A high-resolution spectroscopy survey of β Cephei pulsations in bright stars

Telting, J.H.; Schrijvers, C.; Ilyin, I.V.; Uytterhoeven, K.; De Ridder, J.; Aerts, C.; Henrichs, H.F.

DOI
10.1051/0004-6361:20054730

Publication date
2006

Document Version
Final published version

Published in
Astronomy & Astrophysics

Citation for published version (APA):
Telting, J. H., Schrijvers, C., Ilyin, I. V., Uytterhoeven, K., De Ridder, J., Aerts, C., & Henrichs, H. F. (2006). A high-resolution spectroscopy survey of β Cephei pulsations in bright stars. *Astronomy & Astrophysics*, *452*(3), 945-953. https://doi.org/10.1051/0004-6361:20054730

A&A 452, 945–953 (2006)
DOI: 10.1051/0004-6361:20054730

Astronomy & Astrophysics

A high-resolution spectroscopy survey of β Cephei pulsations in bright stars[⋆,⋆⋆]

J. H. Telting[1], C. Schrijvers[2,3], I. V. Ilyin[4], K. Uytterhoeven[5], J. De Ridder[5], C. Aerts[5,6], and H. F. Henrichs[2]

[1] Nordic Optical Telescope, Apartado 474, 38700 Santa Cruz de La Palma, Spain
e-mail: `jht@not.iac.es`
[2] Astronomical Institute Anton Pannekoek, University of Amsterdam, and Center for High Energy Astrophysics, Kruislaan 403, 1098 SJ Amsterdam, The Netherlands
[3] Royal Dutch Meteorological Institute (KNMI), Wilhelminalaan 10, 3732 GK De Bilt, The Netherlands
[4] Astrophysikalisches Institut Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany
[5] Instituut voor Sterrenkunde, Katholieke Universiteit Leuven, Celestijnenlaan 200B, 3001 Leuven, Belgium
[6] Radboud Universiteit, Toernooiveld 1, 6525 ED Nijmegen, The Netherlands

Received 20 December 2005 / Accepted 28 February 2006

ABSTRACT

We present a study of absorption line-profile variations in early-B type near-main-sequence stars without emission lines. We have surveyed a total of 171 bright stars using the Nordic Optical Telescope (NOTSA), William Herschel Telescope (ING) and Coudé Auxiliary Telescope (ESO). Our sample contains 75% of all O9.5−B2.5 III-V non-emission-line stars brighter than 5.5 mag. We obtained high signal-to-noise, high-resolution spectra of the SiIII λ4560 triplet – for 125 stars of our sample we obtained more than one spectrum – and examined these for pulsational-like line-profile variations and/or structure.

We conclude that about half of our sample stars show evidence for line-profile variations (LPV). We find evidence for LPV in about 65% of our sample stars brighter than $V = 5.5$. For stars with rotational broadening $V \sin i \sim 100\,\mathrm{km\,s^{-1}}$, we find evidence for LPV in about 75% of the cases. We argue that it is likely that these LPV are of pulsational origin, and that hence more than half of the solar-neighbourhood O9.5-B2.5 III−V stars is pulsating in modes that can be detected with high-resolution spectroscopy. We detected LPV in 64 stars previously unknown to be pulsators, and label these stars as new β Cep candidates. We conclude that there is no obvious difference in incidence of (pulsational) LPV for early-B type near-main-sequence stars in binaries or in OB associations, with respect to single field stars.

Key words. line: profiles – stars: early-type – stars: oscillations – stars: variables: general

1. Introduction

Throughout the 20th century β Cephei stars have been discovered through their photometric and radial-velocity variations (see e.g. the review of Sterken & Jerzykiewicz 1993, and the very recent catalog by Stankov & Handler 2005). These stars are early-B type near the main-sequence, and undergo radial and/or non-radial pulsations (see Stankov & Handler for a modern definition of β Cephei stars). In the latest decades it has become possible to detect the pulsations using high-resolution spectroscopy, as they give rise to line-profile variations (see review of Aerts & De Cat 2003, and references therein; see Walker 1991 for an early review paper). So far only several tens of solar-neighbourhood β Cephei stars are known. As line-profile variations reveal pulsations up to much higher pulsational degrees ℓ than can be achieved by photometric and radial-velocity studies, high-resolution spectroscopy offers to study the incidence of pulsations in the group of early-B type near main-sequence stars in much more detail.

In rotating stars the stellar disk is partly resolved in velocity space due to the Doppler effect: the receding part of the star is imaged onto the red side of the rotationally broadened photospheric absorption line profile, the approaching part onto the blue side of the profile. The surface temperature and surface velocity variations associated with non-radial pulsations will give rise to a pattern of moving bumps in the line profiles (Vogt & Penrod 1983; and e.g. Schrijvers et al. 1997). Even for slow rotators, i.e. stars for which the rotational line broadening is not much larger than the atmospheric line broadening, line-profile variations can be seen in the form of variations in line skewness and width (Osaki 1971; e.g. Smith 1977).

Early-type stars that show line-profile variations similar to that expected from pulsations have been classified as (a.o.) ζ Oph stars, 53 Per stars, and β Cep stars. Since the theoretical breakthrough that led to the understanding of the excitation mechanism of pulsation in these stars (Dziembowski & Pamyatnykh 1993; Gautschy & Saio 1993), it has become clear that main-sequence early-B type line-profile variables with pulsation periods of a couple to several hours can all be understood as β Cep stars (e.g. Balona & Dziembowski 1999). Recent asteroseismological case studies of β Cep stars have been presented by Aerts et al. (2003), Ausseloos et al. (2004) and Pamyatnykh et al. (2004).

[⋆] Based on observations from the Nordic Optical Telescope (NOTSA), William Herschel Telescope (ING) and Coudé Auxiliary Telescope (ESO).

[⋆⋆] Full Table 2 is only available in electronic form at `http://www.edpsciences.org`

Table 1. Brightness distribution of the sample. Percentages are with respect to numbers of BSC5+BSCS entries for the given brightness range, for the spectral type and luminosity class selection mentioned in Sect. 2.

Brightness	# Stars	Cumulative # stars
$V < 5.0$	84 (80%)	84 (80%)
$5.0 \leq V < 5.5$	25 (63%)	109 (75%)
$5.5 \leq V < 6.0$	36 (51%)	145 (67%)
$6.0 \leq V < 6.5$	11 (13%)	156 (53%)
$6.5 \leq V$	15 (13%)	171 (41%)

Stability analyses (such as presented by Dziembowski & Pamyatnykh 1993; Gautschy & Saio 1993) provide no information about the fraction of stars in the β Cep instability strip that is expected to be pulsating, and about which modes are preferably excited. Photometric and radial-velocity studies have so far led to the discovery of ~70 bright β Cep stars. Sterken & Jerzykiewicz (1993) list 32 secure and 38 suspects with $V < 6.5$: this means 66 of the 541 O9.5−B3 III-V stars in the Bright Star Catalogue (or 12%). Given the observational bias towards low-degree ℓ pulsators, it is not clear if only 12% of the stars in the instability strip actually pulsates, or if this 12% is just the tip of the iceberg of pulsators, with the intermediate/high-ℓ pulsators yet to be discovered.

In this paper we present the results of a high-resolution spectroscopy survey for line-profile variations in a total of 171 O9.5−B2.5 III-V stars. Our sample contains 75% of all non-emission line stars brighter than 5.5 mag in this spectral range (see Table 1). The sample is chosen from the Bright Star Catalogue (BSC5 and BSCS, Hoffleit & Warren 1991), and is a good representation of main-sequence early-B type stars in the solar neighbourhood. Our aim is to designate stars as β Cep suspects based on line-profile characteristics, and to determine the incidence of β Cep pulsations in early-B type near main-sequence stars.

Preliminary results of this survey were presented by Schrijvers et al. (2002) and Telting et al. (2003). Case studies of individual stars as follow up of the survey have been presented by Telting & Schrijvers (1998: ω^1 Sco), Schrijvers (1999: β Lup), Schrijvers & Telting (2002: ν Cen), Schrijvers et al. (2004: ϵ Cen), and Uytterhoeven et al. (2005b: ϵ Lup).

2. Sample and observations

Our stellar sample has been chosen from the BSC with spectral type and brightness as main discriminators (see Table 1). The spectral-type range was limited to O9.5 – B2.5, such that the SiIII triplet around 4560 Å is clearly present. Our sample avoids known Be stars, as they often have metal emission lines in the same wavelength region, contaminating the photospheric SiIII profiles. Giants and supergiants, luminosity class I and II, have not been observed as they are in general outside the β Cep strip (see e.g. Pamyatnykh 1999, for the theoretical instability strip). An exposure-time limit of 20 min was adopted to avoid smearing of the pulsational variation, which effectively limits the brightness range of the sample to brighter than approximately 6.5 mag.

We have obtained spectra of in total 171 stars; for 125 stars we obtained more than one spectrum. For a minor fraction of the spectra, only two out of the three SiIII triplet lines are available: for 7 stars the 4552 Å line is not available.

Of 171 sampled objects, 45 stars have been reported to pulsate in the literature (see Table 2). Twenty seven of these are established members of the β Cep class (Sterken & Jerzykiewicz 1993; Aerts & De Cat 2003). Four established and two suspected β Cep stars (Sterken & Jerzykiewicz; Aerts & De Cat) with $V < 5.5$ mag that meet our spectral type requirements have escaped our sample due to observing time constraints: IS Vel, β Cru, ϵ Per, η Ori, V343 Car and 2 Vul.

The observations of this survey were carried out on the Coudé Auxiliary Telescope (ESO, La Silla), the Nordic Optical Telescope (La Palma), and the William Herschel Telescope (La Palma), with the CES, SOFIN, and UES spectrographs respectively.

The spectrograph settings and slits were chosen to obtain a spectral resolution of $R = 50\,000{-}70\,000$, in some cases depending on the rotational broadening of the line profiles. Wavelength calibration was obtained from ThAr lamps. The peak *S/N* ratio in the reduced spectrum for the individual stars ranges from around 200 to well over 800.

All observations were done between 1995 and 2002, either in visitor mode by us, or in service mode by observatory staff. Data were reduced with IRAF (CES/UES) and with dedicated SOFIN software (Ilyin 2000), using standard reduction steps. Stars with more than one observation were sampled in different observing runs, or in the same run lasting up to two weeks. However, for many objects the observational timing is such that periodicities due to orbital motion ($P > 1$ d) and due to pulsations ($P < 0.5$ d) can be distinguished.

In Table 2 we list object name and HD number, spectral type and brightness as listed in the BSC. The 5th column lists the rotational broadening $V \sin i$ in km s^{-1} as determined by Abt et al. (2002: labelled $*$), Brown & Verschueren (1997: labelled $+$), and the BSC (unlabelled). Note that for stars with published values of $V \sin i$ that deviate much from a visual determination based on our SiIII spectra, our estimate is given in the last column of the table. Our $V \sin i$ estimates are based on the points where the line profile meets the continuum. Then the table lists whether orbital solutions are available (Batten et al. 1989) and whether the object is a probable member ($P \geq 90\%$) of an OB association (De Zeeuw 1999). Columns 8−10 list the number of spectra obtained with the CAT, NOT and WHT telescopes respectively. Column 13 lists the central depth of the 4552 Å profile in continuum units; Col. 14 the peak *S/N* of the reduced spectra. Columns labelled *bumps*, *degree* and *flags* list the detections of line-profile variations with additional quality flags (see Sect. 3); stars which appear as clear double-lined binaries in the SiIII profiles are marked “2” in the *flags* column. The last column lists references to previously known pulsational characteristics and classifications of the sample stars.

3. Line-profile variations: observational criteria

We have visually examined the spectra of the sample stars for line-profile variations or line-profile structure similar to those expected for radial and non-radial pulsations. We have used all 3 SiIII profiles for this examination: only if the structure is present in more than one line it is recognised to be intrinsic to the star. We classified the spectra of the individual stars in Table 2, according to the criteria described in the next subsections.

3.1. Bumps and suspected bumps

For stars with more than one observation we have looked for line-profile variations (LPV) in the shape of bumps and troughs that migrate through the SiIII profiles. Stars with clear moving

Table 2. Target list and results.

Object	HD	Spec. type	V	$V \sin i$	Binary	Member	C	N	W	Bumps	Degree	Depth	S/N	Flags	Liter./remarks
γ Peg	886	B2IV	2.83	0			2	1			lo	0.42	250		a)
ζ Cas	3360	B2IV	3.66	10				1				0.26	300		c)
53 Psc	3379	B2.5IV	5.89	55				3		s	hi	0.05	350	n	SPB e) b)
ξ Cas	3901	B2V	4.80	140	SB1O			3	1			0.02	500		
V486 Cas	3950	B1III	6.91	40^*	SB2O				1			0.15/0.07	250	2	

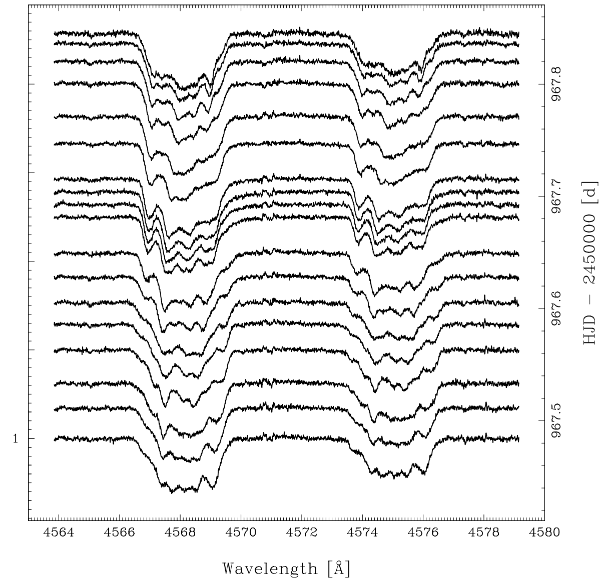

Fig. 1. One night of data of the SiIII 4567 and 4574 Å lines of β Lup (see Schrijvers 1999), with the spectra offset according to acquisition time. Each small tickmark on the left axis equals 0.01 continuum unit.

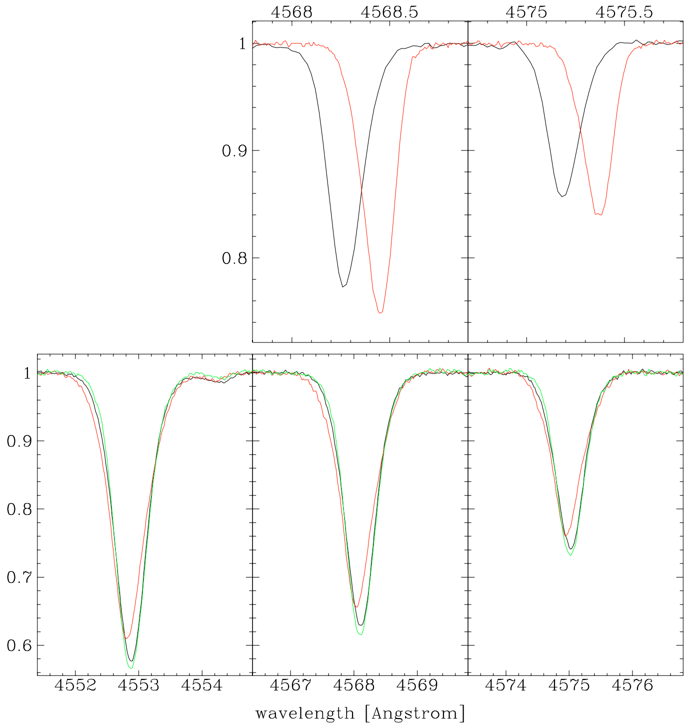

Fig. 2. Three spectra of the SiIII triplet of α Pyx (*bottom row*) and two spectra of V357 Car (*top row*). For clarity, individual spectra each have their own colour/shade of grey. Clear variations in line depth, width, and skewness are visible.

bumps are labelled "Y" in the *bumps* column in Table 2. An example of such bump-like LPV is given in Fig. 1, showing variable line profiles of the star β Lup.

Stars with bump-like patterns, but for which the *S/N* of the spectra is such that the pattern is not conclusive, are marked "s" for suspect in the *bumps* column and with "n" for noisy in the *flags* column. Stars for which the interpretation of bumps may be affected by difficult continuum rectification are marked "r" in the *flags* column.

The essential power that high-resolution spectroscopy offers is that in just one high *S/N* spectrum the presence of pulsations can be detected. Nevertheless, we mark stars that are observed only once but that show *clear* bumps with a cautionary "s" for suspect in the *bumps* column, as variability can not be proven from just one observation.

Where possible we have used the timing information of our spectra to rule out binarity as the cause of the LPV. Nevertheless, there remains the possibility that in some of the snap shots of LPV the variability is due to double-lined spectroscopic binarity. Such bump patterns can only be caused by binarity if the orbital velocities do not exceed the rotational broadening of the binary components. Profiles with bumps for which we could not rule out this binary scenario are marked with "b" in the *flags* column of Table 2. Clear cases of double-lined binaries are labeled "2" in this column.

Our criteria have been applied in a conservative fashion: some known line-profile variables (ζ Oph, 22 Ori, υ Ori) did not fulfill our criteria of clear LPV detection, partly because of lack of sufficient spectra.

3.2. Moment variations

For stars with more than one observation and that have relatively little rotational broadening, we have looked for variability in the skewness and width of the profiles. The stars with a positive detection are marked "lo" in the *degree* column of Table 2, as they are probably low-degree pulsators ($\ell \leq 2$). An example of such moment variations is given in Fig. 2, showing variable line profiles of the stars α Pyx and V357 Car.

We have not used radial-velocity variability as an indicator of pulsations, as the observations are taken with different instruments and instrument settings, and because of confusion with single-lined spectrocopic binarity.

As the moment variations were used as a criterion only if more than one spectrum of a star is available, we have not detected some known line-profile variables of our sample: e.g. α Lup and 12 Lac.

4. Results

Table 2 lists for each star the result of our LPV examination. Table 3 lists the results for all stars as a function of the brightness of the objects. For each of the listed brightness ranges up to $V \sim 6.0$ we find a consistent fraction of LPV detections.

Table 3. Brightness distribution of the sample stars with LPV detection. Percentages are with respect to the full sample of 171 stars (3rd column) and with respect to the full sample within the given brightness range (2nd column).

Clear and suspected LPV detections ("Y", "s" and/or "lo")		
Brightness	# Stars	Cumulative # stars
$V < 5.0$	53 (63%)	53 (63%)
$5.0 \leq V < 5.5$	18 (72%)	71 (65%)
$5.5 \leq V < 6.0$	19 (53%)	90 (62%)
$6.0 \leq V < 6.5$	2 (18%)	92 (59%)
$6.5 \leq V$	3 (20%)	95 (56%)
clear LPV detections ("Y" and/or "lo")		
Brightness	# Stars	Cumulative # Stars
$V < 5.0$	40 (48%)	40 (48%)
$5.0 \leq V < 5.5$	13 (52%)	53 (49%)
$5.5 \leq V < 6.0$	13 (36%)	66 (46%)
$6.0 \leq V < 6.5$	1 (9%)	67 (43%)
$6.5 \leq V$	1 (7%)	68 (40%)

For stars fainter than $V \sim 6.0$, we find a drastically lower fraction of LPV detections, which is due to *S/N* constraints.

The LPV detection criteria described above lead to the following observational constraints: 1) we find no bumps for stars with peak $S/N < 200$, 2) we find no bumps for stars with a 4552 Å line depth < 0.02 or a depth > 0.26, 3) for stars with the product (depth * *S/N*) < 12 we do not find bumps, and 4) we do not find moment variations for stars with line depth shallower than 0.04.

For stars with reported pulsation behaviour in the literature (see Table 2) we find that, according to our conservative LPV detection criteria, 31 out of 45 have LPV ("Y", "s" and/or "lo"), or 69%. Some stars known to show bumps have not passed our screening because of lack of sufficient spectra (see Sect. 3.1) and some known moment-variable stars have escaped our detection for the same reason (see Sect. 3.2). Furthermore, we have not used radial-velocity variation as a criterion for LPV, whereas for low-degree pulsations radial-velocity variations are expected.

For stars with unknown pulsation history we find that as much as 64 out of 126 have LPV ("Y", "s" and/or "lo"), or 51%. These results indicate that LPV are very common among early-B type near-main-sequence stars. In Figs. 1, 2, 4, and 5 we show the observed line-profile variations for some sample stars for which no previously known pulsational history has been reported in the literature.

Table 4 lists the sample stars grouped as a function of spectral type. For each spectral subtype the incidence of LPV detections is indicated. For the hottest stars we find only few with evidence for LPV, which can only partly be explained by brightness (i.e. *S/N*) restrictions.

Figure 3 shows the LPV-detection power of high-resolution spectroscopy for rotating stars. For low values of the rotational broadening $V \sin i$ the Doppler effect is suppressed by other line-broadening mechanisms and by limited spectral resolution, which inhibits the detection of bumps and hence of intermediate/high degree ($\ell \gtrsim 2$) pulsation modes. For very high values of $V \sin i$, i.e. very broad and shallow absorption lines, the detection of bumps is troubled by continuum rectification problems and limited *S/N*. However, for intermediate values of $V \sin i$, NRP-like bumps and troughs are relatively easy to detect: for stars with $V \sin i \sim 100$ km s^{-1} we find evidence for LPV in about 75% of the sample stars.

Table 4. LPV detections according to BSC spectral type. Each box holds the number of LPV detections and the total number of sampled stars.

	O9.5	B0	B0.5	B1	B1.5	B2	B2.5	B3
III		1/4	0/2	6/10 [b]	4/5 [c]	5/9 [d]		0/1
IV		0/1	2/5 [a]	2/4	7/8	16/24	8/9	1/1
IV-V						12/15		
V	0/3	0/4	0/3	10/15	6/11	9/24	6/13	

For stars in our sample and that are either confirmed or suspect β Cep according to Sterken & Jerzykiewicz (1993). As above, each box holds the number of LPV detections and the total number of sampled stars.

	O9.5	B0	B0.5	B1	B1.5	B2	B2.5	B3
III		0/1		5/5 [b]	1/2 [c]	1/4		
IV			1/2	2/2	3/3	8/10	1/1	
IV-V						2/2		
V		0/1		1/1	1/2	1/1		

Notes for stars with non-standard spectral types: [a] includes δ Sco; [b] includes β CMa and α Vir; [c] includes α Lup; [d] includes HD148703 and β Lup.

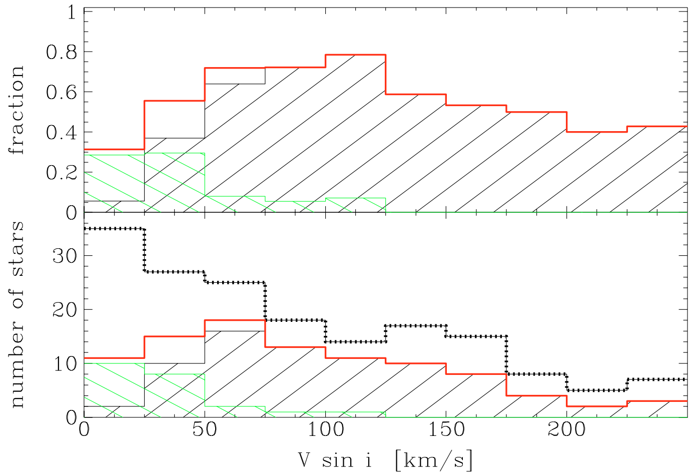

Fig. 3. Distribution according to $V \sin i$ of our sample. Note that the highest $V \sin i$ bin is open ended, and hence contains all sample stars with $V \sin i \geq 250$ km s^{-1}. *Bottom*: total sample (thick beaded line) and subsample (thick red or grey) with LPV detection. The LPV subsample is divided into stars with bumps (slanted up) and stars with moment variations (slanted down), with some stars present in both these subdivisions. *Top*: normalized with respect to total sample.

Similarly, it is clear from Fig. 3 that our moment-variation detection criterion triggers especially on stars with relatively low values of the rotational broadening.

5. Origin of the observed LPV

It is clear from the results discussed in the previous section, that many early-B type near-main-sequence stars display line-profile variability. For line profiles with rotational broadening on the order of $V \sin i \sim 100$ km s^{-1} it is the norm rather than an exception to find bump-like patterns (see Fig. 3). For stars with very high and very low values of the rotational broadening, the LPV are somewhat less commonly observed, but as argued in the previous section, this can be due to observational effects.

The presence of pulsations is a very plausible explanation for the observed LPV in our sample stars. Most bright stars that are located inside the (theoretical) β Cep strip are expected to have excited pulsation modes (e.g. Pamyatnykh 1999), although

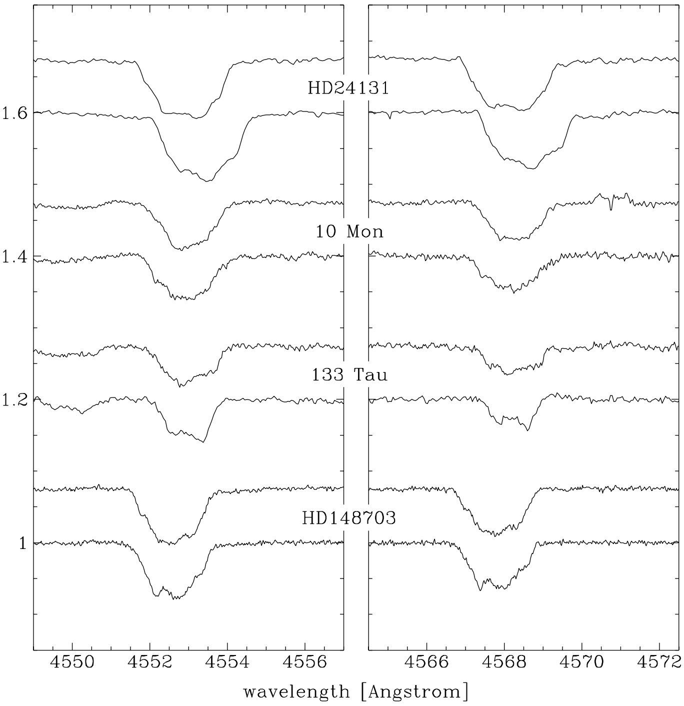

Fig. 4. LPV of stars without previously known pulsation history. For each star two spectra are shown.

it is not a priori clear with what amplitude and in which mode. Depending on the geometry (e.g. stellar inclination), some large-amplitude modes are relatively easy to detect using photometric and/or spectroscopic techniques; other large-amplitude modes may be difficult to detect. In general, low-amplitude modes will be difficult to detect, regardless of the observational technique. We can conclude from Table 2 and Fig. 3 that about half of our sample of early-B type near-main-sequence stars shows LPV, and hence that about half of the early-B type near-main-sequence stars in the solar neighbourhood is pulsating in modes that can be detected with high-resolution high-*S/N* spectroscopy. Below we argue that other proposed causes of LPV are not likely to be commonly observed in the SiIII profiles of our sample stars, and that hence this conclusion is valid.

It has been suggested for some O stars, some Be stars, but also for some β Cep stars (e.g. ϵ Per see Harmanec 1999, κ Sco see Uytterhoeven et al. 2005a) that the bump-like LPV are due to stellar-surface structure with magnetic origin. Whereas there is much indirect evidence for the presence of magnetic fields in some massive early-type stars (see e.g. the review by Henrichs et al. 2005), such as UV stellar-wind variability and anomalous X-ray emission, there are only 5 O and early-B stars with actual detections of magnetic fields (besides of course the well-known magnetic He-peculiar Bp stars that we do not consider here). Two of these 5 OB stars are established β Cep stars (V2052 Oph, see Neiner et al. 2003; β Cephei itself, see e.g. Henrichs et al. 2000), and in neither of these does the magnetic field seem to have much influence on their pulsational behaviour (see e.g. Telting et al. 1997, for the case of β Cephei), other than a possible magnetically induced shift of the pulsation periods. In both stars the LPV observed in photospheric SiIII lines are dominantly caused by pulsations, while the magnetic field gives rise to rotational modulation in some of the observables.

One expects for multiperiodic LPV with purely magnetic origin that the observed frequencies are all multiples of the rotation period, whereas for multiperiodic pulsational LPV this should in general not be the case. Hence, one can distinguish these two possible sources of variability observationally, from observing campains with abundant coverage of the periods and beat periods. The limited amount of spectra of our survey is not sufficient for this purpose.

Henrichs et al. (2005) found that the presence of certain types of pronounced UV resonance-line variations is the most reliable indirect indicator of magnetism in massive stars. They have searched the IUE archive for such variations in more than 400 OB stars. In our 171-star sample there are 108 stars that are observed with the SWP camera of the *IUE* satellite. Five of these stars are known to be magnetic, which are ζ Cas, the He strong star HD 64740 (HR 3089), β Cep, V2052 Oph and τ Sco. Whereas the latter is a pole-on star that does not allow to detect magnetically induced rotational wind modulation, the first 4 of these stars all show the characteristic magnetic-type variability near the rest wavelength, but only in the stellar wind lines, and not in photospheric lines. This must be a relatively strong effect as the *S/N* of these IUE spectra rarely exceed 20.

Apart from these known magnetic stars, there are 34 stars that have more than one IUE observation and for which we found evidence for LPV in our SiIII profile data. None of these 34 stars do clearly show the magneticly induced wind-line variability in the IUE data. Combined with the fact that for V2052 Oph and β Cephei the LPV in photospheric lines are dominated by pulsations, the fraction of magnetic candidates in our sample is sufficiently low for us to conclude that it is likely that most of the LPV we have detected in our sample stars must be due to pulsations.

Therefore, we label the 64 stars without previous pulsational record and with new LPV detection, see Sect. 4, as new β Cep candidates. This practically doubles the number of solar-neighbourhood β Cep stars and candidates. As we have too little spectra of most of the sample stars in order to derive frequencies of the pulsational LPV, it is very possible that some of the latest spectral-type stars of our sample have longer-period SPB-like pulsations rather than β Cep pulsations. Based on their spectral types, possible SPB candidates are 53 Psc, 22 Ori, α Tel and HD 172910 (HR 7029).

6. Discussion

6.1. Comparison with photometric β Cep studies

Aerts & De Cat (2003, see their Fig. 9) show that there is a strong bias towards low rotational velocity among the established β Cep stars, of which most are detected through photometric and/or radial velocity studies. In Sect. 4 and Fig. 3 we show that our survey results point to no such bias: we find β Cep candidates regardless of the rotational velocity of the stars, with a peak around $V \sin i \sim 100\ \mathrm{km\,s^{-1}}$ where our detection method is most effective (see Sect. 4). It is therefore evident that the above mentioned bias among the established β Cep stars is a result of observational selection effects.

Photometric and radial velocity studies are effective in detection of low-degree modes only, as for higher-degree modes the pulsational amplitudes are averaged out over the unresolved stellar disc. Using high-resolution spectroscopy the stellar disc is partly resolved in velocity space due to the Doppler effect, which allows to detect intermediate to high degree modes as well. We argue that the observed bias towards low rotational velocity among the established β Cep stars is caused by an observational bias towards low-degree modes. This implies that there

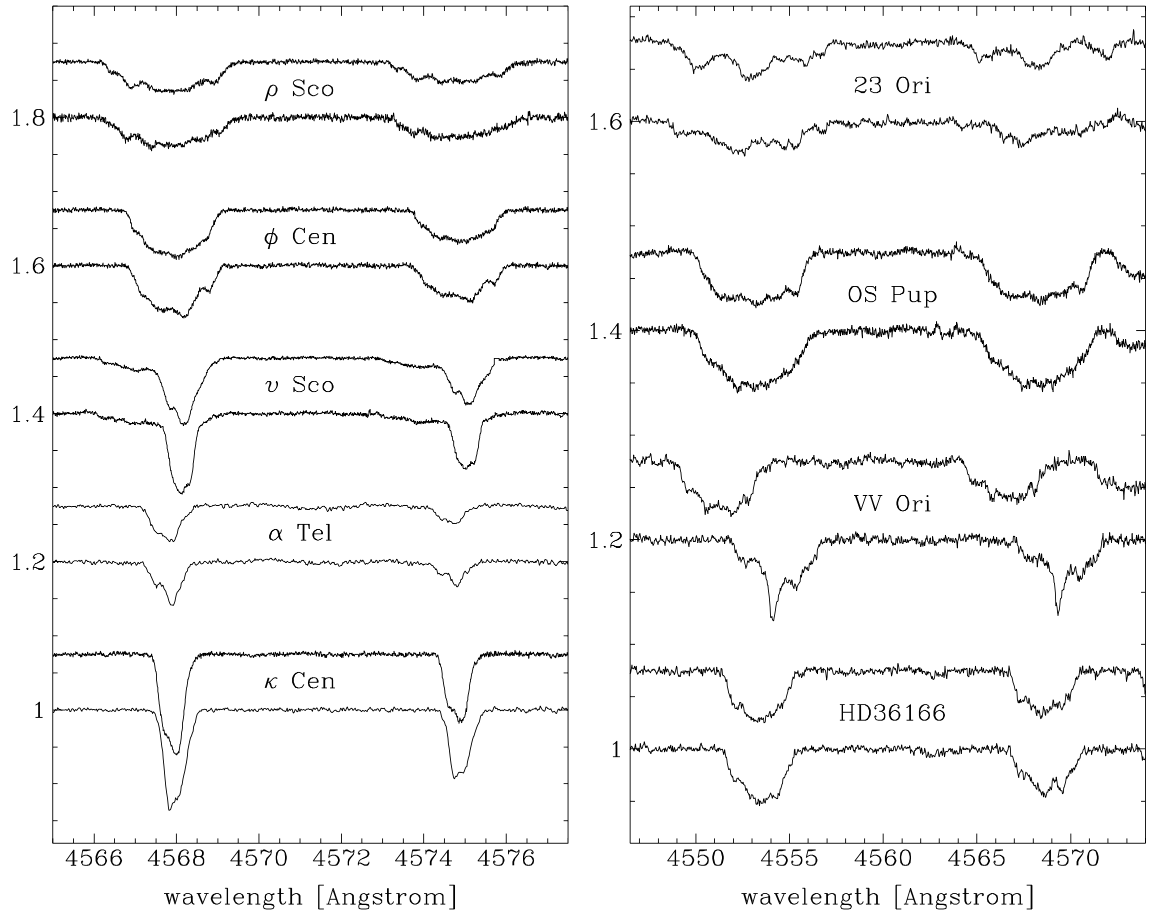

Fig. 5. LPV of stars without previously known pulsation history. For each star two spectra are shown.

is a physical relation between high rotation rate and low incidence of low-degree modes. Our survey shows that there is no such strict relation for intermediate to high-degree modes.

Stankov & Handler (2005, see their Fig. 4) show that the highest photometric amplitudes are found for the slowest rotators. There is no reason to suspect that photometric variations caused by low-degree modes are more easy to detect for slowly rotating stars than for stars with higher rotation rates. Consequently, Stankov & Handler conclude that rotation affects the pulsation-mode selection in β Cep stars in a way that rapid rotation inhibits low-degree modes to be excited. Our study shows that the incidence of intermediate to high-degree modes is not greatly affected by the stellar rotation rate.

6.1.1. Previously rejected β Cep candidates

Recently Stankov & Handler (2005) have rejected a fair amount of β Cep candidates, based on the fact that these stars show insufficient pulsational evidence in photometric and/or radial-velocity data.

For some of these previously rejected stars, our high-resolution spectra do show evidence for pulsational behaviour. These stars are HD 24640, 16 Mon, QZ Pup, HD 64740, δ Cru, α Mus, and ω^1 Cyg. Therefore we do include these objects in our list of β Cep candidates. In Fig. 6 we show example spectra for HD 24640 and δ Cru with clear LPV on a time scale of hours.

6.2. Pulsational LPV in binaries

In close binaries pulsations can be induced by tidal forcing. Such forced oscillations are thought to be a means of dissipation of orbital energy, in the process of circularization of the orbit and synchronization of the rotation of the companions. Although many β Cep stars are known to be part of a binary, there is very little evidence to suggest that the pulsations in these stars are tidally induced. In general, the observed pulsation frequencies are not a multiple of the orbital frequency, which is a requirement for tidally excited modes. See Aerts & Harmanec (2004) for a recent review of pulsations in close binaries.

Our sample of 171 stars contains 47 known binaries for which orbits have been determined (see Table 2 and Batten et al. 1989). In addition, we find 6 more stars with clear double-lined SiIII profiles. In this total of 53 binaries we find that 30 show evidence for pulsational LPV. Note that only 11 of these 53 binaries were previously known to contain a β Cep pulsator (see Table 2). Of the 27 known short-period binaries ($P < 10$ d), 16 show evidence for pulsational LPV. Of the 8 known short-period binaries with (almost) circularized orbits ($e \leq 0.01$), 4 show evidence for pulsational LPV.

Given the numbers above, we find no clear evidence that the evolutionary binary state and/or binary membership has any influence on the incidence of pulsational LPV in early-B type main sequence stars. In fact, the incidence of LPV in the above-mentioned subsamples does not seem to deviate much from that of the whole sample of 171 stars. Hence we confirm the general conclusion from previous case studies (e.g.

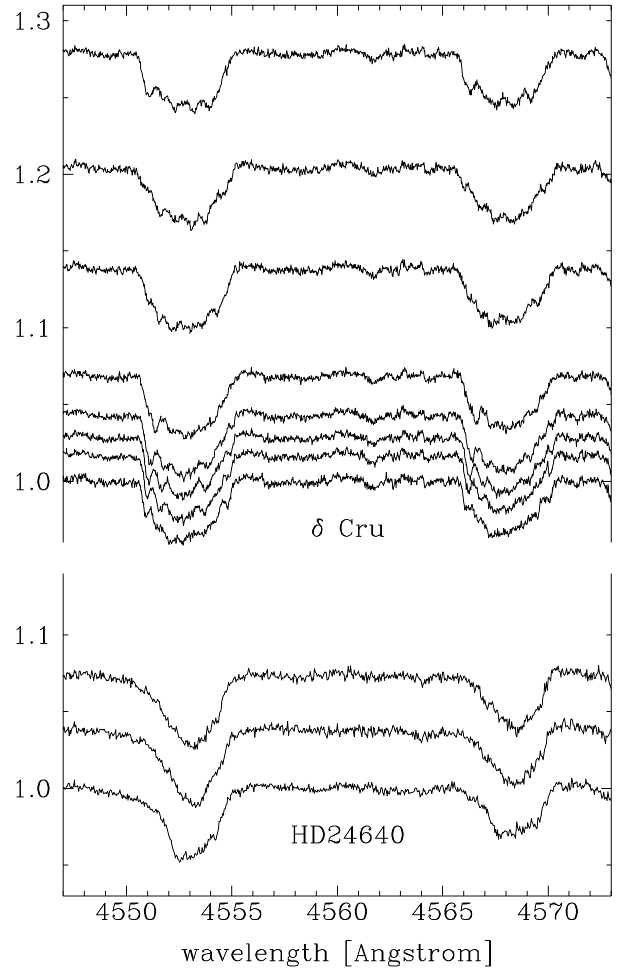

Fig. 6. Example spectra of δ Cru (*top* 8) and HD 24640 (*bottom* 3), showing profile variations on a time scale of hours. The spectra are offset according to acquisition time, with 0.1 continuum units corresponding to two hours.

Uytterhoeven et al. 2004a,b; Schrijvers & Telting 2002; Telting et al. 2001) that there is very little evidence to suggest that pulsations in binary β Cep stars are tidally excited, or that binarity affects the pulsation amplitudes.

6.3. Equivalent width and metallicity effects

It is interesting to search for effects of stellar metallicity abundance on the occurrence of pulsations in our sample stars. As the pulsations are excited through the κ mechanism in metallicity-dependent opacity bumps, one can expect a change of incidence in pulsationally induced LPV between high and low metallicity stars. Although one would not expect large differences in metallicity content in our sample of solar-neighborhood stars on a global galactic perspective, it is possible that some high or low metallicity stars are part of the sample.

In principle the equivalent width (EW) of the SiIII 4552 line can be used to estimate the SiIII abundance if the temperature and the surface gravity of the stars are well established. We have used the subsample of stars sampled by the CAT telescope, to look for changes in equivalent width as a function of spectral type and luminosity class, where the latter two are used as rough measures of temperature and gravity respectively. For each spectral type and luminosity class subgroup we find a range of EW of about a factor two. This range can be explained roughly by the presence of binary components contributing to continuum levels, and by the fact that the subdivision in luminosity class is too coarse to obtain a well-sampled EW distribution that can be used to study abundance effects.

Table 5. Clear and suspected LPV detections ("Y", "s" and/or "lo"), for stars in OB associations with membership probability $P \geq 90\%$. Ages are in Myr and are taken from De Zeeuw et al. (1999, and references therein).

	# Stars with LPV	Total # stars in OB assoc.	Assoc. age
Upper Scorpius	3	6	~5
Lower Cen Crux	4	5	~10
Upper Cen Lupus	6	7	~13
Vel OB2	3	3	$\lesssim$10
Lac OB1	0	4	

Considering all subgroups of spectral type and luminosity class, we find that there is no strict or clear relation between the EW within a subgroup and the presence of LPV. Although this may indicate that there is no clear evidence in our data for the abundance to affect the pulsational characteristics, more conclusive results may be expected from a detailed analysis involving homogeneously determined temperatures and gravities for our sample stars, with abundances derived from spectral fits. Such a detailed study is beyond the scope of this paper.

6.4. LPV in members of OB associations

As one may expect the stars within an OB association to be of similar origin, it is interesting to investigate LPV properties within such OB associations. Secondly, whereas it is in some cases difficult to determine ages and distances of individual field stars with sufficient accuracy, indirect age and distance indicators come from membership of OB associations. In Table 2 we have marked stars in OB associations that have a membership probability of $P \geq 90\%$ (De Zeeuw et al. 1999).

For four OB associations (see Table 5) we have data of very high *S/N* for more than two stars. For these four associations more than 50% of the member stars in our sample show pulsational LPV. For a fifth OB association, Lac OB1, we have spectra with $S/N \leq 400$ for four stars, with only one spectrum per star. These data did not suffice to detect LPV according to our detection criteria. Note that one of these four stars is the well-known β Cep variable 12 Lac.

In general we find no drastic difference of the incidence of LPV in field stars and stars that are member of OB associations. A possible exception is the association Lac OB1, for which our observations are not abundant and not of the best quality.

6.5. Comparison with other types of massive stars

6.5.1. O stars

Fullerton et al. (1996) surveyed 30 stars with spectral type between O4 and O9.5, and found that 3 out of their 9 luminosity class V dwarfs show LPV. They found no LPV in dwarfs earlier than O7, and argue that the incidence of LPV could be relatively high for O9 dwarfs. From velocity considerations they find that the LPV found in their O-dwarf sample is largely of photospheric origin. They argue that, unlike for the O-giant population, for the late-type O dwarfs the origin of LPV likely lies in the pulsational κ mechanism, as is the case for the early B-type main-sequence stars that neighbour this group of O stars in the HRD. Balona & Dziembowski (1999) show that the pulsations in late-type O dwarfs (luminosity class V) can indeed be explained by β Cep like pulsations, although p-mode instabilities only arise for pulsational degrees lower than $\ell = 10$.

Nevertheless, we find for the O9.5–B0.5 stars in our sample that the incidence of LPV is quite low (3 out of 22), especially for luminosity class V stars (see Table 4). This can only partly be explained by the relative faintness of these objects: for 11 out of these 22 stars we have spectra with *S/N* exceeding 400. For the known or suspected pulsators 1 Cam, υ Ori, ξ^1 CMa, and ζ Oph our data is insufficient to detect LPV (see Table 2). We conclude that for the bluest stars in our sample the incidence of detectable pulsations is lower than for the redder stars, which is consistent with the distribution of β Cep stars shown by Stankov & Handler (2005).

6.5.2. Be stars

Practically all Be stars show LPV in emission lines that are of circumstellar origin. Additionally, many early-type Be stars show LPV in photospheric lines (e.g. Rivinius et al. 2003), which are qualitatively similar to the LPV that we are discussing here. A likely origin of these LPV in (quasi-)photospheric lines, is, as for our non-emission line sample, non-radial pulsation, although one cannot exclude surface magnetic fields to contribute to such profile variations as a result of surface spots or co-rotating structures (e.g. Balona & James 2002).

According to Rivinius et al. (2003) the low-order LPV seen in the majority of early-type Be stars can be successfully modelled with retrograde $\ell = m = 2$ modes. Nevertheless some early-type Be stars also show higher-order bump-like LPV similar to many of the LPV seen in our sample of early-type B stars; for instance γ Cas (Yang et al. 1988), η Cen (Janot-Pacheco et al. 1999), δ Sco (Smith 1986), ζ Oph (e.g. Kambe et al. 1997), and π Aqr (Rivinius et al. 2003). For early-type Be and B stars the apparent periods of these higher-order bump-like LPV are comparable, although the intrinsic co-rotating frequencies may still be different, due to the differences in rotation frequency between Be and B stars. If the photospheric LPV in early-type B and Be stars are due to pulsations, then it is still not clear if the excitation mechanism and/or restoring forces are the same, even though they populate the same region in the HRD. Note that recent theoretical results show that it is plausible that near-critically rotating early-type Be stars can pulsate both in p-modes and g-modes (Townsend 2005).

Our survey shows that LPV are very abundant in non-emission line main-sequence early-B type stars. It is obvious that the presence of photospheric variations alone is not sufficient to make a Be star, or else many of our sample stars should be Be stars. If the build-up of circumstellar matter in Be stars has its origin in photospheric variations triggered by for example pulsations or magnetic fields, then these photospheric variations should be either different from the variations in our sample stars (e.g. g-modes versus p-modes, or magnetic versus pulsational origin) or else the fundamental differences between the groups, such as the rotation rate and/or evolutionary history, determine that similar types of photospheric variations can lead to the Be-phenomenon in one group, and lead to little to no circumstellar activity in the other.

7. Conclusions

Is is clear from our study that in high-quality high-resolution spectra of early-B type near-main-sequence stars without emission lines it is the norm rather than an exception to find line-profile variations (LPV). From Table 2 and Fig. 3 we conclude that about half of our sample of such stars shows LPV. We find evidence for LPV in about 65% of our sample stars brighter than $V = 5.5$. For stars with rotational broadening $V \sin i \sim 100\,\mathrm{km\,s^{-1}}$, we find evidence for LPV in about 75% of the cases.

We have argued that the likely origin of most of these LPV is pulsation induced by the κ mechanism, as for established β Cep stars. We detected LPV in 64 bright stars previously unknown to be pulsators, and label these stars as new β Cep candidates. This practically doubles the number of bright solar-neighbourhood β Cep stars/candidates.

As our sample of 171 bright stars is a good representation of all solar neighbourhood early B-type near-main-sequence stars, we conclude that well more than half of the solar-neighbourhood O9.5-B2.5 V−III stars is pulsating in modes that can be detected with high-resolution high-*S/N* spectroscopy using medium-sized telescopes. This implies that *at least* half the late O to early B solar-neighbourhood stars that are located in the β Cephei strip are actually pulsating in radial and/or non-radial modes. The LPV that we observed are consistent with pulsational amplitudes on the order of $\sim 10\,\mathrm{km\,s^{-1}}$; stars with much lower-amplitude pulsations will have escaped detection (due to *S/N* constraints), as will stars with high-degree pulsation modes ($\ell \gtrsim 20$).

Our sample contains 53 binaries, and we detect LPV in 30 of them. We confirm the general conclusion from previous case studies that there is very little evidence to suggest that the few-hour period pulsations in binary β Cep stars are tidally excited.

The incidence of LPV in field stars and stars that are member of OB associations is similar. A possible exception is the association Lac OB1, for which our observations are not optimal, however.

Stankov & Handler (2005) show that from photometric studies, which are sensitive to low-degree modes only, it follows that the highest photometric pulsation amplitudes are found for the slowest rotators. Following Stankov & Handler, we argue that stellar rotation affects the pulsation-mode selection in β Cep stars to inhibit low-degree modes to be excited or to reach large amplitudes. Our spectroscopic survey, which is sensitive to low and intermediate-degree modes, does not show such a bias towards stars with low rotation rates in the case of intermediate-degree modes.

Acknowledgements. Based on observations obtained with the Nordic Optical Telescope, which is operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. Based on observations obtained with the William Herschel Telescope, which is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias Based on observations collected at the European Southern Observatory, Chile. J.H.T. thanks Dr. P. Groot, as he was Co-I on the first observing run of this survey. This CAT run was originally aimed at a research topic different from that described in this paper. J.D.R. is a fellow of the Fund for Scientific Research of Flanders.

References

Abt, H. A., Levato, H., & Grosso, M. 2002, ApJ, 573, 359
Aerts, C., & De Cat, P. 2003, Space Sci. Rev., 105, 453
Aerts, C., & Harmanec, P. 2004, ASP Conf. Ser., 318, 325
Aerts, C., Thoul, A., Daszyt'nska, J., et al. 2003, Science, 300, 1926
Ausseloos, M., Aerts, C., Uytterhoeven, K., et al. 2002, A&A, 384, 209

Ausseloos, M., Scuflaire, R., Thoul, A., & Aerts, C. 2004, MNRAS, 355, 352

Balona, L. A., & Dziembowski, W. A. 1999, MNRAS, 309, 221

Balona, L. A., & James, D. J. 2002, MNRAS, 332, 714

Batten, A. H., Fletcher, J. M., & MacCarthy, D. G. 1989, Publ. of the Dominion Astrophysical Obs., 17, 1

Brown, A. G. A., & Verschueren, W. 1997, A&A, 319, 811

De Zeeuw, P. T, Hoogerwerf, R., de Bruijne, J. H. J., Brown, A. G. A., & Blaauw, A. 1999, AJ, 117, 354

Donati, J.-F., Wade, G. A., Babel, J., et al. 2001, MNRAS, 326, 1265

Dziembowski, W. A., & Pamyatnykh, A. A. 1993, MNRAS, 262, 204

Fullerton, A. W., Gies, D. R., & Bolton, C. T. 1996, ApJS, 103, 475

Gautschy, A., & Saio, H. 1993, MNRAS, 262, 213

Harmanec, P. 1999, A&A, 341, 867

Harmanec, P., Hadrava, P., Yang, S., et al. 1997, A&A, 319, 867

Harmanec, P., Uytterhoeven, K., & Aerts, C. 2004, A&A, 422, 1013

Henrichs, H. F., De Jong, J. A., Donati, J.-F., et al. 2000, in The Be phenomenon in Early-type stars, ed. M. A. Smith, H. F. Henrichs, & J. Fabregat, IAU Coll., 175, 324

Henrichs, H. F., Schnerr, R. S., & Ten Kulve, E. 2005, in The nature and evolution of disks around hot stars, ed. R. Ignace, & K. Gayley, ASP Conf. Ser., 337, 114

Heynderickx, D. 1992, A&AS, 96, 207

Hoffleit, D., & Warren Jr., W. H. 1991, Bright Star Catalogue, Astronomical Data Center, NSSDC/ADC

Holmgren, D., Hadrava, P., Harmanec, P., Koubsky, P., & Kubat, J. 1997, A&A, 322, 565

Ilyin, I. V. 2000, Ph.D. Thesis, Univ. of Oulu, Finland

Janot-Pacheco, E., Jankov, S., Leister, N. V., Hubert, A. M., & Floquet, M. 1999, A&AS, 137, 407

Kambe, E., Hirata, R., Ando, H., et al. 1997, ApJ, 481, 406

Le Contel, J.-M., Mathias, P., Chapellier, E., & Valtier, J.-C. 2001, A&A, 380, 277

Neiner, C., Henrichs, H. F., Floquet, M., et al. 2003, A&A, 411, 565

Osaki, Y. 1971, PASJ, 23, 485

Pamyatnykh, A. A. 1999, Acta Astron., 49, 119

Pamyatnykh, A. A., Handler, G., & Dziembowski, W. A. 2004, MNRAS, 350, 1022

Rivinius, Th., Baade, D., & Stefl, S. 2003, A&A, 411, 229

Schrijvers, C. 1999, Ph.D. Thesis, Univ. of Amsterdam

Schrijvers, C., & Telting, J. H. 2002, A&A, 394, 603

Schrijvers, C., Telting, J. H., Aerts, C., Ruymaekers, E., & Henrichs, H. F. 1997, A&AS, 121, 343

Schrijvers, C., Telting, J. H., & De Ridder, J. 2002, in Radial and nonradial pulsations as probes of stellar physics, ed. C. Aerts, T. R. Bedding, & J. Christensen-Dalsgaard, Proc. IAU Coll., 185, ASP Conf. Ser., 259, 204

Schrijvers, C., Telting, J. H., & Aerts, C. 2004, A&A, 416, 1069

Smith, M. A. 1977, ApJ, 215, 574

Smith, M. A. 1986, ApJ, 304, 728

Stankov, A., & Handler, G. 2005, ApJS, 158, 193

Sterken, C., & Jerzykiewicz, M. 1993, Space Sci. Rev., 62, 95

Telting, J. H., Aerts, C., & Mathias, P. 1997, A&A, 322, 493

Telting, J. H., & Schrijvers, C. 1998, A&A, 339, 150

Telting, J. H., Abbott, J. B., & Schrijvers, C. 2001, A&A, 377, 104

Telting, J., Uytterhoeven, K., & Ilyin, I. 2003, in Asteroseismology Across the HR Diagram, ed. M. J. Thompson, M. S. Cunha, & M. J. P. F. G. Monteiro, 401, (CDROM)

Townsend, R. H. D. 2005, MNRAS, 360, 465

Unno, W., Osaki, Y., Ando, H., Saio, H., & Shibahasi, H. 1989, Non-radial oscillations of stars, 2nd edition (University of Tokyo Press)

Uytterhoeven, K., Willems, B., Lefever, K., et al. 2004a, A&A 427, 581

Uytterhoeven, K., Telting, J. H., Aerts, C., & Willems, B. 2004b, A&A, 427, 593

Uytterhoeven, K., Briquet, M., Aerts, C., et al. 2005a, A&A, 432, 955

Uytterhoeven, K., Harmanec, P., Telting, J. H., & Aerts, C. 2005b, A&A, 440, 249

Vogt, S. S., & Penrod, G. D. 1983, ApJ, 275, 661

Walker, G. A. H. 1991, in Rapid Variability of OB-stars: Nature and Diagnostic Value, ed. D. Baade, ESO, 27

Yang, S., Ninkov, Z., & Walker, G. A. H. 1988, PASP, 100, 233

Online Material

Table 2. Target list and results.

Object	HD	Spec. type	V	$V \sin i$	Binary	Member	C	N	W	Bumps	Degree	Depth	S/N	Flags	Liter./remarks
γ Peg	886	B2IV	2.83	0			2	1			lo	0.42	250		a)
ζ Cas	3360	B2IV	3.66	10				1				0.26	300		c)
53 Psc	3379	B2.5IV	5.89	55				3		s	hi	0.05	350	n	SPB e) b)
ξ Cas	3901	B2V	4.80	140	SB1O			3	1			0.02	500		
V486 Cas	3950	B1III	6.91	40*	SB2O				1			0.15/0.07	250	2	
	6675	B0.5III	6.90	68*					1			0.23	200		
1 V436 Per	11241	B1.5V	5.52	198*		Cas-Tau		1	3			0.03	400	2	SB2O NRP? see f)
	12509	B1III	7.09	80*					1			0.34	200		
δ Cet	16582	B2IV	4.07	5			5	1			lo	0.38	100		a)
53 Ari	19374	B1.5V	6.11	5			2					0.25	400		b)
HR 1074	21856	B1V	5.90	105				6	3	Y	hi	0.07	500		
40 Per	22951	B0.5V	4.97	10		Per OB2		2	1			0.22/0.04	400	2	$V \sin i \sim 30/{\sim}80$
o Per	23180	B1III	3.83	90	SB2O			11	2			0.15/0.02	500	2	
HR 1163	23625	B2.5V	6.57	20	SB2O				1	s	hi	0.07	250	2?,b,n	$V \sin i \sim 70$
	23675	B0.5III	6.73	54*					1			0.22	250		
HR 1191	24131	B1V	5.77	95				2	2	Y	hi	0.09	550		
HR 1215	24640	B1.5V	5.49	150				5	2	Y	hi	0.05	600		b)
SZ Cam	25639	B0V	7.00	160*	SB2O				1			0.08	350		
1 Cam	28446	B0III	5.77	310					1			0.03	350		b)
ν Eri	29248	B2III	3.93	20			3		2		lo	0.25	550		a)
	30677	B1/IIIn:	6.86	162*					1	s	hi	0.10	450		$V \sin i \sim 60$
π^4 Ori	30836	B2III+B2IV	3.69	35	SB1O			5	1		lo	0.25	550		
103 Tau	32990	B2V	5.50	55	SB1O			5	3	Y	hi	0.08	450		
λ Lep	34816	B0.5IV	4.29	25					1			0.23	450		
HR 1763	34989	B1V	5.80	40				2	1			0.12	500		
22 Ori	35039	B2IV-V	4.73	11$^+$	SB1O?		1	1	1			0.38	400		c)
23 Ori	35149	B1V	5.00	220			1	5	1	Y	hi	0.03	600		
8 Lep	35337	B2IV	5.25	15			1					0.29	350		
γ Ori	35468	B2III	1.64	55			1	1	1			0.15	600		
HR 1803	35588	B2.5V	6.16	170	SB1O				1			0.03	450		
114 Tau	35708	B2.5IV	4.88	10					2	s	hi	0.19	300	b	$V \sin i \sim 30$
ψ^2 Ori	35715	B2IV	4.59	110	SB2O		1		3	Y	hi	0.06	400	2	b) g)
	35762	B2V	6.74	155*					1			0.03	450		
HR 1820	35912	B2V	6.41	5					1			0.20	350		
HR 1833	36166	B2V	5.78	125				4	2	Y	hi	0.05	600		
HR 1840	36285	B2IV-V	6.33	15			1					0.31	300		
33 Ori	36351	B1IV+B1.5V	5.46	20					2			0.19	300		
υ Ori	36512	B0V	4.62	10				1	2			0.22	400		c) b)
VV Ori	36695	B1V	5.34	120	SB2O		1	5	1	Y	hi	0.05	700		
HR 1871	36741	B2V	6.59	175					1			0.03	550		
121 Tau	36819	B2.5IV	5.38	105				6	2	s	hi	0.03	500	n	
ϕ^1 Ori	36822	B0III	4.41	20	SB1O?			1	1			0.31	550		
λ Ori B	36862	B0.5V	5.61	35					2			0.06	450		
HR 1886	36959	B1V	5.67	5					1			0.40	450		
HR 1887	36960	B0.5V	4.78	20				3				0.26	500		
42 Ori	37018	B1V	4.59	20			1	1	1			0.22/0.03	400	2	$V \sin i \sim 20/{\sim}120$
θ^2 Ori	37041	O9.5Vp	5.08	170*	SB1O		1		1			0.02	450		
HR 1911	37209	B1V	5.72	35				1	2			0.14	350		
σ Ori	37468	O9.5V	3.81	94*				1	1			0.08	550		$V \sin i \sim 45$
HR 1933	37481	B1.5IV	5.96	90					1	s	hi	0.08	450	n	
HR 1952	37756	B2IV-V	4.95	75	SB2O			3	1	Y	hi	0.08	500	b	
133 Tau	38622	B2IV-V	5.29	70*				6	3	Y	hi	0.06	600		
55 Ori	39291	B2IV-V	5.35	150				7	1	s	hi	0.04	500	n	
57 Ori	39698	B2V	5.92	115	SB2O			7	2	s	hi/lo	0.04	400	n	d)
HR 2058	39777	B1.5V	6.57	20			1					0.19	250		
γ Col	40494	B2.5IV	4.36	96*			1	1		s	hi	0.05	450		
HR 2205	42690	B2V	5.05	0					2		lo	0.35	450	b	
HR 2266	43955	B2V	5.52	40					1			0.05	300		
7 Mon	44112	B2.5V	5.27	95			2	6	1	Y	hi	0.05	550	b	
ζ CMa	44402	B2.5V	3.02	25	SB1O		3	6		s	hi/lo	0.08	700	2?,b	d)
β CMa	44743	B1II-III	1.98	17			5				lo	0.40	650		a)
10 Mon	45546	B2V	5.06	70				4	1	Y	hi	0.06	700		

Table 2. continued.

Object	HD	Spec. type	V	$V \sin i$	Binary	Member	C	N	W	Bumps	Degree	Depth	S/N	Flags	Liter./remarks
ξ^1 CMa	46328	B0.5IV	4.33	0			1		1			0.50	400		a)
HR 2479	48434	B0III	5.90	50					2			0.16	400		
16 Mon	48977	B2.5V	5.93	20				4		Y	hi	0.11	450		$V \sin i \sim 35$
EY CMa	50707	B1IV	4.83	49*			2			Y	hi/lo	0.26	450		a)
HR 2640	52670	B2V	5.63	17		Coll 121			1			0.10	350		
19 Mon	52918	B1V	4.99	270					1	s	hi	0.05	450	b,n	a)
FN CMa	53974	B0.5IV	5.39	130					1	s	hi	0.08	450	b	b)
PT Pup	61068	B2III	5.74	10			2					0.36	300		a)
HR 3004	62747	B1.5III	5.62	95					2	Y	hi	0.11	450		
HR 3023	63271	B2IV-V	5.90	30					1	s	hi	0.12	350	n	$V \sin i \sim 60$
HR 3037	63578	B1.5IV	5.23	154*			1					0.07	300	2	$V \sin i \sim 80$
QS Pup	63949	B1.5IV	5.84				2			s	hi	0.14	350	n	a) $V \sin i \sim 50$
QU Pup	64365	B2IV	6.04			Vel OB2	2				lo	0.22	300		a) $V \sin i \sim 30$
QZ Pup	64503	B2.5V	4.49	187*	SB1O		7			s	hi	0.02	600	n	d)
V372 Car	64722	B1.5IV	5.70	147*		Vel OB2	25			Y	hi	0.07	450		a)
HR 3089	64740	B1.5Vp	4.63	160*			1			s	hi	0.04	450	n	
γ^1 Vel	68243	B1IV	4.27	119*	SB1O		2					0.07	500		
OS Pup	69081	B1.5IV	5.08	213*			2			Y	hi	0.05	500		
HR 3293	70839	B1.5III	5.97	178*			13			Y	hi	0.08	200		
HR 3294	70930	B1V	4.82	169*		Vel OB2	46			Y	hi	0.08	250		
HR 3358	72108	B2IV	5.33	66*			36			Y	hi	0.11	200		SB1O
HR 3359	72127	B2IV	4.99	163*			1			s	hi	0.06	350		
HR 3453	74273	B1.5V	5.90	181*			4			s	hi	0.07	350	n,b,2	$V \sin i \sim 70/{\sim}200$
HX Vel	74455	B1.5Vn	5.51	285*			1			s	hi	0.04	300	r,b,n	
α Pyx	74575	B1.5III	3.68	19*			3				lo	0.40	550		
HR 3476	74753	B0IIIn	5.16	288*			1			s	hi	0.04	300	r,b,n	
V357 Car	79351	B2IV-V	3.44	30*	SB1O		9				lo	0.28	600	b	
HR 3663	79447	B3III	3.97	21*			10					0.20	500		
HR 3819	83058	B1.5IV	5.01	207*			19			Y	hi	0.09/0.02	500	2	$V \sin i \sim 70/{\sim}40$
HR 3952	87015	B2.5IV	5.66	215				2				0.03	600	r	
θ Car	93030	B0Vp	2.76	151*	SB1O?		2					0.08	700	r	
HR4590	104337	B1.5V	5.26	95	SB2O			9		s	hi	0.07/0.02	500	2,r,n	$V \sin i \sim 120/{\sim}40$
θ^2 Cru	104841	B2IV	4.72	25$^+$	SB1O?		1					0.11	400		b)
δ Cru	106490	B2IV	2.80	135$^+$		LCC	18			Y	hi	0.04	750		b)
ζ Cru	106983	B2.5V	4.04	65$^+$			1					0.04	500		
σ Cen	108483	B2V	3.91	169$^+$		LCC	4			s	hi	0.03	800	r,n	
α Mus	109668	B2IV-V	2.69	114$^+$		LCC	14			Y	hi	0.05	800		b)
μ^1 Cru	112092	B2IV-V	4.03	34$^+$		LCC	1			s	hi	0.13	550	b,n	
ξ^2 Cen	113791	B1.5V	4.27	15$^+$	SB1O	LCC	1					0.26	500		
α Vir	116658	B1III-IV+B2V	0.98	130	SB2O		3			Y	hi	0.05	800		a)
ϵ Cen	118716	B1III	2.30	114$^+$			539			Y	hi	0.07	800		a)
ν Cen	120307	B2IV	3.41	65$^+$	SB1O	UCL	98			Y	hi	0.08	800		a)
ϕ Cen	121743	B2IV	3.83	79$^+$		UCL	6			Y	hi		600		
υ^1 Cen	121790	B2IV-V	3.87	124$^+$		UCL	3			s	hi	0.03	700	n	
β Cen	122451	B1III	0.61	139*			4			Y	hi	0.10	600	2,b	a) SB2O h)
τ^1 Lup	126341	B2IV	4.56	15$^+$			1					0.36	550		a)
α Lup	129056	B1.5III/Vn	2.30	16$^+$			2					0.48	600		a)
BU Cir	129557	B2III	6.10	53*			1					0.28	300		a)
β Lup	132058	B2III/IV	2.68	92$^+$			85			Y	hi		800		
κ Cen	132200	B2IV	3.13	32$^+$		UCL	7			Y	hi	0.16	750	b	
δ Lup	136298	B1.5IV	3.22	193$^+$		UCL	2			Y	hi	0.04	750		a)
ϵ Lup	136504	B2IV-V	3.37	41$^+$	SB2O		3			Y	hi	0.06/0.03	750	2	i) $V \sin i \sim 50/{\sim}30$
ζ^4 Lib	138485	B2Vn	5.50	212$^+$					1			0.02	400		
τ Lib	139365	B2.5V	3.66	134$^+$	SB2O	UCL	2						400		
λ Lib	142096	B2.5V	5.03	146$^+$	SB1O				1				400		narrow double shell lines
2 Sco	142114	B2.5Vn	4.59	240$^+$		US			1			0.01	450		
ρ Sco	142669	B2IV-V	3.88	98$^+$	SB1O		2		1	Y	hi		600		
π Sco	143018	B1V+B2V	2.89	100$^+$	SB2O	US	1	3	1	s	hi	0.05/0.02	800	2,n	$V \sin i \sim 120/{\sim}80$
δ Sco	143275	B0.3IV	2.32	148$^+$			121			Y	hi	0.06	650		j) SiIII emission wings
β^1 Sco	144217	B1V	2.62	91$^+$	SB2O		2	3	1	s	hi	0.07	750	2,b,n	NRP? k)

Table 2. continued.

Object	HD	Spec. type	V	$V \sin i$	Binary	Member	C	N	W	Bumps	Degree	Depth	S/N	Flags	Liter./remarks
β^2 Sco	144218	B2V	4.92	56^+				3	1	Y	hi	0.07	600	b,n	a) narrow shell lines
ω^1 Sco	144470	B1V	3.96	100^+		US	89			Y	hi	0.07	750		
13 Sco	145482	B2V	4.59	174^+	SB1O	US		1	1			0.03	650		
σ Sco	147165	B1III	2.89	56^+	SB1O?	US	5				lo	0.20	600		a)
ρ Oph A	147933	B2IV	5.02	196^+					1			0.02	500		
ρ Oph B	147934	B2V	5.92	223^+					1			0.03	550		
22 Sco	148605	B2V	4.79	195^+				1	1			0.02	600		
HR 6143	148703	B2III-IV	4.23	70^+			6			Y	hi	0.08	650		
τ Sco	149438	B0V	2.82	10^+		US	19		1			0.46	650		
ζ Oph	149757	O9.5Vn	2.56	320^+			1						600	n	l)
μ^2 Sco	151985	B2IV	3.57	52^+		UCL	1			s	hi	0.11	600	b	
HR 6353	154445	B1V	5.64	130				4	1			0.06	500		
68 Her	156633	B1.5Vp+B5III	4.82	140	SB2O			4	3	Y	hi	0.05	550	2	
θ Oph	157056	B2IV	3.27	30			4				lo	0.20	600		a) SB1O m)
υ Sco	158408	B2IV	2.69	28^+			10			Y	hi	0.13	650	2	
λ Sco	158926	B2IV+B	1.63	150^+			26			Y	hi	0.07	600		a) SB2O n)
κ Sco	160578	B1.5III	2.41	131^*			18			Y	hi	0.06	600		a) SB2O o)
HR 6601	161056	B1.5V	6.30	235					1			0.03	200		
V2052 Oph	163472	B2IV-V	5.82	75			7		1	s	hi/lo	0.09	500		a)
HR 6719	164432	B2IV	6.34	50					1	s	hi	0.11	300	n	
102 Her	166182	B2IV	4.36	30				1	2			0.13	600		
α Tel	169467	B3IV	3.51	23^+			19			Y	hi	0.09	700	b	
HR 6941	170580	B2V	6.69	0					2			0.27	400		
HR 6946	170740	B2V	5.72	25				3	1	Y	hi	0.12	450	b	$V \sin i \sim 60$
HR 6960	171034	B2IV-V	5.28	107^+			3			Y	hi		400		
HR 7029	172910	B2.5V	4.87	12^+			4			Y	hi/lo		400	b	
	174298	B1.5IV	6.56	109^*					2		lo	0.26	450	b	$V \sin i \sim 50$
σ Sgr	175191	B2.5V	2.02	165			2					0.02	500		
δ^1 Lyr	175426	B2.5V	5.58	110	SB1O			2	3			0.03	600		
HR 7210	177003	B2.5IV	5.38	10					2		lo	0.15	450		
η Lyr	180163	B2.5IV	4.39	10	SB1O?				2	s	lo/hi	0.11	600	b	$V \sin i \sim 40$
V380 Cyg	187879	B1III+B3V	5.69	90	SB2O			3	1			0.15	600		
HR 7591	188252	B2III	5.91	80				2	4	Y	hi	0.12	500		
α Pav	193924	B2IV	1.94	39^*	SB1O		2				lo	0.15	550	b,n	
ω^1 Cyg	195556	B2.5IV	4.95	145				2	3	s	hi	0.03	450	b,n,r	
	196025	B2IV-V	6.99	93^*					1			0.11	150		$V \sin i \sim 40$
51 Cyg	197511	B2V	5.39	35				3		Y	hi	0.09	500		
β Cep	205021	B1IV	3.23	20	SB1O?				2		lo	0.27	400		a)
HR 8341	207563	B2V	6.29	85					1			0.04	350		
HR 8399	209339	B0IV	6.66	25					1			0.06	300		$V \sin i \sim 130$
V365 Lac	209961	B2V	6.27	145	SB1O	Lac OB1			1			0.04	400		
35 Aqr	210191	B2.5IV	5.81	10				2	1		lo	0.29	400	b	
HR 8553	212978	B2V	6.14	120		Lac OB1			1			0.04	350		
6 Lac	213420	B2IV	4.51	70	SB1O?			1	1			0.10	450		
	214263	B2V	6.85	125^*		Lac OB1			1			0.05	350		
12 Lac	214993	B2III	5.25	30		Lac OB1			1			0.03	350		a)
1 Cas	218376	B0.5IV	4.85	15				1	1			0.29	300		
HR 9005	223128	B2IV	5.95	10				1				0.38	450		
σ Cas	224572	B1V	4.88	150				6	1	Y	hi	0.06	550		

a) Established β Cep star (Aerts & De Cat 2003; Sterken & Jerzykiewicz 1993; Heynderickx 1992).
b) Listed as β Cep suspect in Sterken & Jerzykiewicz (1993).
c) Listed as 53 Per in Unno et al. (1989).
d) Listed as β Cep suspects in BSC (Hoffleit & Warren 1991).
e) LeContel et al. (2001).
f) Harmanec et al. (1997).
g) Telting et al. (2001).
h) Ausseloos et al. (2002).
i) Uytterhoeven et al. (2005b).
j) Smith (1986).
k) Holmgren et al. (1997).
l) E.g. Vogt & Penrod (1983).
m) M. Briquet (Leuven Univ.; priv comm.).
n) Uytterhoeven et al. (2004ab).
o) Harmanec et al. (2004), Uytterhoeven et al. (2005a).