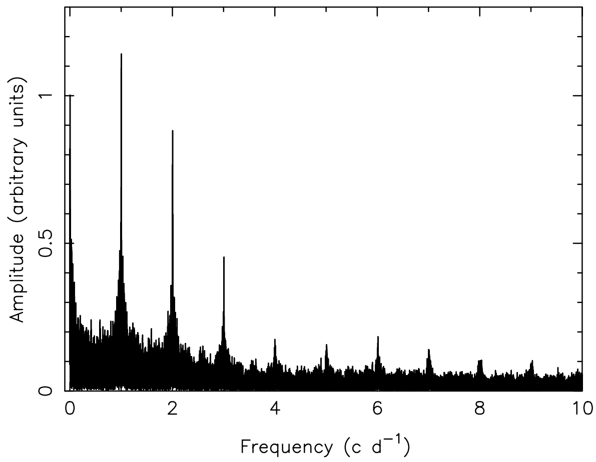


**Fig. 1.** The spectral window of our photometric data of HD 129929.

occurrence of core overshooting in the star with an overshooting parameter $\alpha_{\rm ov} = 0.1$. Moreover, they have shown the star to have non-rigid slow rotation.

The current paper is the first one in a series of three devoted to the in-depth physical interpretation of the variability of HD 129929. In this first paper we provide the full frequency content based on all available measurements of this star. We show that at least six oscillation modes at millimagnitude level are excited in HD 129929. Moreover, we compare the rotation velocity predicted by Aerts et al. (2003) from the photometric variability with a recently obtained high-resolution spectrum of the star. Our extensive seismic study will be published in a subsequent paper in this series (Dupret et al. 2004, hereafter termed Paper II) while a detailed comparison between independent evolution and oscillation codes, with HD 1299929 as a case study, constitutes a third paper in the series (Daszyńska-Daszkiewicz et al., in preparation, Paper III).

## 2. Observations

In an effort to resolve and understand the discrepant frequency determinations by Heynderickx (1992) and Waelkens & Rufener (1983), HD 129929 was kept in the long-term programme of photometric monitoring of variable B stars performed by the Institute of Astronomy of the University of Leuven with the 0.7 m Swiss photometric telescope. This telescope was operational at the La Silla observatory until 1997. It was equipped with the Geneva multicolour photometer P7.

Many members of the Institute of Astronomy gathered in total 1493 good-quality data points with a total time base of 21.2 years. The data were assembled during numerous three-week observing runs, spread throughout the 21 years. We omit the complete observing log because of the extent of the data set. However, the reduced data are given in Table 1, which is only available electronically.

The spectral window of the data is shown in Fig. 1. It shows a marked peak at 1.002744 c d$^{-1}$ and its aliases. The peak at 0.002744 = 1/364.4315 c d$^{-1}$ corresponds to the yearly observation season. We come back to these frequency peaks of the spectral window in the following section.

Only high-quality data, with a typical individual error less than 5 mmag, were retained in our analysis. An example of the lightcurve in the Geneva $V$ filter for an observing run of 11 days is shown in Fig. 2. It is evident from this graph that HD 129929 behaves multiperiodically and that large beating effects occur on a timescale of a week. Such beat periods are typical for multiperiodic $\beta$ Cep stars.

In order to confirm the important result that the star exhibits non-rigid rotation with a very low equatorial rotation velocity of some 2 km s$^{-1}$ (Aerts et al. 2003), we have taken one high-resolution (wavelength step of 0.0298 Å) échelle spectrum of HD 129929 with the FEROS spectrograph attached to the ESO 2.2 m telescope. We integrated over 2000 s to reach a signal-to-noise ratio of some 200 at 4550 Å. This spectrum leads to a radial velocity of 64±1 km s$^{-1}$, from which we derive a velocity of 22 km s$^{-1}$ perpendicular to the Galactic plane. This is largely sufficient to bring the star to its current position and suggests that it was kicked out of the Galactic plane, rather than having formed outside of the plane. If so, it must have been kicked when it was 10 million years old if we consider it to move with constant speed ever since.

We show some particular selected absorption lines of the spectrum in Fig. 3. We see that the star is indeed sharp-lined. An upper limit of the overall (thermal+pulsational+rotational) broadening can be derived from the FWHM of the different metal lines in the spectrum. This leads to a value of some 17 km s$^{-1}$. Taking into account the thermal broadening of a B3V star (some 10 km s$^{-1}$) and the fact that considerable pulsational broadening must occur, the spectrum provides independent evidence for the slow rotation of the star. We find an upper limit of ~13 km s$^{-1}$ (assuming no pulsational broadening nor any turbulence) for $v \sin i$ which is compatible with the estimate of $\Omega R$ = 2 km s$^{-1}$ provided by Aerts et al. (2003).

Finally, we mention that some low-resolution IUE spectra of HD 129929 are publicly available and have led previously to a radial-velocity estimate of 66 km s$^{-1}$ which is entirely compatible with our new result. These UV spectra also already showed that the star is sharp-lined but the resolution of these data is much lower than that of our FEROS échelle spectrum.

## 3. Frequency analysis

For seismic analyses of stars to be successful, accurate frequency determinations of as many oscillation modes as possible have to be derived. Heynderickx (1992) already pointed out, on the basis of some 800 datapoints with a time base of some 15 years, that the star has closely spaced frequencies. Meanwhile, the addition of a significant amount of data since the study by Heynderickx (1992) has allowed us to refine the frequency analysis considerably.

We have performed Phase Dispersion Minimisation (PDM, Stellingwerf 1978), Scargle (Scargle 1982) and CLEAN (Roberts et al. 1987) analyses on all data in the three different broad filters of the Geneva system. We first concentrated on the $U$ filter as the $\beta$ Cep stars are known to have the largest amplitude in the blue (e.g. Heynderickx et al. 1994). The frequencies will therefore be easiest to find in the bluest broad filter.

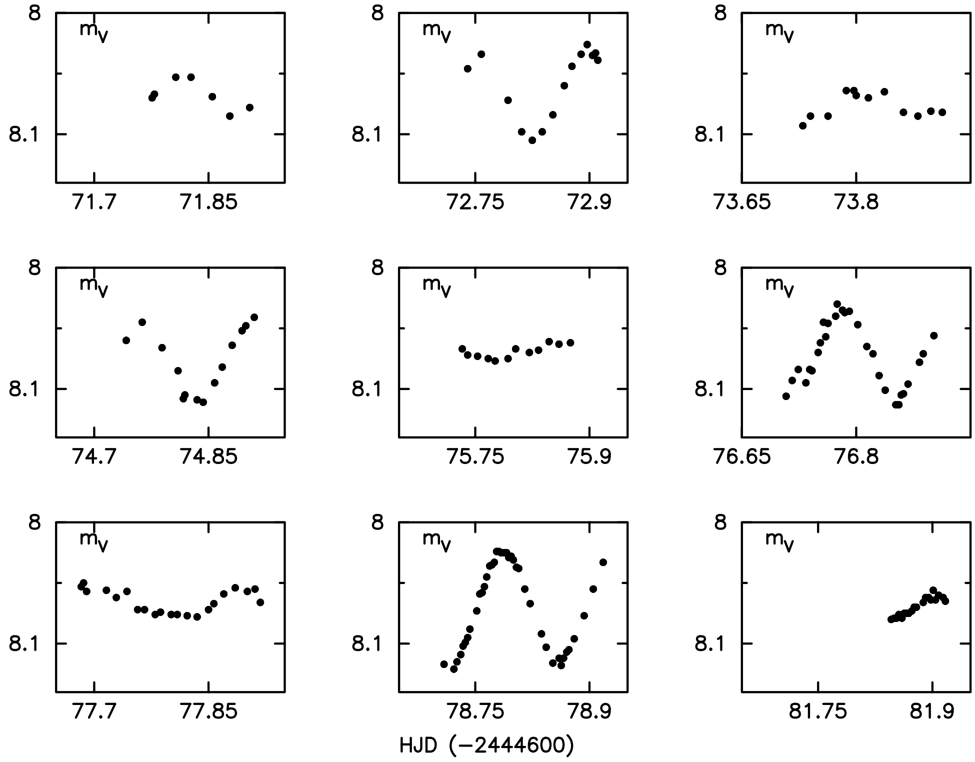


**Fig. 2.** Geneva *V* lightcurve of HD 129929 obtained during 11 consecutive nights. A beating phenomenon clearly occurs.

Subsequently, we considered the *B* and *V* filters as a compatibility check of the results.

The accuracy of the frequency estimates is determined by the total time span of the data, by the number of data points, by the average noise level of the individual measurements and by the amplitudes of the variations (see, e.g., Cuypers 1987 for a discussion of the empirically derived expressions of this error estimate). This leads to an uncertainty of some $1.3 \times 10^{-7}$ c d$^{-1}$ for the main frequency in the *U* filter and to twice this value for the frequency with the lowest amplitude. As the data are not homogeneously spread across the 21 years (e.g. the first 1200 days contain only 10 measurements), however, we adopt $10^{-6}$ c d$^{-1}$ as a more realistic estimate of the frequency accuracy. We have hence searched for frequencies with a step of $10^{-6}$ c d$^{-1}$ in the interval [0, 10] c d$^{-1}$.

The results are very similar for the PDM and Scargle analyses, on which we report first (the CLEAN analyses will be discussed later on). We restrict our illustrations to Scargle amplitude diagrams. In Fig. 4 we show the Scargle periodograms for subsequent stages of prewhitening in the Geneva *U* data. The dotted line in each panel indicates the final selected frequency. The first four frequencies indicated as dotted lines in Fig. 4 are $f_1 = 6.461699$, $f_2 = 6.978305$, $f_3 = 6.449590$ and $f_4 = 6.990431$ c d$^{-1}$. One immediately notices that $f_1 - f_3 \simeq 0.0121$ c d$^{-1}$ $\simeq f_4 - f_2$. The frequency spectra of $\beta$ Cep stars are quite sparse for slow rotators (e.g. Pamyatnykh 1999), which is the case for HD 129929 (Fig. 3). We therefore conclude that we are dealing with two frequency multiplets due to rotational splitting. The rotational period averaged over all layers of HD 129929 can hence be derived with a very high precision from the splittings. In the case of a zero Ledoux constant it amounts to some 83 days, which is remarkably slow for such a massive star. We improve this value significantly in Paper II, in which we also infer the occurrence of non-rigid rotation throughout the star from seismic modelling.

Subsequently we found a clear frequency peak at 5.588196 c d$^{-1}$ in *U* (see middle panel Fig. 4). We select, however, the alias frequency which occurs at $f_5 = 6.590940$ c d$^{-1}$ (=5.588196+1.002744 c d$^{-1}$, see dotted line in Figs. 4 and 5). The reason is that, as we will show in Paper II, all models that obey $f_1, \ldots, f_4$ do *not* lead to a mode frequency at 5.588196 c d$^{-1}$ or any other alias of $f_5$, while they *all* result in the radial fundamental mode at $f_5$. We are therefore able to pick out the correct frequency *from the models*. Moreover, a CLEAN analysis (see further), in which the daily and yearly alias pattern is taken into account explicitly, points immediately towards $f_5$ (see Fig. 6).

Subsequent prewhitening leads to a frequency in the neighbourhood of 7.96892 c d$^{-1}$. This frequency is equal to $f_2$ + 1.00274 – 0.01213 c d$^{-1}$. We therefore interpret it as the alias of the third component of the frequency multiplet around $f_2$ for the same reason as for $f_5$, i.e. because there is *no* model frequency available near 7.96892 c d$^{-1}$ for $\ell < 3$ while it perfectly fits a triplet-like structure with $f_2$ and $f_4$ due to rotation. A frequency search around $f_2 - 0.01213 = 6.96618$ c d$^{-1}$ with a step of $10^{-6}$ c d$^{-1}$ leads to the highest amplitude at $f_6 = 6.966172$ c d$^{-1}$, which is indicated as a dotted line in Figs. 4–6.

The frequencies that show up after prewhitening with $f_1, \ldots, f_6$ no longer coincide for the different analysis methods. In the Scargle periodogram of the Geneva *U* data we find $f_7 = 6.99027$ c d$^{-1}$ and subsequently $f_8 = 6.97984$ c d$^{-1}$, or

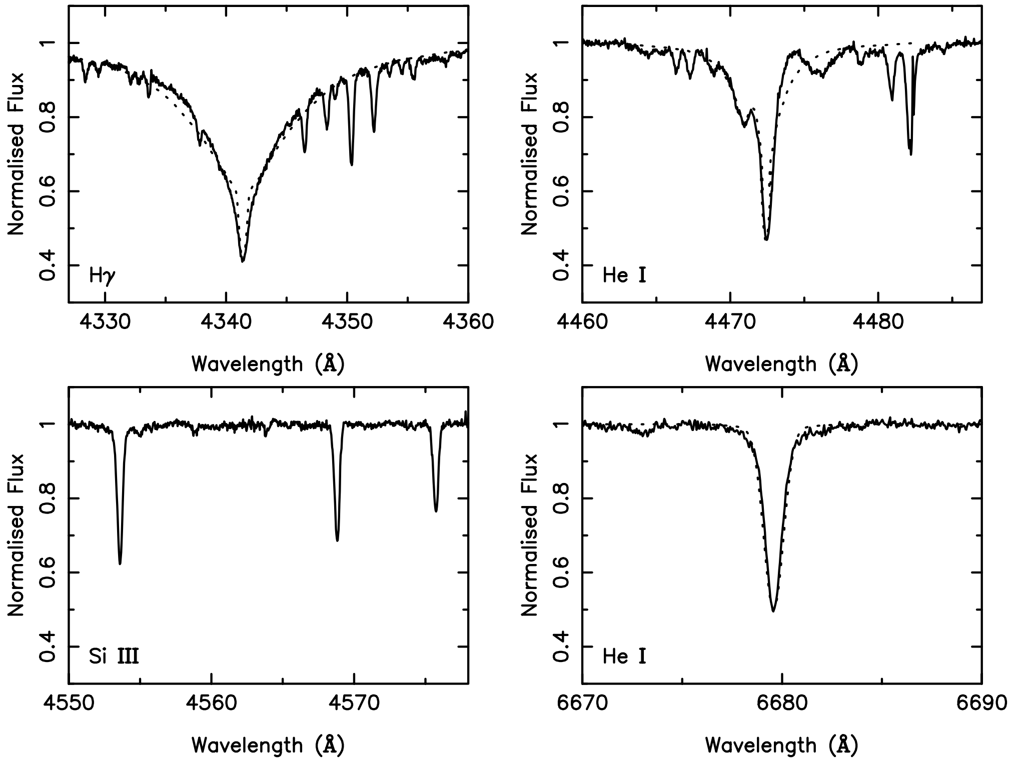


**Fig. 3.** Some selected spectral lines of HD 129929. The full lines are the observed data while the dotted lines are derived from a NLTE atmosphere model with log $T_{\rm eff}$ = 4.348, log $g$ = 3.90 and broadened according to the average FWHM of the metal lines.

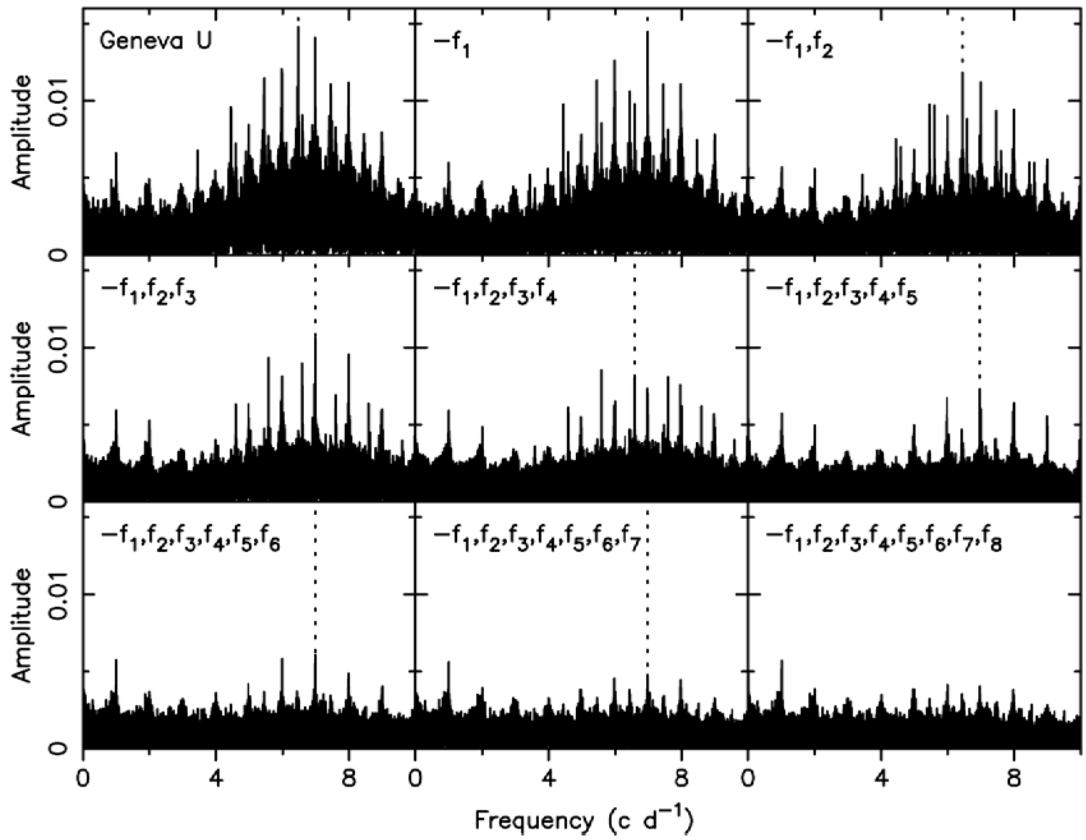


**Fig. 4.** Scargle periodograms for the Geneva $U$ data for subsequent stages of prewhitening. For the values of the frequencies and the explanation of the dotted lines we refer to the text.

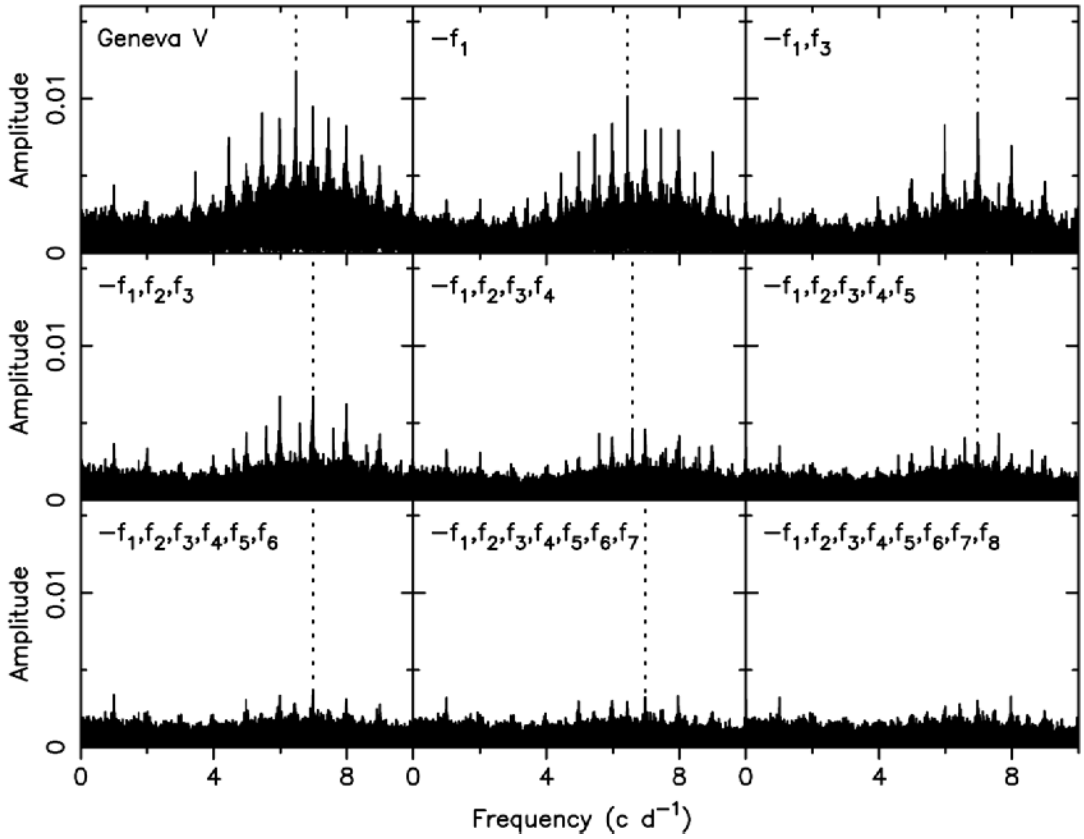


**Fig. 5.** Same as Fig. 4, but for the *V* band.

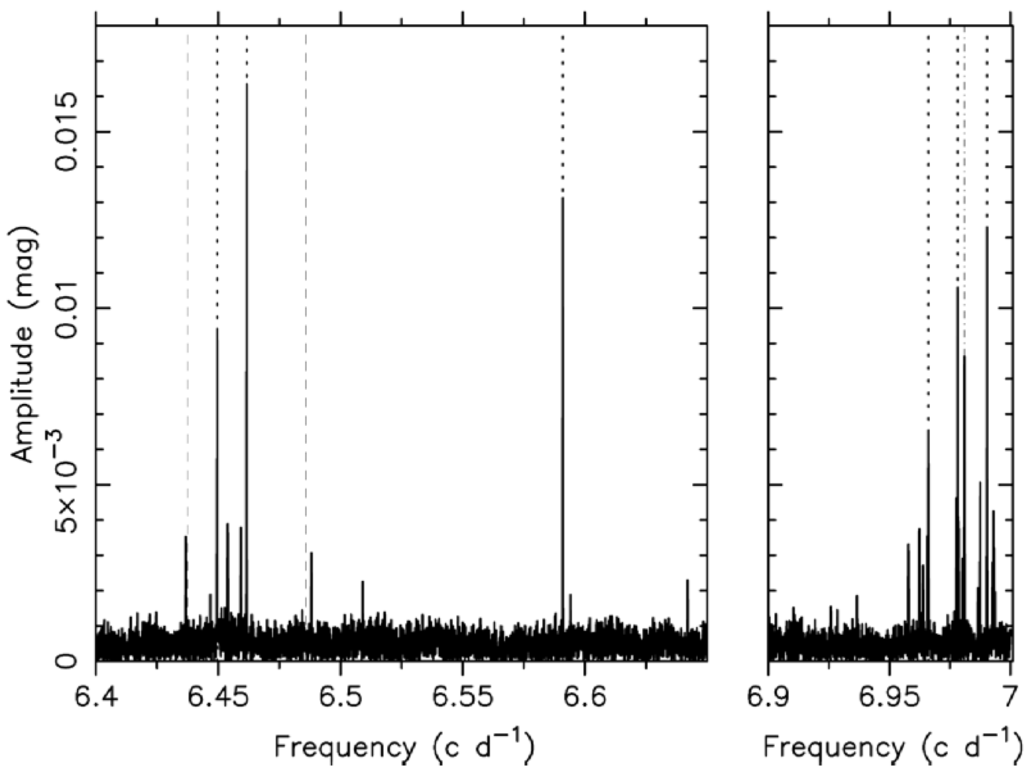


**Fig. 6.** CLEANed periodogram for the Geneva *U* data HD 129929, using a gain factor of 0.5 and 100 iterations. The dotted lines mark the positions of the six frequencies $f_1, \ldots, f_6$ resulting from the Scargle analysis. The dashed-dotted line marks the position of an alias of $f_2$. The two thin dashed lines indicate the positions $f_1 \pm 2\times(f_1 - f_3)$, i.e. the predicted additional outer quintuplet components in the case of equidistant splitting around $f_1$ for an axisymmetric $\ell = 2$ mode.

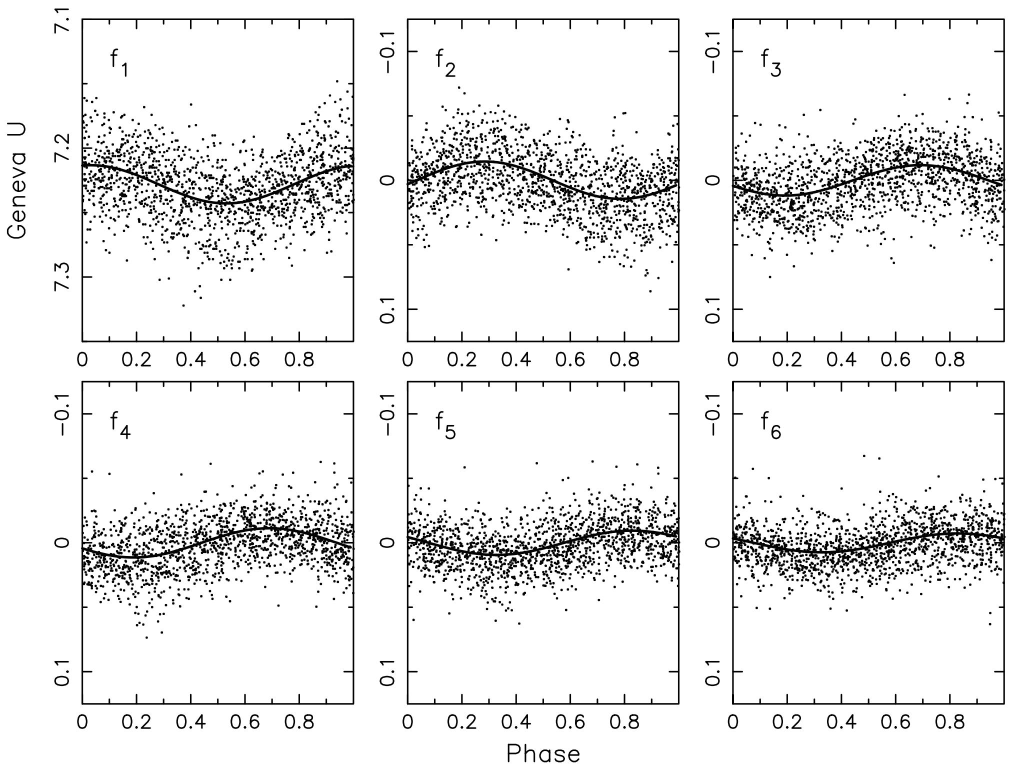


**Fig. 7.** Phase diagrams for the six accepted frequencies $f_1, \ldots, f_6$ after subsequent stages of prewhitening for the Geneva $U$ data of HD 129929. The dots are the observations and the full line is a harmonic fit.

their aliases, which all still have amplitudes above the noise level (see the dotted lines in Fig. 4). However, $f_7$ has a beat period of 6250 days with $f_4$ and $f_8$ of 671 days with $f_2$. These two beat periods correspond to respectively the time base of the intensive monitoring and a period without any observation within the dataset. We hence regard them as ambiguous for the moment and we turn to the frequency analysis of the Geneva $V$ data.

The first four frequencies $f_1, \ldots, f_4$ are also found in the Geneva $V$ data (see Fig. 5), although the order of $f_2$ and $f_3$ is switched there. Again, an alias of $f_5$ is found after prewhitening with the first four frequencies. Subsequent prewhitening does not lead to $f_6$, as can be seen in Fig. 5, as this frequency already has a much lower amplitude than in $U$ (4.8 compared to 7.6 millimagnitudes). After a forced prewhitening with $f_6$, the Geneva $V$ data reveal slightly different values for the most likely frequencies, occurring at a millimagnitude level, and we can no longer find a reason to prefer $f_7$ and $f_8$ above the other ones. The results for the Geneva $B$ data are very similar to the $V$ data and are not given explicitly for brevity.

We next turn to the CLEAN analysis. While CLEANing, one explicitly takes into account the spectral window (Roberts et al. 1987) and so this allows us to check to what extent the identified peaks suffer from the daily and yearly aliasing. In our case the spectral window is very well determined (see Fig. 1) such that the CLEANing procedure is justified. We have CLEANed the Geneva $U$, $B$ and $V$ data with a gain of 0.5 while performing 100 iterations. Again for brevity, only the results for the $U$ filter are shown. The CLEANing clearly leads to the same main five frequencies (see dotted lines in Fig. 6), of which the values differ less than $5 \times 10^{-6}$ c d$^{-1}$ from the corresponding ones of $f_1, \ldots, f_6$. Besides these, a peak occurs at an alias of $f_2$ (dashed-dotted line in Fig. 6) and at the third triplet frequency $f_6$. Besides these frequencies, several additional peaks are noted at low amplitude. We do not accept these, but two of these additional frequency peaks occur at frequencies which are very close, but not *exactly* equal to the outermost quintuplet components that one would expect for equidistant splitting around $f_1$ should this be an $\ell = 2$ axisymmetric mode (these are marked as thin dashed lines in Fig. 6). The highest of these two frequencies also occurs in the CLEANed spectrum of the $B$ and $V$ data while the situation is less clear for the leftmost peak. We would never accept these frequencies at low amplitude without the additional fact that they seem to fit into a quintuplet structure. Also, their amplitude is too low to be of any use in mode identification. We keep them in mind for the seismic modelling in Paper II, without firmly accepting them at present.

We stop the frequency search at this point, accepting the six frequencies $f_1, \ldots, f_6$ mentioned above. A summary of them is given in Table 2 and Fig. 8. The phase diagrams for the Geneva $U$ data for $f_1, \ldots, f_6$ after subsequent stages of prewhitening are shown in Fig. 7.

We conclude that we have firmly establised six frequencies in HD 129929 and that, very probably, additional low-amplitude modes are excited. It is clear that the six frequencies consist of one isolated frequency and (parts of) two multiplets. The beat period connected to $f_1$ and $f_5$ is about 8 days, and the one connected to $f_1$ and $f_2$ is some 2 days. The consequences of both these beatings are readily seen in Fig. 2.

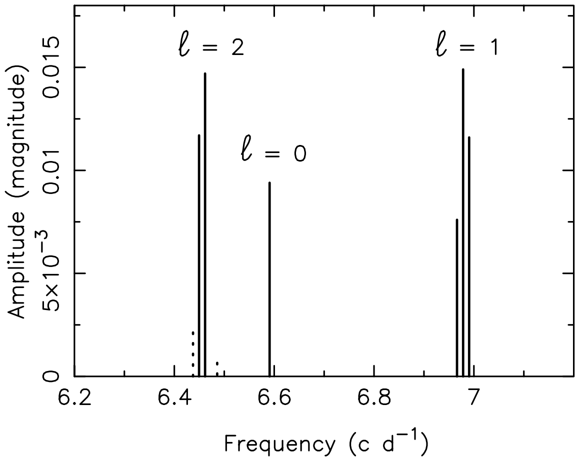


**Fig. 8.** The final amplitude spectrum of the Geneva $U$ data for HD 129929. The dotted lines are frequencies that occur only from a CLEAN analysis; they are not firmly established. The indicated mode identifications are derived in Paper II.

**Table 2.** Accepted frequencies for HD 129929.

| Oscillation Frequencies | Frequency Splittings |
|---|---|
| $f_1 = 6.461699$ c d$^{-1}$ | |
| $f_2 = 6.978305$ c d$^{-1}$ | |
| $f_3 = 6.449590$ c d$^{-1}$ | |
| $f_4 = 6.990431$ c d$^{-1}$ | $f_1 - f_3 = 0.012109$ c d$^{-1}$ |
| $f_5 = 6.590940$ c d$^{-1}$ | $f_4 - f_2 = 0.012126$ c d$^{-1}$ |
| $f_6 = 6.966172$ c d$^{-1}$ | $f_2 - f_6 = 0.012133$ c d$^{-1}$ |

The results of harmonic fits of the form

$$y_j = \sum_{i=1}^{6} A_i \sin(2\pi f_i t_j + \phi_i) + \text{constant} \quad (1)$$

with $i = 1, \ldots, 6$ and $j = 1, \ldots, 1493$ to the data are given in Table 3, in which we provide the amplitudes $A_i$ and phases $\phi_i$ for all six frequencies $f_1, \ldots, f_6$ in all seven filters, as well as the overall variance reduction of the fits. The reference epoch for the phase is the time of minimum magnitude (i.e. maximum light). We note that we have also determined such fits by including in addition to the six frequencies those indicated as dotted lines in Fig. 8. This does not increase the variance reduction significantly (less than 0.5% for four additional free parameters). Also, we have determined fits with the six frequency values derived from the CLEAN analysis. This leads to amplitude values within the indicated standard errors given in Table 3 and a slightly lower variance reduction (on average 0.5% less for all the filters). We therefore prefer to work with the frequency values listed in Table 2, which result from a Fourier analysis without any further manipulation except for the account of the yearly aliasing for $f_5$ and $f_6$ as explained above.

We have checked explicitly that there is no frequency peak at the rotation frequency of the star.

Several conclusions can already be drawn from Table 3. We have established significant amplitudes and phases for all six modes. The variance reduction of the fits range from 60–65%, clearly pointing out that additional modes are present in the data, as already mentioned above. We find no significant phase differences for any of the frequencies. The largest differences occur for $f_5$, which suggests that this mode is radial as will be confirmed from the modelling in Paper II. The drop-off of the amplitude of the mode with $f_5$ with a factor ~2 from $U$ to $G$ is indeed fully consistent with $\ell = 0$, while all other modes have a less steep decrease in amplitude from blue to red. Moreover, the decrease in amplitude is clearly less for the modes with frequencies $f_1$ and $f_3$ than for those with frequencies $f_2, f_4$ and $f_6$. This indicates that the former two modes probably have higher degrees than the latter three modes. We will quantify these statements in Paper II, where it will be shown that we are dealing with $\ell = 1, p_1$ for $f_2, f_4, f_6$, $\ell = 2, g_1$ for $f_1, f_3$ and the radial fundamental for $f_5$.

## 4. Physical parameters of the star

The physical parameters of HD 129929 were already estimated from calibrations of three photometric systems (Walraven, Geneva, Strömgren) by Shobbrook (1985) and by Heynderickx et al. (1994). The range in effective temperature and gravity listed by these authors is $\log T_{\rm eff} \in [4.35, 4.38]$; $\log g \in [3.87, 3.94]$.

Recently, Daszyńska-Daszkiewicz & Niemczura (in preparation) have determined iron abundances of $\beta$ Cep stars from IUE spectra on the basis of LTE Kurucz atmosphere models. Such UV data are the best diagnostic to derive the metallicity of $\beta$ Cep stars, as such objects have by far the largest number of spectral lines in the UV part of their spectrum. For HD 129929, they have derived $Z = 0.018 \pm 0.004$ and $\log T_{\rm eff} = 4.380 \pm 0.022$ by fixing $\log g = 3.92$ as derived from Strömgren photometry (Shobbrook 1985).

We have also performed spectroscopic modelling of hydrogen and helium lines in terms of the NLTE line-formation code FASTWIND (Santolaya-Rey et al. 1997) kindly put at our disposal by Prof. Joachim Puls. We have first considered the H$\gamma$ line to estimate the gravity of the star, taking effective temperatures in the range derived from the photometric calibrations. We particularly focus on the right wing of that line, although it is heavily blended with O II lines. The H$\gamma$ line deduced from the best fitting NLTE atmosphere model is shown as a dotted line in Fig. 3. The line width at the center of the predicted H$\gamma$ line is narrower than that of the observed spectrum (as happens more often, e.g. Herrero et al. 1992) but we base our derivation of $\log g$ on the right wing only (the left wing suffering more than the right one from uncertainties in the normalisation of the spectrum). We derive $\log g = 3.90 \pm 0.05$. We used the helium lines to fix the effective temperature and the helium content of the star. This leads to $\log T_{\rm eff} = 4.35 \pm 0.02$ and a normal helium main-sequence content using the broadening derived from the metal lines. The theoretical line profiles of the He I 4471 Å and 6678 Å lines for the best fitting NLTE model are also shown in Fig. 3. We note that all the NLTE atmosphere models we calculated have a very thin stellar wind with a negligible mass loss as is appropriate for mid-$B$ main sequence stars. The effective temperature derived from this NLTE modelling

**Table 3.** Results of harmonic fits to the Geneva lightcurves of HD 129929. A stands for the amplitude, expressed in millimag, and $\phi$ for the phase, expressed in units of $2\pi$ radians.

| | | $U$ | $B_1$ | $B$ | $B_2$ | $V_1$ | $V$ | $G$ |
|---|---|---|---|---|---|---|---|---|
| $f_1$ | A | 14.7 ± 0.6 | 12.2 ± 0.5 | 12.1 ± 0.5 | 11.7 ± 0.5 | 11.4 ± 0.5 | 11.8 ± 0.4 | 11.6 ± 0.5 |
| | $\phi$ | 0.538 ± 0.005 | 0.537 ± 0.004 | 0.536 ± 0.004 | 0.534 ± 0.005 | 0.535 ± 0.004 | 0.539 ± 0.004 | 0.536 ± 0.005 |
| $f_2$ | A | 14.9 ± 0.8 | 11.0 ± 0.6 | 11.0 ± 0.6 | 10.8 ± 0.6 | 10.3 ± 0.6 | 10.3 ± 0.5 | 10.2 ± 0.6 |
| | $\phi$ | 0.755 ± 0.007 | 0.755 ± 0.007 | 0.757 ± 0.007 | 0.754 ± 0.007 | 0.748 ± 0.007 | 0.754 ± 0.006 | 0.756 ± 0.007 |
| $f_3$ | A | 11.7 ± 0.6 | 10.0 ± 0.5 | 9.8 ± 0.4 | 9.8 ± 0.4 | 9.2 ± 0.4 | 9.1 ± 0.4 | 9.0 ± 0.4 |
| | $\phi$ | 0.178 ± 0.004 | 0.180 ± 0.003 | 0.181 ± 0.003 | 0.190 ± 0.004 | 0.185 ± 0.004 | 0.182 ± 0.003 | 0.182 ± 0.004 |
| $f_4$ | A | 11.6 ± 0.8 | 8.4 ± 0.6 | 8.5 ± 0.6 | 7.6 ± 0.6 | 7.6 ± 0.5 | 7.5 ± 0.5 | 7.7 ± 0.6 |
| | $\phi$ | 0.207 ± 0.006 | 0.205 ± 0.006 | 0.211 ± 0.006 | 0.206 ± 0.006 | 0.202 ± 0.006 | 0.204 ± 0.006 | 0.207 ± 0.007 |
| $f_5$ | A | 9.4 ± 0.8 | 6.0 ± 0.6 | 5.5 ± 0.6 | 5.3 ± 0.6 | 5.2 ± 0.6 | 4.9 ± 0.5 | 4.8 ± 0.6 |
| | $\phi$ | 0.324 ± 0.013 | 0.337 ± 0.016 | 0.340 ± 0.017 | 0.345 ± 0.018 | 0.334 ± 0.017 | 0.346 ± 0.017 | 0.349 ± 0.020 |
| $f_6$ | A | 7.6 ± 0.6 | 5.5 ± 0.5 | 5.5 ± 0.5 | 5.0 ± 0.5 | 4.8 ± 0.4 | 4.8 ± 0.5 | 4.8 ± 0.5 |
| | $\phi$ | 0.254 ± 0.013 | 0.248 ± 0.013 | 0.253 ± 0.013 | 0.246 ± 0.014 | 0.249 ± 0.014 | 0.264 ± 0.015 | 0.240 ± 0.014 |
| variance reduction | | 64.0% | 63.4% | 65.5% | 63.2% | 63.4% | 66.0% | 60.0% |

is somewhat lower than the one derived from the multicolour photometry.

We compare these observational values of the stellar parameters with their seismically derived analogues in Paper II.

## 5. Discussion

With our analysis of the light variation of HD 129929 we reconcile the seemingly discrepant results obtained earlier by Waelkens & Rufener (1983) and Heynderickx (1992) by doubling the data set and so we rule out their suggestion of dealing with changing frequencies in the star. HD 129929 is the first pulsating B star in which *more than one multiplet* has been found – but see our comments on $\nu$ Eridani below. The difference in spacing in the two multiplets will be explored in Paper II in order to test the rigidity of the rotation. A firm establishment of the current study is an estimate of the rotational frequency of the star with an extremely high accuracy from the splittings: 0.0121 $\mathrm{c\,d^{-1}}$.

Frequency multiplets have not very often been established in $\beta$ Cep stars. Two well-known cases are $\nu$ Eridani and 12 Lacertae. A thorough overview of the frequency analysis of photometric data of $\nu$ Eridani was done by Cuypers & Goossens (1981), which led to results in full agreement with Kubiak's (1980) earlier analysis of available radial-velocity data. Very recently, Handler (2003) announced a breakthrough in the interpretation of the frequency spectrum of this star on the basis of a large photometric and spectroscopic multisite campaign of several months, which led to the detection of nine independent frequencies among which are several multiplet components (also: Handler et al., in preparation). The future seismic interpretation for $\nu$ Eridani will therefore be even more constraining than the one presented in Paper II for HD 129929.

As for 12 Lacertae, six frequencies were detected from photometric measurements by Jerzykiewicz (1978). These were independently found in line-profile variations by Mathias et al. (1994). Among these six frequencies, a triplet occurs. Its interpretation is, however, unclear. Indeed, Dziembowski & Jerzykiewicz (1999) give three possible explanations: rotational splitting, splitting in the framework of an oblique pulsator model or non-linear phase locking. It is not clear at present which of these three is the correct one, although Dziembowski & Jerzykiewicz consider the magnetic interpretation as the least likely as it would require a strong dipole magnetic field, which is not observed.

One frequency quintuplet centered on the radial fundamental mode has been found by Telting et al. (1997) in the prototype $\beta$ Cephei. A magnetic field was established in $\beta$ Cephei (Donati et al. 2001) and the quintuplet is therefore naturally explained in terms of an oblique pulsator model as shown by Shibahashi & Aerts (2000). The observed splitting constant of the star, $\Omega = 0.165\ \mathrm{c\,d^{-1}}$, then leads to a rotational period of some 6 days. However, UV spectra of the star reveal EW changes with a period of some 12 days and so the interpretation of the frequency quintuplet remains controversial for $\beta$ Cephei.

Finally, Handler et al. (2003) interpreted the two dipole modes they detected for the $\beta$ Cep star IL Velorum as rotationally split components of a mode originating from $p_1$ when the star was on the zero-age main sequence. It is to be expected that the future space missions COROT and Eddington, which will observe selected stars during several months, will provide many more well-resolved frequency multiplets in massive stars.

We will use the observational results presented in this paper for in-depth seismic modelling of HD 129929, which is the topic of Paper II. The results of such modelling have been summarized already in Aerts et al. (2003).

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## References

Aerts, C., Thoul, A., Daszyńska, J., et al. 2003, Science, 300(5627), 1926
Cuypers, J. 1987, The Period Analysis of Variable Stars, Academiae Analecta, Royal Academy of Sciences, 49, 3
Cuypers, J., & Goossens, M. 1981, A&AS, 45, 487
Donati, J.-F., Wade, G. A., Babel, J., et al. 2001, MNRAS, 326, 1265
Dupret, M.-A., Thoul, A., Scuflaire, R., et al. 2004, A&A, 415, 251 (Paper II)
Dziembowski, W. A., & Jerzykiewicz, M. 1999, A&A, 341, 480
Handler, G. 2003, in Proceedings of the 2nd Eddington Workshop, ESA-SP, in press
Handler, G., Shobbrook, R. R., Vuthela, F. F., et al. 2003, MNRAS, 341, 1005
Herrero, A., Kudritzki, R. P., Vilchez, J. M., et al. 1992, A&A, 261, 209
Heynderickx, D. 1992, A&AS, 96, 207
Heynderickx, D., Waelkens, C., & Smeyers, P. 1994, A&AS, 105, 447
Hill, P. W., Kilkenny, D., & van Breda, I.G. 1974, MNRAS, 168, 451
Jerzykiewicz, M. 1978, Acta Astron., 28, 465
Kubiak, M. 1980, Acta Astron., 30, 41
Lindblad, P. O., Loden, K., Palous, J., & Lindegren, L. 1997, in Proc. of the ESA Symp., Hipparcos - Venice '97, ESA SP-402, 665
Mathias, P., Aerts, C., Gillet, D., & Waelkens, C. 1994, A&A, 289, 875
Roberts, D. H., Lehár, J., & Dreher, J. W. 1987, AJ, 238, 946
Rufener, F. 1981, A&AS, 45, 207
Santolaya-Rey, A. E., Puls, J., & Herrero, A. 1997, A&A, 323, 488
Scargle, J. D. 1982, ApJ, 263, 835
Shibahashi, H., & Aerts, C. 2000, ApJ, 531, L143
Shobbrook, R. R. 1985, MNRAS, 214, 33
Stellingwerf, R. F. 1978, ApJ, 224, 953
Telting, J. H., Aerts, C., & Mathias, P. 1997, A&A, 322, 493
Waelkens, C., & Rufener, F. 1983, A&A, 119, 279