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Bright Be-shell stars*

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Abstract. Echelle observations are presented and discussed for 23 of the 27 known 'normal' shell stars brighter than about 6.5 mag. In addition to those typical cases, three stars with known transitions between emission & shell and pure emission line appearance, and three rapidly rotating B stars without records of line emission (Bn stars) are added to the sample. Long-term V/R emission-line variability and central quasi emission bumps (CQEs) in photospheric lines were found in 75% of all normal shell stars. This strongly suggests that the velocity law in most, if not all, disks of Be stars is roughly Keplerian. Both phenomena may occur in the same star but not at the same time. This is in agreement with the previous conclusion that CQEs only form in the presence of negligible line-of-sight velocities while long-term V/R variations are due to non-circular gas particle orbits caused by global disk oscillations. V/R variations associated with binary orbits are much less pronounced. Similarly, phase lags between different lines were detected in long-term V/R variable stars only. A binary fraction of only one-third is too low to support binary hypotheses as an explanation of the Be phenomenon. CQEs detected in 3 out of 19 Bn stars reveal the presence of disk-like equatorial concentrations of matter in B stars without emission lines. Accordingly, there seem to be intermediate cases between disk-free B stars and Be stars. Previous claims of the existence of shell stars with low $v \sin i$ could not be confirmed. Shell stars are Be stars viewed equator-on, and their observed rotational velocities are indistinguishable from the equatorial ones which are the same as in Be stars. The mean fraction of the critical rotation velocity is 81±12%. The standard deviation is comparable to, or even less than, the observational uncertainties. Since this would require star-to-star differences to be negligible, which is unrealistic, the correlation between the widths of strong spectral lines and the stellar rotation velocities may be truncated or severely distorted at its extreme end. A number of not previously known facts about individual stars is also reported.

1. Introduction

Phenomenologically, shell stars are stars with strongly rotationally broadened photospheric lines and additional narrow absorption lines. Some of the latter appear roughly at the center of the photospheric instance of the same atomic transition while those of low excitation do not have a photospheric counterpart. B-type shell stars, which typically also have Balmer emission, are commonly understood as ordinary Be stars seen edge-on, so that the line of sight towards the star probes the circumstellar, equatorial disk (see Porter & Rivinius 2003, for a review). The often strong contamination of most spectral lines by features formed in the disk poses severe problems for the analysis of the central star. On the other hand, this combination provides special opportunities for instance, central quasi emission bumps (CQE) predicted by Hanuschik (1995) and attributed to the shell nature of the star by Rivinius et al. (1999) strongly favour Keplerian rotation of the disk. A significant fraction of Be stars, and thus also shell stars, undergoes long-term variability of the violet-to-red emission peak height ratio (V/R). This, too, is indicative of Keplerian motion in the disk (Hanuschik et al. 1995).

Also observable in shell stars is the temporal evolution of the disk, like the disk dissipation seen in θ CrB in the early 1980s, and the slow outward motion of the density maximum indicating evolution of the undisturbed disk to-

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wards a more ring-like structure (Rivinius et al. 2001a, and references therein).

In order to identify possible differences between Be stars and rapidly rotating B stars that were never found to exhibit emission lines, HEROS observed nearly 20 Bn stars, which are ordinary B stars with broad and shallow lines, hence rotating rapidly and seen at a close to equatorial orientation.

The numerous HEROS observing runs of the past decade were primarily focused on the short-term variability of individual Be stars. However, as a by-product, many observations of shell stars were obtained at irregular intervals to follow their medium- and long-term variability.

Special features or events sometimes also prompted somewhat denser series of observations. In this way, a database covering 23 of the 27 known shell stars brighter than 6.5 mag was accumulated.

The homogeneity of the database (see Sect. 2 and Appendix A), its high spectral resolution, signal-to-noise, and wavelength coverage as well as its relatively long time baseline offer an excellent opportunity to assemble a statistically meaningful picture of the rotational properties of the disk, the disk structure and life cycles, and the frequency and effects of companion stars. The results are discussed in Sect. 4.3. Eventually, they should result in a more complete knowledge and understanding of the dominant forces acting on and in the disks of Be stars.

For completeness, the sample is augmented (see Appendix B) by 3 more stars, which have gone through phases of significant line emission with and without shell absorption lines. In the other 23 stars, shell absorption lines were never reported missing when significant line emission was present. This suggests that either the structure or the orientation of the disks of these 3 stars was different from the others. The data on Bn stars are presented in Appendix C.

The edge-on orientation of shell stars eliminates the uncertainty about the inclination of the rotational axis. From this, the equatorial rotation velocities and, by means of calibrations of the spectral type, fractions of the critical rotation rates can be derived for the central stars of Be systems in general. This is done in Sect. 4.2.1 and follows the method developed by Porter (1996). In addition, the much larger sample of stars with CQEs and/or V/R variations permits the velocity structure of the disks to be revisited (Sect. 4.3). The frequency of binaries among Be stars is studied, taking advantage of the relatively accurate radial velocity measurements enabled by the sharp shell lines (Sect. 4.4). The conclusions are summarized in Sect. 5. The discussions of individual stars in the Appendices are available online.

2. Observations

The data were secured using the echelle spectrographs HEROS (coverage 3500 Å to 8600 Å with resolving power $R = \lambda/\Delta\lambda = 20\,000$; starting in 1995 at La Silla [ESO, Chile]); after 1999 used in the northern hemisphere only), and FEROS (coverage 3700 Å to 9000 Å with $R = 48\,000$; used since 1999 at La Silla [ESO, Chile]). The northern-hemisphere observing runs with HEROS took place at various European observatories (Landessternwarte Heidelberg 1996 and 1997, Calar Alto 1998, Wendelstein 2000, Ondřejov 2000–2003). For a few stars data were also obtained in 1991 and 1992 with FLASH (coverage 4000 Å to 6700 Å with $R = 12\,000$) at the Tautenburg 2-m telescope.

These spectra will be published in electronic form together with the Appendices. Spectra of 59 Cyg, o And and η Cen, which are being investigated in dedicated projects, will be withheld until these projects have been completed. More detailed descriptions of the instruments and reduction procedures can be found in Rivinius et al. (2001b) and references therein. A paper summarizing the findings of the line profile variability project has been published, giving an overview of the individual observing runs (Rivinius et al. 2003).

Additional spectra of the Hα region of many of the northern objects were secured with the coudé spectrograph of the Ondřejov 2-m telescope between 1993 and 2000, equipped with a Reticon array, and between 2002 and 2003 equipped with a CCD. They cover the range from 6300 to 6740 Å. The widths of the telluric lines in the observed wavelength range correspond to a resolving power of about 8 000.

Moreover, for objects of particular interest, namely binaries and stars with long-term V/R variations, characteristic quantities like V/R and radial velocity were measured and are published as electronic tables (see Table 2 for a template).

Apart from ν Gem (Table 2), such tables are made available for ϕ Per (Table 5), ψ Per (Table 6), 28 Tau (Table 7), ζ Tau (Table 8) 4 Her (Table 9), 48 Lib (Table 10), ϵ Cap (Table 11), and EW Lac (Table 12).

3. The observed sample

Table 1 summarizes the 27 known Be shell stars brighter than about 6.5 mag, the 3 objects that have shown transitions between mixed emission & shell and pure emission-type spectra and about 3 Bn stars that may be surrounded by weak disks.

Only for four of the conventional shell stars do we not have our own spectra. These are HR 7415, and 1 Del, marked as shell stars by Slettebak (1982), and HR 1772 and HD 193 182, noted to be shell stars by Hanuschik (1996).

The HEROS data of ϕ Per were already discussed by Štefl et al. (2000) and Hummel & Štefl (2001). Results for the disks of ϵ Cap, η Cen, 4 Her, o And, ν Pup and ω Car were published by Rivinius et al. (1999, 2001a). Of them, only ϵ Cap, 4 Her, and o And are also discussed below, because more recent data permit additional or stronger conclusions to be drawn.

Infrared observations have shown that 51 Oph possesses a fossil disk composed of gas as well as dust, not dissimilar to the one of β Pic (e.g. Fajardo-Acosta et al.

Table 1. The shell stars considered in this study and their observed parameters. Unless otherwise noted here or in Sect. 3, Sp. type and $v \sin i$ were taken from Slettebak (1982), but always cross-checked against our data where possible. w was calculated using $v_{\rm crit}$ given in Table 2 of Yudin (2001), who interpolated values by Moujtahid et al. (1999). For stars without available luminosity class, the $v_{\rm crit}$ for dwarfs was used to obtain a lower limit to w. Since Sect. 4.3 relies on simultaneously obtained data for a given star, the columns for V/R variability and CQE only list the state of the disk during our observations, although such information is available from the literature also for other times and the other stars.

HD number	HR number	name	Sp. type	$v \sin i$ [km s^{-1}]	$w \sin i$	V/R variable	CQE occurrence	binary	References
Conventional shell stars (Appendix A)									
10 516	496	ϕ Per	B1.5 (V:)e shell	450	0.90:	√	—	√	1
13 709	652	μ For	A0 V	320	0.82	—	√	—	2
22 192	1087	ψ Per	B5 IIIe shell	280	0.90	?	—	—	
35 165	1772		B5 IVnp	280	0.73		no own spectra		3,4
37 202	1910	ζ Tau	B1 IVe shell	320	0.66	√	—	√	5
41 335	2142		B2 IVe	350	0.79	√	—	√	
45 542	2343	ν Gem B	B8 IIIe	—	—	√	—	√	
45 725	2356	β Mon A	B4 Ve shell	300	0.68	—	√	—	
47 760	2451	ν Pup	B8 III	230	0.84	—	—	—	6
56 014	2745	27 CMa	B3 III(e)p shell	280	0.82	—	√	—	7
89 080	4037	ω Car	B8 IIIe shell	220	0.80	—	√	—	
91 120	4123		B9 IVe	250	0.73	—	?	—	
93 563	4221		B8 III(e) shell	280	1.02	—	—	—	
110 335	4823	39 Cru	B6 IVe	250	0.67	—	—	—	
127 972	5440	η Cen	B2 IV(e)	350	0.79	—	√	—	
137 387	5730	κ^1 Aps	B3 IVe - 2 sp.?	350	0.83	—	√	—	
138 749	5778	θ CrB	B6 III	320	1.08	—	√	—	
142 926	5938	4 Her	B7 IVe shell	300	0.83	—	√	√	
142 983	5941	48 Lib	B3: IV:e shell	400	0.95:	√	—	—	
162 732	6664	88 Her	B6 IVe	300	0.80	—	—	√	8,9
183 656	7415		B6e shell	300	>0.73		no own spectra		
193 182			B8.5 III	200	0.73		no own spectra		10
195 325	7836	1 Del	B8-9:(e) shell	280:	>0.71:		no own spectra		
205 637	8260	ϵ Cap	B3 IIIe	250	0.74	—	√	√	
209 409	8402	o Aqr	B7 IIIe shell	300	1.06	—	√	—	
217 050	8731	EW Lac	B3: IV:e shell	300	0.71:	√	—	—	
217 675	8762	o And	B6 III	260	0.88	—	√	√	
Be stars having had both shell and emission phases (Appendix B)									
5394	264	γ Cas	B0.5 IVe	380	0.76	√	—	√	11
23 862	1180	28 Tau	B8 (V:)e shell	320	0.81:	√	—	—	
200 120	8047	59 Cyg	B1 Ve	≥379	≥0.73	√	—	√	7
Bn stars showing weak edge-on disk evidence (Appendix C)									
141 637	5885	1 Sco	B3 V	225	0.49	—	√	—	12
142 114	5904	2 Sco	B2.5 Vn	250	0.53	—	√	—	12
213 998	8597	η Aqr	B9 IV-Vn	245	0.68	—	√	—	12

1: Poeckert (1981), 2: Royer et al. (2002), 3: Hiltner et al. (1969), 4: Balona (1995), 5: Yang et al. (1990), 6: Rivinius et al. (1999), 7: Chauville et al. (2001), 8: Divan & Zorec (1982), 9: Slettebak (1976), 10: Denizman et al. (1993), 11: Harmanec (2002), 12: Abt et al. (2002)

1993). Since disks of Be stars are formed from gas lost by the central star, 51 Oph is not considered in this study.

The available observations of the Be shell stars, the stars with Be ⇔ shell transitions, and the Bn stars are presented and discussed in the Appendices A, B, and C, respectively. Summaries are given in the following subsections.

3.1. Conventional Be shell stars

These objects were originally classified by either Slettebak (1982, those classified as 'shell' in Table 1) or Hanuschik (1996). One new shell star is identified from the present observations (see, however, also Appendix C, introducing three further stars with supposedly circumequatorial matter). All stars in this subsection have in common that, when significant line emission was present, narrow shell absorption lines were always observed as well.

Table 2. Line parameters for ν Gem: Next to the heights (in continuum units) of the V and R emission peaks the one of the central peak is given, when a triple-peaked profile was present (C peak). The radial velocities correspond to the local minima (modes) in these lines (for Hα of the central depression). The typical error is 11 and 3 km s^{-1} for the He I 6678 measurements in the Ondřejov coudé and HEROS data, respectively, and about 1 and 0.2 km s^{-1} for the much sharper Hα absorption core. The full table and similar tables for other stars are published electronically only.

JD HJD-2400000	V peak $[I_{\rm violet}/I_{\rm cont}]$	R peak $[I_{\rm red}/I_{\rm cont}]$	V/R	peak sep. [km s^{-1}]	C peak $[I_{\rm cent}/I_{\rm cont}]$	$v_{\rm H\alpha}$ [km s^{-1}]	$v_{\rm He\,I\,6678}$ [km s^{-1}]	$v_{\rm Si\,II\,6347}$ [km s^{-1}]
49658.692	1.43	1.41	1.02	173.4	—	24.6	47.9	45.0
49661.640	1.42	1.38	1.03	174.5	—	25.8	61.5	47.6
49662.656	1.44	1.39	1.04	186.9	—	26.9	62.8	51.2
49679.699	1.43	1.40	1.02	179.7	—	26.4	31.0	38.8
50015.671	1.51	1.31	1.15	203.4	—	20.4	–2.5	17.3
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮

In all cases, the present observations confirm the shell-star classification also according to the partly quantitative, and more restrictive, definition by Hanuschik (1996). This definition requires that the residual shell absorption, i.e. after correction for the photospheric component, reaches deeper than the base level of the accompanying line emission. In this way, it is ensured that at least part of the central reversal of the emission line is due to absorption of light in front of the star.

Slettebak (1982) only used the narrowness of some lines relative to the supposed photospheric lines as a criterion. The full agreement of the two classifications implies (i) that below some threshold in line width all narrow lines observed in equator-on Be stars form at least in part between the photosphere and the observer and, perhaps more importantly, (ii) that any circumstellar absorption imposed on the spectrum of an equator-on Be star is due at least partly to a zone with a very small range of line-of-sight velocities.

3.2. Stars with emission ⇔ emission & shell transitions

Only 3 of the 30 Be stars in Table 1 are known to fall into this category (cf. Appendix B), i.e. having exhibited the appearance of a conventional shell star at some epochs and that of a pure Be star at others. From what little statistics is available, it seems that these stars are normally observed as pure Be stars and only exceptionally with additional shell absorption lines. In all spectra of the present dataset the 3 stars look like ordinary Be stars without any shell component (Appendix B).

3.3. Bn stars

In three out of 19 Bn stars observed, subtle CQE-like distortions of some absorption line profiles were detected (Appendix C). This suggests that they, too, may posses weakly developed, rotating disks. The quasi-resonance line character of Hα implies that low hydrogen column densities can be seen well before appreciable line emission occurs. This is aggravated in stars with large $v \sin i$, which Bn stars are by definition, as is illustrated in Fig. 1. Therefore, it is plausible that, while there is a relatively clear-cut division between Be and non-Be stars, self-absorption in edge-on disks has a much larger dynamical range. Accordingly, the circumstellar matter of some Bn stars might be the low-density tail of the disks of Be stars.

The mean fraction $\overline{w} = 0.57$ of the critical rotation velocity is considerably lower than that of any of the shell stars (Sect. 4.2.1 and Table 1). But with only 3 such stars known, it would be premature to speculate whether the amount of circumstellar matter depends on w.

CQE stars might play a similar role among non-Be stars as shell stars do among Be stars. They would permit a sample of equator-on stars to be compiled from which the high-rotation limit of non-Be stars could be determined. A comparison with the distribution of rotation velocities in shell stars might, then, offer a clue as to whether Be and Bn stars are fundamentally different populations of stars or possibly only differ in evolutionary stage.

4. Analysis and discussion

4.1. Exceptions from the standard model for Be stars?

As early as 1931, Struve introduced the standard model according to which (i) Be stars rotate extremely rapidly and possess a rotating equatorial disk and (ii) spectra of Be stars take on the appearance of shell stars, with narrow absorption lines imprinted on broad emission lines, if the line of sight passes through the disk, i.e., the star is seen equator on. This model has passed many observational tests (see Porter & Rivinius 2003, and references therein).

However, deviations from this general scheme are sometimes claimed:

(i) Be stars with narrow shell absorptions, but their stellar $v \sin i$ is low. That is, some Be stars are intrinsically slow rotators. The alternative interpretation, namely a non-disk like structure of the matter leading to the shell absorptions, among other arguments, contradicts all the recent interferometric results, see again Porter & Rivinius (2003) for a summary.

(ii) There are Be stars that exhibit line-emission phases with and without shell absorptions, i.e. they undergo emission ⇔ emission & shell transitions. This is not possible for an equatorial disk with constant orientation.

In the following, the published observational evidence for the first claim is re-discussed with the help of the collected database, while the second is compared to recent theoretical works on disk dynamics and shell line formation.

4.1.1. Shell stars with low $v \sin$ i?

Because Struve's model is widely accepted, this may, introduce a bias against the detection of true low $v \sin i$ shell stars. Moujtahid et al. (1998) nominated 6 stars with low $v \sin i$ as candidates exhibiting 'spectrophotometric shell behaviour'. A caveat to this method is that a spectrophotometric classification as a shell star is problematic because for a shell star in the common sense the presence of absorption lines is required, whose narrowness is irreconcilable with the width of the photospheric lines. An even stronger source of concern is that the authors use narrowband photometry only, not spectrophotometric data.

For three of the six stars, observations are available from the database of this study (see Appendix A): 27 CMa really is a shell star, but its $v \sin i$ was underestimated. HR 4074 has not shown any sign of circumstellar material for more than a century (Štefl et al. 2002) so that it cannot possibly have been a shell star. ω CMa is an almost proto-typical pole-on and non-shell star. In spectra of this star, the circumstellar contribution to the Balmer discontinuity (BD) is very obviously in emission, while it should be in absorption for a shell star. Since any attempt to identify shell stars by the photometric amplitude of the BD rests on assumptions for the stellar BD, the determination of the latter was probably problematic in the cases of HR 4074 and ω CMa.

The remaining three stars mentioned by Moujtahid et al. (1998) were not observed by us. But it is noted that two of them (HR 3135 and HR 7249) are one-sigma cases only, w.r.t. the position of the stellar BD assumed by Moujtahid et al. (1998), and available data (e.g. in Hanuschik et al. 1996) do not point to any shell type spectra. Finally, θ Cir might be a border line case between emission and shell type behaviour. According to Hanuschik et al. (1996) the $v \sin i$ of 100 km s^{-1}, adopted by Moujtahid et al. (1998), "seems dramatically underestimated", while Chauville et al. (2001) give 185 km s^{-1}. Unfortunately, this latter analysis was limited to lines affected by shell absorption (the data are available on line). A confirmation from more nearly photospheric lines is desirable. It also needs to be ascertained (cf. the case of ν Gem) whether these lines are not due to a spectrally dominant companion.

Thus, it appears that in none of the 6 cases proposed by Moujtahid et al. (1998) has the evidence of shell absorption lines occurring in low $v \sin i$ stars been advanced sufficiently that it can be accepted.

4.1.2. High $v \sin i$ Be stars with only temporary shell absorption

Stars with emission ⇔ emission & shell transitions are relatively rare but exist (see Appendix B). The mechanisms underlying these changes are not understood. However, they show some characteristics that permit such objects to be clearly distinguished from conventional shell stars. Hummel (1998) summarized those properties: In a pure emission phase, the full width of the lines is typically much narrower than in shell phases. Such a large variability in width is not seen in other Be stars. Also, the emission heights are largest (above the continuum) when the lines are narrow and single-peaked. Similarly, the brightness varies with the emission line width. This led Hummel to suggest a (temporarily) tilted or warped disk for these stars, precessing about the stellar equator. This hypothesis has not yet been tested, but it explains the observations without postulating a model differing from the widely accepted disk model.

Even if the plane of the disk is invariant, shell lines may be transient. They could, for instance, arise from the disk changing its geometrical thickness. Shell lines might also form transiently due to the variable lower boundary radius of the disk, often rather widely separated from the star (Rivinius et al. 2001a). It is possible that the line of sight to the photosphere does not intersect the disk and no shell lines form. Only if and when the gap between star and disk is filled with gas (which also needs to have suitable kinetic properties) can shell lines develop.

Thus, a Be star viewed nearly equator-on may possess an equatorial disk that does not intersect the line of sight, i.e. does not always manifest itself by narrow shell absorptions.

4.2. Rotational properties of shell (and Be) stars

4.2.1. Results of this study

Porter (1996) investigated the rotational velocities of shell stars. The basis of his work was that all shell stars are ordinary Be stars viewed about equator-on so that $\sin i$ would be close to unity. Accordingly, the observed distribution in $v \sin i$ of shell stars provides the most straightforward way of determining the distribution of the equatorial velocities of Be stars because the two should be indistinguishable.

The determination of the equatorial velocity distribution of Be stars from shell stars offers another advantage in addition to its simplicity. If a sample of Be stars with supposedly random inclination angles is analyzed, this sample is likely biased against stars with large inclination angle. The increased width of the emission lines makes them more difficult to detect than the narrower line emission resulting from smaller inclination angles. This is illustrated in Fig. 1, contrasting three typical Be star spectra.

The pole-on star ω CMa, although its emission equivalent width was among the lowest ever observed (Štefl et al. 2003), the star is clearly recognized as a Be star. On account of the deep and narrow absorption core in Hβ, ϵ Cap would probably have been classified as Be-shell star even in lower quality spectra. However, η Cen, having a somewhat weaker shell signature than ϵ Cap, could easily be missed. This illustrates that Be stars with narrow emission lines are easier to find which may introduce biases in samples of Be stars. Moreover, for optically thick emission lines, their flux is roughly proportional to the projected area rather than the volume. This again favours the detection of Be stars with low $v \sin i$. By contrast, shell stars are easy to detect.

Compared to the analysis of Porter (1996), the database of shell stars compiled in Table 1 is somewhat more complete. Furthermore, Porter assumed all objects to be of luminosity class V. The re-analysis presented below differentiates between different luminosity classes. While Porter did not have access to a homogeneous set of observations, the present database permitted all $v \sin i$ values to be put on one common scale. Omitted from the analysis were the three stars, that have shown only intermittent shell features although their line-emitting disks where well developed. It is, therefore, doubtful whether their $\sin i$ is similarly close to unity as for the main sample. Since they only account for 10% of the stars in Table 1, their non-consideration is not critical, especially since neither their $v \sin i$ nor their $w \sin i$ values show systematic deviations.

A full re-determination of rotational velocities is beyond the scope of this work. More importantly, this will only make sense after the question has been answered of whether critical rotation has not so far been found in Be stars because the traditional methods used exclude this: Because of the rotational gravity darkening, the equatorial regions give a very small contribution to the observed line width. This effect would be the strongest in stars viewed equator-on. The most rapidly rotating regions would be missed if only the widths of strong lines are used, and the $v \sin i$ scale would be truncated at some level (Townsend et al. 2004).

In any case, such an error would be systematic, and since the present sample is homogeneous this does not invalidate the results obtained here. If a re-scaling is necessary, this can easily be applied later. The uncertainty of any individual value of w arises from $v \sin i$ but also from the uncertainties in spectral type and luminosity class.

The typical errors in $v \sin i$ are of the order of 10% but there are also outliers. Recently, several studies have determined rotational velocities of Be stars, including shell stars. Frémat et al. (2005) have 22 stars and Levenhagen & Leister (2006) have 4 stars in common with the present study (not considering ν Gem, which is a binary with photospheric profiles not belonging to the Be star - see online material). For three of these stars, there are strong mismatches of the adopted $v \sin i$ values.

For κ^1 Aps, the two other studies yield $250\,\mathrm{km\,s^{-1}}$, while we adopt $350\,\mathrm{km\,s^{-1}}$, which are the lower and higher end, respectively, of the range given by Slettebak (1982). Since the larger value is in good agreement with spectral lines little influenced by the shell absorption, while the two quoted studies rely mostly on data from the He I 4471 and Mg II 4481 lines, we feel justified in keeping the higher value. Conversely, for HR 1772 ($280\,\mathrm{km\,s^{-1}}$ vs. $350\,\mathrm{km\,s^{-1}}$ derived by Levenhagen & Leister 2006) and γ Cas ($380\,\mathrm{km\,s^{-1}}$ vs. $441\,\mathrm{km\,s^{-1}}$ measured by Frémat et al. 2005), the results published by Slettebak (1982) are the lower ones. We retain them mainly for consistency but note that their uncertainty is probably above average.

From a comparison of the MK types given by Slettebak (1982) with determinations by Moujtahid et al. (1998) and Chauville et al. (2001), an uncertainty of up to one spectral subclass and one luminosity class can be deduced. The value of v_{crit}, taken from Table 2 of Yudin (2001), should therefore be accurate to within 20 %. The errors are dominated by the uncertainty of the spectral classification.

Repeating Porter's analysis, it is found that the mean critical fractional rotation of Be stars is $\overline{w} = 0.81$ with $\sigma = 0.12$ (see also Fig. 2). Broken down by luminosity class, the results are $\overline{w}_{\mathrm{LC\,V}} = 0.77 \pm 0.08$, $\overline{w}_{\mathrm{LC\,IV}} = 0.76 \pm 0.09$, and $\overline{w}_{\mathrm{LC\,III}} = 0.89 \pm 0.13$. The corresponding mean equatorial velocities are $\overline{v}_{\mathrm{LC\,V}} = 328 \pm 61\,\mathrm{km\,s^{-1}}$, $\overline{v}_{\mathrm{LC\,IV}} = 306 \pm 51\,\mathrm{km\,s^{-1}}$, and $\overline{v}_{\mathrm{LC\,III}} = 264 \pm 39\,\mathrm{km\,s^{-1}}$. Although there seems to be a trend towards lower v but higher w with decreasing luminosity class, the errors are too large to ascertain its significance.

The above value of $\overline{w}$ is slightly larger than Porter's (1996) result. However, since the spectra available for the present study permitted low $v \sin i$ outliers to be corrected, this is not surprising.

More interesting is that the width of the peak at $\overline{w} = 0.81$, namely $\sigma = 0.12$, is narrower than the estimated intrinsic uncertainties of individual determinations of w of about 20 %. The error estimates made above are, therefore, conservative. But even if the true error in individual values of w was as small as 10%, the width of the peak in their distribution would be not or only marginally resolved. Since there must also be a genuine spread in w, this might signal that the true $\overline{w}$ is higher but that the observational scale of w is truncated. This could lend some additional support to the growing suspicion that, above some threshold in the true rotational velocity, the width of strong spectral lines no longer increases with the equatorial velocity. In any event, the $\overline{w} = 0.81$ derived here should be regarded as a lower limit.

4.2.2. Comparison to other studies

Several other recent works (see e.g. Collins & Truax 1995; Domiciano de Souza et al. 2003; Owocki 2003; Frémat et al. 2003; Townsend et al. 2004, and others), find evidence for a somewhat higher value of $\overline{w}$. However, the more canonical and conservative values $\overline{w} \leq 0.8$ obtained in previous decades were still reproduced in several recent studies (Vinicius et al. 2006; Frémat et al. 2005). Accordingly, there is no obvious trend, and the unambiguous resolution of this discrepancy requires a detailed, dedicated investigation (and the identification of targets suitable for bench marking).

For instance, the critical velocities used by Frémat et al. (2005) are based on stellar parameters obtained from spectral line fitting and somewhat higher than the ones adopted here. This explains part of the difference in $\overline{w}$. However, the results obtained by Frémat et al. may suffer a systematic problem, whereas the reported statistical uncertainties are exceedingly (if not sometimes surprisingly) small. For instance, the reported uncertainty of the inclination angles is typically as low as one to four degrees. In a histogram of these inclination angles with a bin width of 10 degrees, i.e. well above the stated errors, the numbers (omitting ν Gem) are 2 (2), 7 (6), 11 (10), 17 (13), 24 (16), 23 (18), 19 (20), 20 (21), and 5 (22) stars from the pole-on to the equator-on bin, respectively; the numbers in parentheses are for a randomly oriented sample of stars. Among the five stars actually present in the equator-on bin, only one is in common with the present study. For the other stars in this bin, published spectra are available and partly exhibit low-inclination emission-line characteristics as defined by Hanuschik et al. (1996), making the lack of pole-on stars stronger still.

The sample analysed by Frémat et al. (2005) was not compiled to be representative of the true distribution of inclination angles, and emission-line surveys are more likely to miss equator-on objects (cf. above). But, with one exception, even the shell lines in common with the present study fall in the range between 54 and 79 degrees and so exhibit a deficit in the last bin, which in part could be due to underestimated rotation velocities. Indeed, a comparison (Townsend, private communication) of the models of Frémat et al. (2005) and Townsend et al. (2004) suggests some systematic difference. At a given v/v_{crit}, the former leads to broader line profiles or, for a given star, suggests a lower $v \sin i$. The origin of this difference is not presently known.

In summary, not even from the more recent literature can a consistent conclusion be drawn. While it is clear that circumstellar contamination of supposedly photospheric lines is a major contributing circumstance, the full truth may be more complicated. It is, therefore, possibly illuminating that more nearly critically rotating stars are being discovered that do not suffer from strong circumstellar lines, e.g., Regulus (McAlister et al. 2005, $w = 0.86$), Altair (Peterson et al. 2006a, $w = 0.90$), or the important standard Vega (Peterson et al. 2006b, $w = 0.93$). Since they belong to the apparently brightest stars, these findings could be merely the tip of an iceberg. Such stars may also serve as useful quantitative calibrators of models.

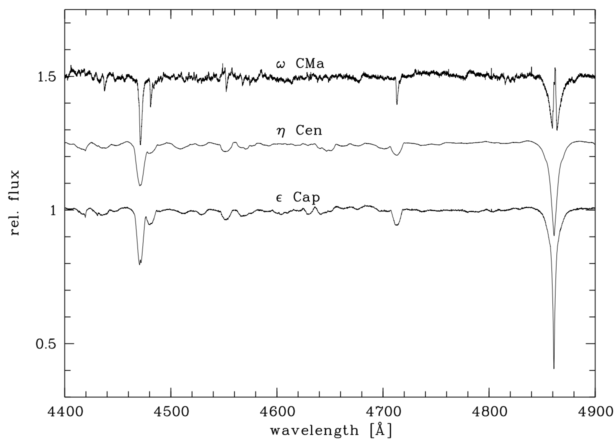

Fig. 1. The part of the wavelength range used by the MK classification process, where the Be nature is most visible, for three early-type Be stars at different inclinations.

4.3. Velocity structure of the disk

Absorption and emission components of circumstellar lines provide complementary information about the dynamics of the disks.

Of the 23 objects, only 4 showed neither CQEs nor long-term V/R variability. Six (maybe 7) were long-term V/R variable during our observations, and 11 (possibly 12) exhibited CQEs. Not in a single star did long-term V/R variability and CQEs occur simultaneously. Taking into account earlier observations one finds, however, that both V/R variability and CQEs may be present in the same star, but at different times (e.g., ϵ Cap and κ^1 Aps used to be V/R variable according to the compilation by Okazaki 1997).

CQEs as an occultation pattern (Hanuschik 1995; Rivinius et al. 1999) form in the line of sight towards the star, at several stellar radii. CQEs can only occur if the radial component of the disk velocity is lower than a few $\mathrm{km\,s^{-1}}$, i.e., there is no strong out- or inflow, and the gas particle orbits are not too eccentric. These conditions are fulfilled by a circular Keplerian disk.

The long-term V/R variablity, on the other hand, is attributed to a density wave pattern in the circumstellar disk. In terms of celestial mechanics, this density wave consists of a common periastron of a set of eccentric Keplerian orbits, precessing about a non-spherical (rotationally flattened) star. Therefore, except when periastron or apastron are in front of the star, there will always be some non-zero radial velocity component projected against the star. Naturally, no CQEs should be formed under such dynamical conditions, which explains why CQEs and V/R variability are not observed simultaneously.

The long-term V/R variations connected to the global density waves were found to exhibit phase lags between various lines for three out of 6 (or 7) stars in our data. This points to a spiral structure of the density wave, i.e. the azimuth angle of the density maximum varies with

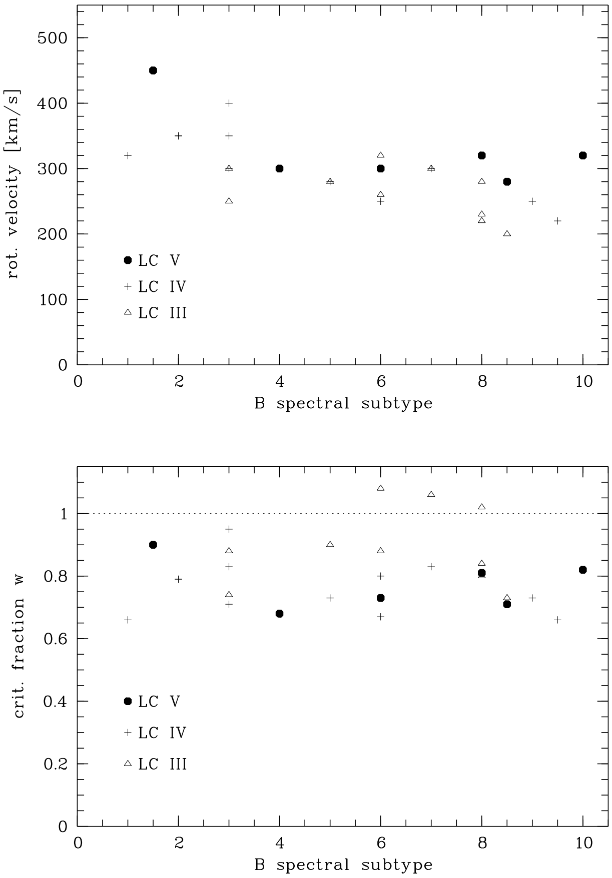

Fig. 2. The values of $v \sin i$ (upper panel) and w (lower panel) of the shell stars in Table 1 (i.e. the ones listed in the upper part) plotted against spectral subtype. While the rotational velocity depends on spectral type, but little on luminosity class, the critical fraction is largely independent of spectral type.

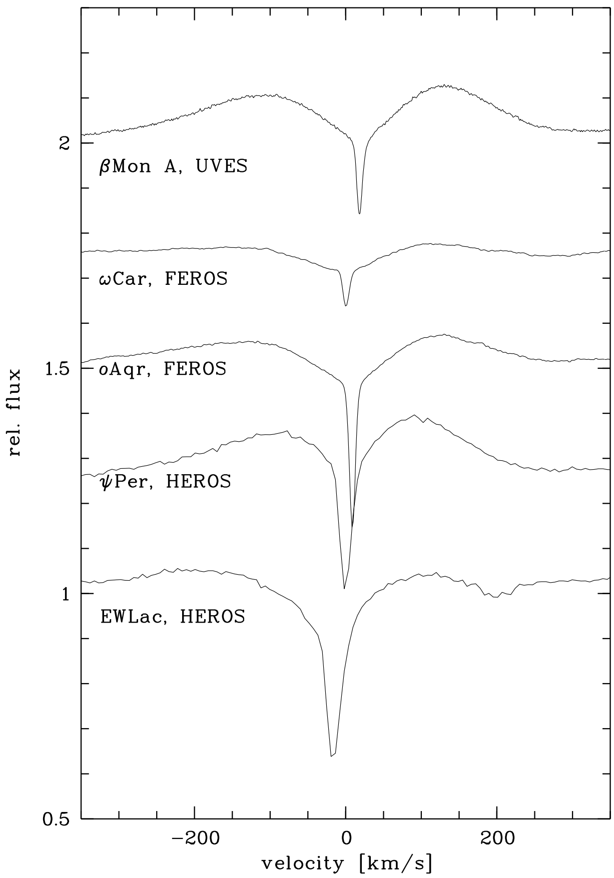

Fig. 3. Narrow absorption cores in the Fe II 5169 profile of five stars. See Table 3 for measured properties.

Table 3. Properties of the narrow cores observed in the Fe II 5169 lines of five shell stars. The resolving power of UVES was $R = 80\,000$, see Sect. 2 for Heros and Feros. The stellar radial velocities $v_\star$ were taken from the General Catalogue of Radial Velocities (Wilson 1953, GCRV) and its revised edition (Evans 1967), respectively. All numbers are given in km s^{-1}.

Star	instr.	resolut.	FWHM$_{\rm shell}$	$v_{\rm shell}$	$v_\star$
EW Lac	Heros	15	20	−15	−11
ψ Per	Heros	15	17	0	−1
o Aqr	Feros	6.3	9.1	9.0	12
ω Car	Feros	6.3	9.6	0.7	7
β Mon A	UVES	3.8	8.4	18.6	20

distance from the star, causing phase lags between the V/R curves of lines formed at different radii.

The requirement for the occurrence of CQEs, namely very small non-circular velocities in the disk, is corroborated by the very small width of the shell lines of some stars. Hanuschik (2000) presented a Fe II 5169 profile of o Aqr, with a core width only a few times wider than the intrinsic thermal one, at about the stellar systemic velocity. Our spectra confirm this for o Aqr and in addition show this for ω Car, ψ Per, β Mon A, and EW Lac (Fig. 3 and Table 3). Like CQEs, such narrow lines are present only in stars which either do not show V/R variability (o Aqr, ω Car), or only weak asymmetries (ψ Per, EW Lac, β Mon A). In Be shell stars with strong V/R variability the Fe II 5169 line is typically much broader (cf. e.g. Figs. A.3, upper panel, and A.13, middle panel)

The two main concurring hypotheses, bound corotation and angular momentum conserving outflow, are unable to explain both the narrowness and position of the shell lines, as well as the existence of CQEs. A corotating circumstellar environment would not allow shell lines to form at all, since not enough material will be projected to a zero line-of-sight velocity. Support for the Keplerian rotation of the disk has also been derived from interferometric data taken with the VLTI (Stee 2006).

An alternative explanation of CQEs by means of an NLTE phenomenon is very unlikely, considering that CQEs are seen with consistent behaviour in a wide range of spectral lines in some of the stars. CQEs are more naturally, i.e. with fewer assumptions, explained by a purely geometrical model.

4.4. Binarity and the Be phenomenon

Eight of the 23 observed shell stars are binaries, four of them contain long-term V/R variable shell stars, three others CQE stars. This does not allow any clear conclusion to be drawn as to whether binarity contributes to the excitation of the global one-armed disk oscillations causing the V/R variability. But the presence of this phenomenon also in clear-cut single stars proves that binarity is not necessary.

In some binaries, V/R variations are observed that are phase-locked to the orbit. Clearly defined cases are ϵ Cap and 4 Her; less pronounced is ϕ Per. ϕ Per is the only object in which both types, orbital and long-term V/R changes, were observed. The peak-to-peak amplitudes are quite weak for the orbital variations (a few percent only) compared to the long-term changes. This is also in agreement with the findings of Negueruela et al. (1998) in Be/X-ray binaries. It would mean that the presence of a stellar companion in most cases affects the global symmetry of Be star disks only slightly. Similarly, the seemingly rare but bizarre triple-peaked emission profiles as seen in ν Gem and ζ Tau (see Appendix A) are linked to a phase of the V/R cycle rather than the orbit. Contrary to the long-term V/R variability, phase differences between different lines were not found in the orbitally phase-locked V/R variations. According to Okazaki (priv. comm.), a purely kinematic model can not explain the phase-locking, except maybe for a too limited range of orbital parameters. Similarly, the understanding of the triple-peaked profile is outside the current models for Be star disks.

Of the three stars having shown transitions between emission & shell and pure emission line appearance, two are binaries. For the third one, Pleione, this is suspected, but could not be confirmed on the basis of the data of this study.

A binary fraction of one third (8/23) does not suggest any difference w.r.t. B-type stars in general. As far as the role of binarity in the Be phenomenon is concerned, it even shrinks to one quarter because the Be stars in o And and ν Gem are merely distant companions to a close non-Be binary. Nevertheless, recent publications proposed a new incarnation of the hypothesis that Be stars in general are a binarity-related phenomenon.

Gies (2000) suggested that Be stars have been binaries in the past, so that the current Be star has been spun up during the binary evolution (like probably ϕ Per and 59 Cyg). This hypothesis mainly seeks an explanation for the unusually high rotation of Be stars, not so much for the mass loss mechanism leading to disk formation. Harmanec et al. (2002a) proposed Be stars to be in binaries, so that the mass loss of an already almost critically rotating star is triggered by the gravitational pull at the equator of the Be star closest to the companion. Still, however, the mass loss would be mainly powered by rapid stellar rotation near the limit of stability (for a discussion of critical rotation see Sect. 4.2.1). Both the above hypotheses would mean that the present study missed two-thirds of all binaries, which is unlikely.

If it is plausible to assume that orbital and rotational angular momentum vectors are roughly parallel, the restriction to shell stars should not discriminate against binaries — on the contrary. Because shell stars are observed equator-on, orbital RV amplitudes are maximal. If shell lines participate in the RV variations, even small amplitudes are detectable (cf. ϵ Cap). Towards longer periods, amplitudes will still be too low for easy detection. However, the gravitational effect on the central B star is, then, small also.

One could suspect that the companion itself might disturb the disk, so that the shell lines become unsuitable to detect binary orbital motion. However, observations of Be/X-ray binaries, which do not show such bias, do not support the idea of the disks being strongly distorted by the companion (Negueruela et al. 1998).

Accordingly, the census of binaries is complete enough to leave no room for a generalized binary model for Be stars. Moreover, once a Be star is rotating at 99% of the critical rate (as speculated by Harmanec et al. 2002a) substantial mass loss will take place in any non-binary star as well. One, or any combination, of radiation pressure, non-radial pulsation, magnetic fields, turbulence, etc. (Owocki 2003) will supply the 1% missing for lift-off.

5. Conclusions

The confirmation of ν Gem and ϵ Cap increases the total number of binaries in the sample to 8 in 23. However, it is unlikely that in all 14 remaining stars, or two thirds of the sample, a companion with significant gravitational interaction with the primary was missed. This eliminates generalized binary explanations of the Be phenomenon.

In the spectra of 11, maybe 12, shell stars central quasi-emission bumps were seen. In 6, maybe 7, stars long-term V/R variability was present. Both phenomena require a disk with Keplerian rotation. But CQEs cannot co-exist with significant non-circular orbits which are characteristic of the density waves observable as V/R variations. In fact, none of the stars mentioned was during the present observations common to both groups. However, ν Pup is a former CQE star and 88 Her was a V/R variable. 5 stars show very narrow shell absorption at about systemic velocity, also requiring a disk with Keplerian rotation for explanation. Since only about 25% of the stars exhibited neither phenomenon during the present observations, it seems safe to conclude that the disks of all shell stars, and hence all Be stars, are primarily rotationally supported.

V/R variations with the orbital period were found in 3 out of 8 binaries. They differ from the ones caused by disk oscillations in having much lower amplitudes, being periodic rather than cyclic, and taking place on much shorter timescales. The latter is probably helped by the difficulty to detect the RV variations caused by a companion with an orbital period of some years. But the low amplitudes even in shorter-period systems show that the de-circularizing effects exerted by a second star on the gas orbits in the disk are weaker than the driving of global disk oscillations. Because the quadrupole moment resulting from the rotational distortion of the central star is responsible for the latter, the comparison with the influence of companions might help to derive a lower limit to the non-sphericity of Be stars. This could offer some statistical insights into the question of how close to the break-up velocity Be stars are rotating.

Phase lags between the V/R variations of emission lines formed at different distances from the star were found in three of the 6 (or 7) long-term V/R-variable shell stars. They might be due to a helical structure of the density wave in the disk, suggested by Okazaki (1991). Such shifts were not seen in stars with V/R variations due to a stellar companion.

Relying on the results of conventional methods, which may not be able to diagnose values close to critical rotation, the mean fraction of the critical rotation is determined as $\overline{w} = 0.81 \pm 0.12$. Since the width of the distribution exceeds the errors of the input data at most marginally, there is the possibility that the classical $v \sin i$ scale is truncated near to 80% of the critical velocity. This could be due to the most rapidly rotating but also most gravity-darkened equatorial regions making only minimal contributions to the profiles of strong lines in stars viewed equator-on. Differences between luminosity classes exist but are not significant with the current database.

A critical case-by-case comparison of the published $v \sin i$ values with the observations has shown that there are no shell stars with low $v \sin i$. This confirms once again that shell stars are rapid rotators, are viewed roughly equator-on, and their disks are geometrically relatively thin.

Transitions between Be and non-Be phases have for decades been observed in a number of Be and shell stars. They are manifestations of the transient nature of the disk forming process. Nevertheless, the detection of CQE and, therefore, small equatorial condensations of circumstellar matter around Bn stars is an interesting novel result. It might imply that there is no strict boundary between Be and rapidly rotating non-emission line B stars. The mean fraction of the critical rotation velocity of these 3 stars is less than that of any of the shell stars studied. But it is too early for speculation as to whether this is the reason for the weakness of their disks. The study of Bn stars with CQE signatures might also help to find out whether there is a population of stars rotating equally rapidly as Be stars but not building a significant disk.

Finally, the following new results were derived for specific objects:

- μ For is a previously unknown shell star.
- θ CrB was in diskless state since 1980. From 2001 on, it showed some circumstellar activity and may rebuild a disk in the coming years.
- ν Gem is at least a triple system. The shell absorption and the dominating photospheric spectrum originate from different stars in the system.
- 1 Sco, 2 Sco, and η Aqr show weak profile distortions in Hα.

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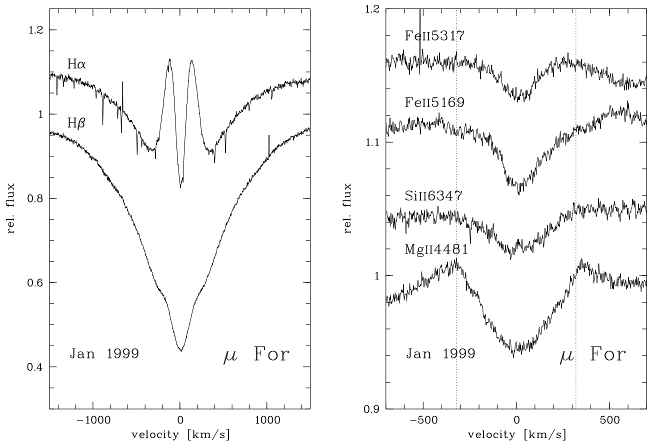
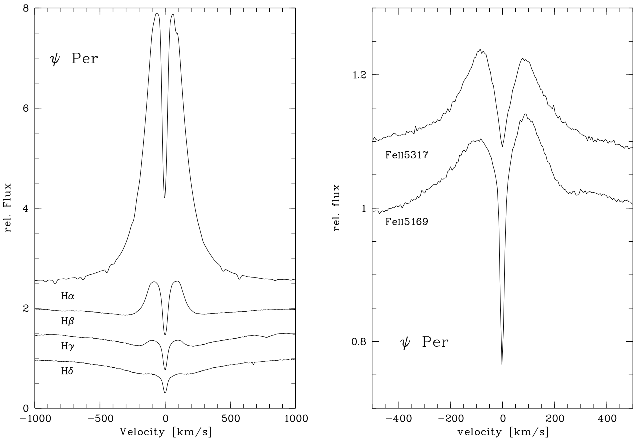


Fig. A.1. Evidence for μ For being a shell star. The dotted lines mark $\pm v \sin i = 320\,\mathrm{km}^{-1}$. The Fe II lines show absorption cores typical of weak shells, and Si II 6347 (second profile from bottom) even exhibits a central quasi emission bump (CQE), which is formed in a Keplerian disk seen edge-on (Rivinius et al. 1999). The Mg II 4481 line shows the undisturbed stellar rotational profile for comparison. The central Hα absorption is also very deep.



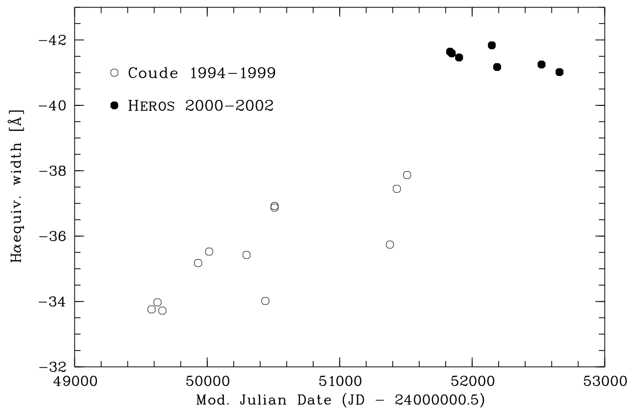


Fig. A.2. Shell lines of ψ Per observed with HEROS in 2002. The V/R is unity for the Balmer lines, but greater than one for Fe II 5317 and less than one for Fe II 5169.

Appendix A: Conventional Be shell stars

μ For (= HR 652 = HD 13 709) is a star not previously known to show Balmer line emission. SIMBAD lists spectral type determinations from B9 V to A2 Vn. The shell phenomenon is common also in A- and even F-type stars. But since the presence of line emission is unusual among them, we count μ For as a 'Be-star' in this study, even if the 'median' spectral type is only A1 V and the most recent determination by Royer et al. (2002) is A0 V. The latter was adopted for the determination of the stellar parameters.

The star was observed only once with FEROS in January, 1999 (Fig. A.1). The Fe II lines are narrow compared to the measured $v \sin i$ and do not exhibit a profile typical of rotational broadening, but rather of weak shells (cf. Figs. 1 and 7 of Rivinius et al. 1999). The CQE apparent in Si II 6347 and the depth of the Hα absorption core support the conclusion that μ For is a weak shell star. Royer et al. (2002) derived a $v \sin i$ of $320\,\mathrm{km\,s^{-1}}$, but did not see anything unusual in spectra obtained between 1989 and 1995.

ψ Per (= HR 1087 = HD 22 192) was observed from Ondřejov thirteen times with the coudé spectrograph (1994 to 1999) and seven times with HEROS (2000 to 2002).

The profiles of this B5 IIIe-shell star did not exhibit significant shape variations. But the Hα emission equivalent width increased slowly in absolute value from $W_\lambda = -34$ Å to -42 Å. Although the coincidence of the jump in W_λ with the change from the Ondřejov coudé instrument to HEROS is suspicious, there is no other reason to dismiss it as spurious. Almost equally large variations are seen within the coudé instrument data alone, e.g. around JD=50 500. The various emission lines with $V/R \neq 1$ may indicate long-term V/R variability in the order of 1 % due to a weak global density wave pattern in the disk. But in the three years observed with HEROS no change was observed. Also, the invariable differences in V/R between various lines (Fig. A.2) do not match the cyclic V/R behaviour expected from density waves (Hanuschik et al. 1995).

ζ Tau (= HR 1910 = HD 37 202) was observed 1991 with FLASH, 1993 to 2000 with the Ondřejov coudé, and finally 1998 and 2000 to 2002 with HEROS. It is a binary with a period of about 133 d (e.g. Harmanec 1984).

Inspection of lines with little circumstellar contribution, such as He I 4009, 4026, or 4713, favours $v \sin i = 320\,\mathrm{km\,s^{-1}}$, given by Yang et al. (1990, see also Fig. A.3), over lower values also sometimes published. In the strongest of these lines, He I 4026, the orbital motion is clearly apparent also in the broad, supposedly photospheric component. The circumstellar shell itself is also variable with narrow, but strong absorption in 1998, becoming broader and shallower in the following years (Fig. A.3).

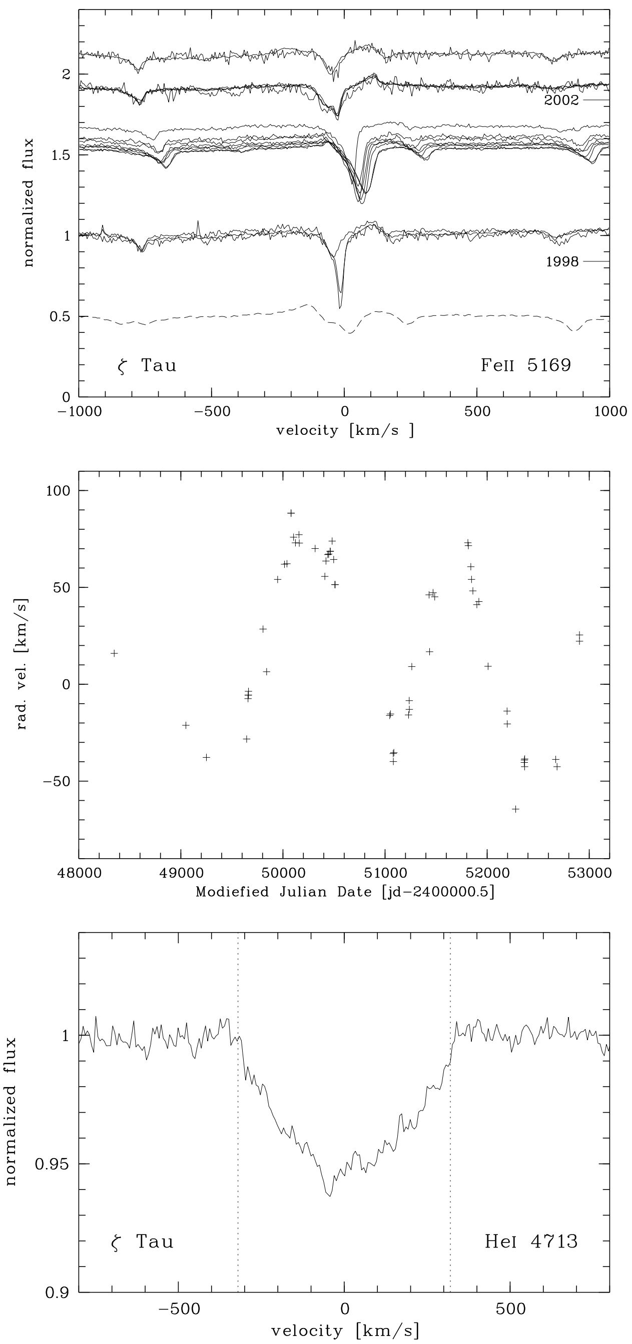


Fig. A.3. The evolution of the circumstellar shell Fe II lines of ζ Tau observed with FLASH/HEROS is shown in the upper panel. The spectra have an offset upwards proportional to time, except the 1991 spectrum, which is included as dashed line. The radial velocity curve of the Si II 6347 shell absorption, including also the Ondřejov data, is plotted in the middle panel. The lower panel displays He I 4713, relatively unaffected by the shell, and two dotted lines at $\pm v \sin i = 320\,\mathrm{km\,s^{-1}}$.

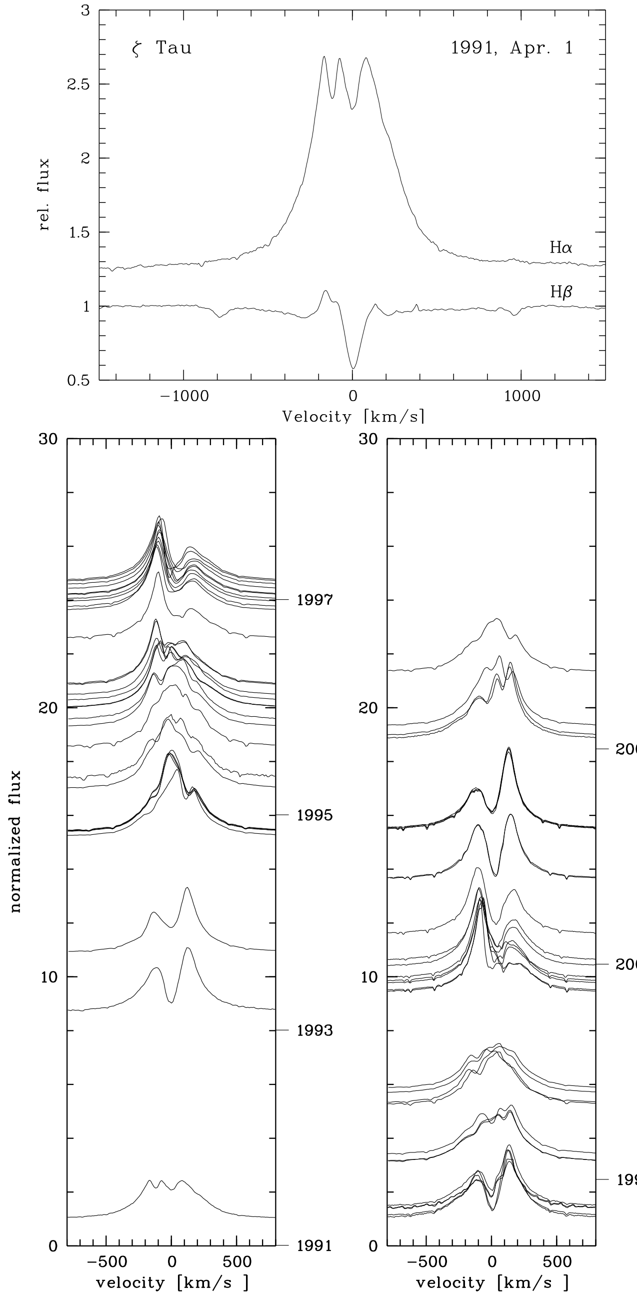


Fig. A.4. Triple-peaked profiles in ζ Tau. The upper panel shows the spectrum taken on April 1, 1991. Note that strong telluric absorptions exist in the red part only of Hα. The evolution of the Hα line from 1991 to 2003 is shown in the lower panels. The vertical offset of the profiles is proportional to time and corresponds to one continuum unit per 1/4 year. The lowermost spectra were taken Apr. 1, 1991 (left) and Aug 19, 1998 (right), respectively . Triple peaked profiles occur when the V/R ratio changes from < 1 to > 1.

In the past years, ζ Tau continued its long-term V/R variations with cycle lengths of about 4 years. This is also reflected in the radial velocities (RV) of the shell lines, e.g., Si II 6347; 2 cycles of remarkable similarity were recorded (Fig. A.3). A formal period analysis of the Si II 6347 RVs yields 1503 ± 18 d, removing almost all power from the power spectrum. The binary motions, for which the present data suggest a period of 134.6 ± 0.6 d with a semi-amplitude of $10\,\mathrm{km\,s^{-1}}$, only rank as the third-strongest feature, after the first harmonic of the 1503 d cycle.

On April 1, 1991 a very unusual Hα profile was observed, which was found later also in Ondřejov coudé observations in 1996 and 1999 (Fig. A.4). Similar profiles were seen already 1982 by Hanuschik et al. (1996) and ascribed to disk distortions due to the companion. However, the occurrence of this peculiar type of profile does not correspond to any special phase of the ephemeris given by Harmanec (1984). Rather, it appears linked to a change of the V/R-ratio from $\ll 1$ to $\gg 1$ (cf. Fig. 1 of McDavid et al. 2000). According to Telting et al. (1994), such a behavior is consistent with a prograde precessing density wave (see also Vakili et al. 1998). It occurs when the dense part of the global wave is behind the star as seen from Earth, so that the V/R ratio changes from smaller to larger than unity.

Such a peculiar profile was seen to accompany a change in sign of $\log(V/R)$ also in ν Gem, which like ζ Tau is a binary. But contrary to ν Gem the positions of the peak substructure in ζ Tau were not stable in radial velocity (Fig. A.4).

Similar profiles were reported also for ϕ Per (Galkina 1990), which is another binary with V/R variations seemingly unrelated to the orbital motions. Two profiles in the present database confirm this. In the current theoretical understanding of Be star disks, these types of profiles cannot be understood in a purely geometrical way (Okazaki, priv. comm.), but ask for a refinement of the dynamical models with the help of spatially resolved data, as from interferometric observations.

HR 2142 (= HD 41 335) shows periodic shell absorptions, similar to ϕ Per, and is a binary with $P = 80.86$ d (Peters 1983). However, the nature of the secondary is not entirely clear. It could either be a hot subdwarf, causing the same phenomenon as in ϕ Per (Waters et al. 1991; Hummel & Štefl 2001), or a mass-transferring cool star, in which case the shell absorption would arise from the mass-transfer stream passing the line of sight (Peters 2001). In the latter case the inclination would be less than about 77°, since no eclipses are observed, which would make the listed $w = 0.79$ a lower limit, but probably not much less, since then the mass-transfer stream would not intersect the line of sight (under the assumption that orbit and stellar rotation are co-planar). In this sense, HR 2142 is kept in Table 1.

In addition, HR 2142 is a V/R variable. But because of the orbital variations of the Balmer lines this is better visible in Fe II and similar lines, which are relatively unaffected by the companion.

ν Gem (= HR 2343 = HD 45 542) is part of a very close visual pair ($< 0.2''$) with a magnitude difference of the order of 1 mag, for which micrometer, speckle and lunar-occultation observations are available (e.g. Blow et al. 1982; Baize 1992; Mason 1997, and references therein). It was also reported to be a spectroscopic binary with $P = 40.198$ d, $K = 19.9\,\mathrm{km\,s^{-1}}$ and $\gamma = 34.7\,\mathrm{km\,s^{-1}}$ (Jarad et al. 1989), but the authors caution that the "period may well be spurious". Our data were taken from 1994 to 2003 and clearly confirm strong radial velocity variations. The Ondřejov coudé and HEROS data (Table 2), however, cannot be sorted with the 40-d period, but with 53.72 d (Fig. A.5). Older photographic data by Jarad et al. (1989, 21 points spanning 475 days in 1983–1985) are unfavourably distributed to permit a check on the 53-d period; some points do not fit the corresponding radial velocity (RV) curve. There are 39 older measurements from 1919 to 1932 by Harper (1934) that thus cannot be co-phased with the present data. However, although the measurements are of a different line and their errors are large, they are consistent with the 53.7-d period, in the sense that they provide an RV curve similar to the one in Fig. A.5 when phased with that period.

Accordingly, ν Gem has at least three components: the main system Aa+Ab with $P = 53.72$ d and the speckle component B, orbiting Aa+Ab in about

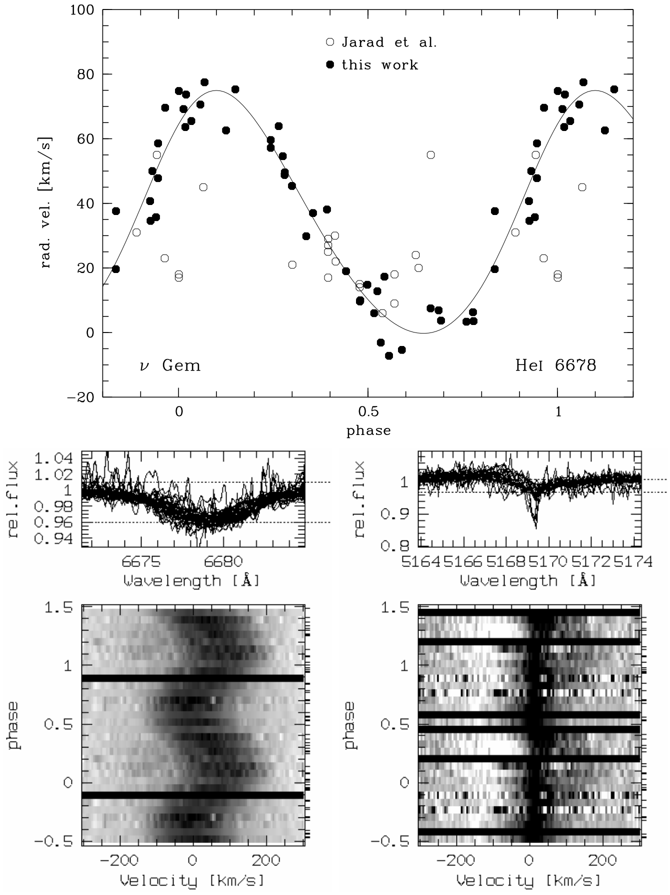


Fig. A.5. Upper panel: He I 6678 radial velocity curve of ν Gem (Table 2), phased with $P = 53.72$ d. The parameters of the radial velocity curve plotted are listed in Table A.1, VELOC solution. Open symbols mark photographic measurements taken 1983–1985 by Jarad et al. (1989). Lower panels: Photospheric lines like He I 6678 are RV variable, while circumstellar shell lines like Fe II 5169 (only covered by HEROS spectra) do not follow this period, although an underlying stellar component can be seen to vary.

Table A.1. Binary parameters derived from the radial velocities (RVs) of ν Gem (Fig. A.5) and ϵ Cap (Fig. A.14) by means of VELOC (Schmutz, unpublished, e.g. used also by Schmutz et al. 1997) and FOTEL (Hadrava 2002). Since the eccentricity is zero for ϵ Cap, T_0 denotes the time of maximal RV. The VELOC and FOTEL solutions agree very well within their errors.

Star	γ $[\frac{\mathrm{km}}{\mathrm{s}}]$	K $[\frac{\mathrm{km}}{\mathrm{s}}]$	P [d]	T_0 JD	ϕ $^\circ$	e	code
ϵ Cap	−8.9	8.7	128.5	51030	–	0.00	VELOC
ϵ Cap	-9.2 ± 0.2	8.8 ± 0.3	128.3 ± 0.2	51029.1 ± 0.6	–	0.00	FOTEL
ν Gem	34.4	37.6	53.733	51005	316	0.11	VELOC
ν Gem	34.5 ± 1.1	38 ± 8	$53.731 \pm .017$	51004.7 ± 4.2	315 ± 29	0.11 ± 0.05	FOTEL

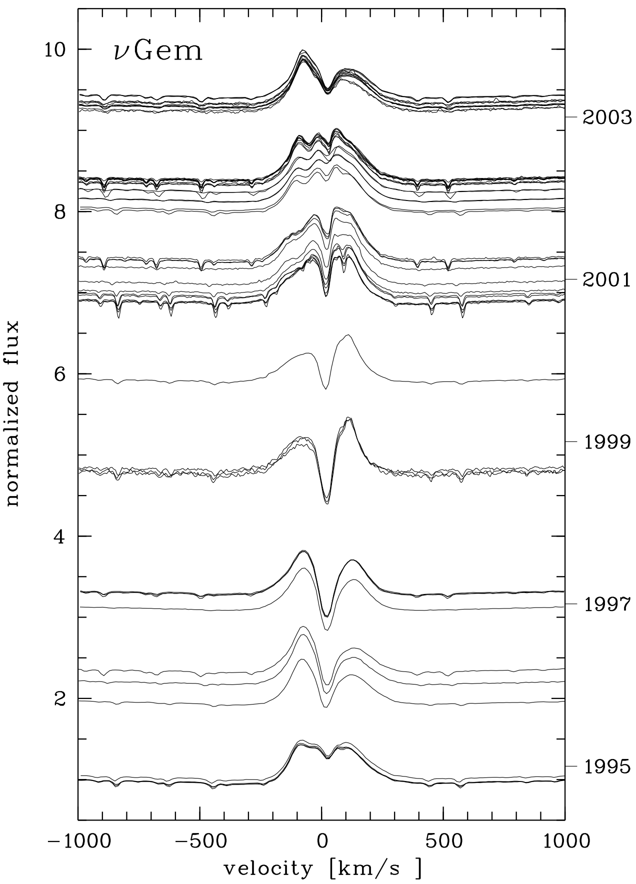


Fig. A.6. Line profiles of Hα of ν Gem. A vertical offset of one flux unit corresponds to one year. The first spectrum was taken Nov. 2, 1994. Note the remarkable similarity of the Hα profiles in 2002 to that of ζ Tau in 1991 (Fig. A.4). Both stars are binaries. The red peak of the late 2000 profiles is affected by strong telluric absorption.

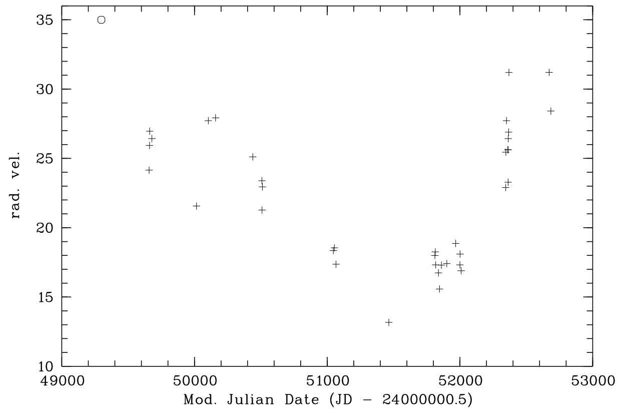


Fig. A.7. Radial velocity of the Hα core of ν Gem. The circle was taken from Hummel & Vrancken (1995).

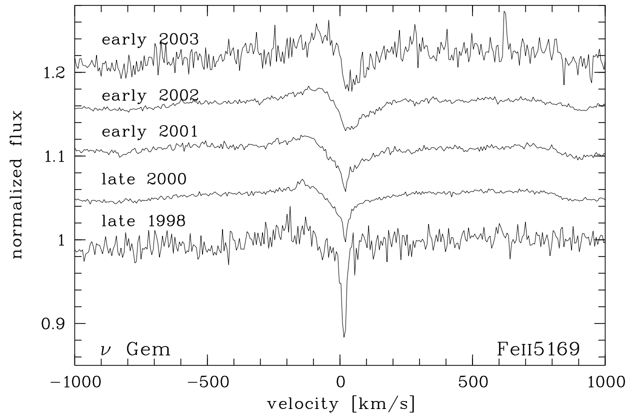


Fig. A.8. Mean circumstellar shell component of the spectrum of ν Gem in Fe II 5169. This spectral range is covered by HEROS data only. Note the early 2002 profile, which is similar to the Fe II profile of ζ Tau in 1991 (Fig. A.3), as are the Hα profiles.

a decade. Conspicuously, the circumstellar lines, i.e. Balmer emission and shell lines, do not take part in the 53.72 d orbital motion, but only show secular motion (Figs. A.5 to A.8). This poses the question of whether the disk surrounds the entire Aa+Ab system, or if the shell star is component B. Given the relatively long period of 53.72 d, the former hypothesis is unlikely. In addition, the depth of the shell absorption of only 10 % in Fe II is, judging by bona fide single shell stars, very small relative to the strength and shape of the Balmer emission (Fig. A.6). This, too, does not support the possibility of the shell absorption forming on the line of sight towards the primary Aa+Ab components of ν Gem. Consequently, the spectrum of type B6 III with $v \sin i = 170\,\mathrm{km\,s}^{-1}$ would not belong to the emission line star. In fact, such a $v \sin i$ is extraordinarily low for a shell star (see Table 1). Therefore, spectral type B8 III is adopted for the shell star, following the classification by Mason (1997) of component B.

For the speckle-resolved subsystem, i.e. A+B, Mason (1997) gives an eccentricity of 0.923 ± 0.010. Hence one should expect large RV variations around the periastron times ($T_0 = 1983.51 \pm 0.05 + E \times 13.00 \pm 0.17$) in the spectral features arising from component B, namely the line emission. Owing to the period of 13.00 years, the periastron itself would always be unobservable (the sun being only a few degrees away in early July). But the spectra taken in 1996 on Jan. 22, Mar. 16, Nov. 23, and Dec. 22 do not show a trace of such a behaviour, either (Table 2). Fig. A.7 illustrates the actually observed smooth RV curve of the sharp absorption core in the Hα emission line (which should follow component B). It appears to be inconsistent also with the provisional orbital elements by Baize (1992, $e = 0.86, T_0 = 1986.44 + E \times 11.70$).

These proposed orbital motions cannot explain the RV variations of the sharp absorption core in the Hα emission line. Instead, the disk oscillations causing the V/R variability might explain the smooth RV curve of the sharp Hα absorption.

The peculiar Hα profile observed in Mar./Apr 2002 (Fig. A.6) is reminiscent of the disturbed profile of ζ Tau observed in 1991 which, too, is a binary. Previously, Hanuschik et al. (1996, ; see also Hummel & Vrancken (1995)) observed towards the end of 1993 the onset of a phase with a similar triple-peaked Hα emission profile, which after nearly 3 months was fully developed. For the present project ν Gem was observed from Nov. 15 2001 to Feb. 16 2002 with the Ondřejov coudé instrument and from Mar. 5 to Apr. 4 2002 with Heros, i.e. 140 days, with the RV-stable triple peaked profile present in all spectra (Fig. A.6) . The blueshifted emission minimum resided at $-52.4 \pm 1.5\,\mathrm{km\,s^{-1}}$ all the time. The occurrence of such a peculiarity is, therefore, not dependent on the phase of the Aa+Ab 53.7-d orbit. This is the same conclusion as for ζ Tau where, furthermore, there are reasons to attribute it to the V/R variability.

β Mon A (= HR 2356 = HD 45 725,) is one of the longest observed shell stars. It used to be V/R variable in the past (Cowley & Gugula 1973; Telting et al. 1994), but the cycle seems to have stopped and only marginal asymmetries are present in our data, taken during January 2000. The spectrum of β Mon A showed CQEs in lines like Ti II 4824, as well as very narrow and deep cores in profiles like the one of Fe II 5169. Another spectrum of β Mon A was obtained in the framework of the Paranal Observatory Project (POP[1]) with UVES in March 2001. The V/R ratios are mostly unity also in this spectrum, at best as asymmetric as in ψ Per (see Fig. A.2).

[1] http://www.eso.org/santiago/uvespop/

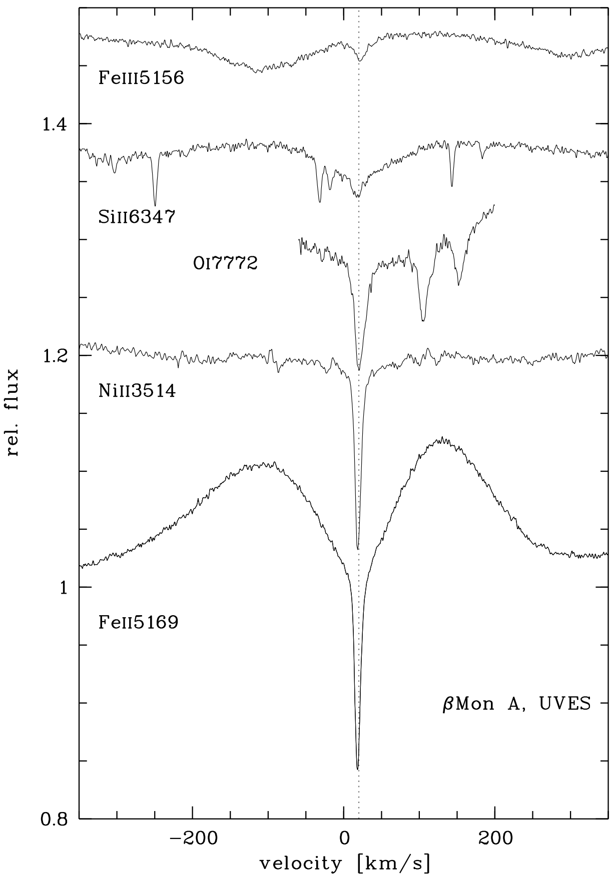


Fig. A.9. Narrow shell lines in the UVES spectrum of β Mon A. These lines are seen in our own Feros data as well, but are fully resolved only by UVES. The dotted line marks the systemic radial velocity given in the GCRV, $20\,\mathrm{km\,s^{-1}}$ (Wilson 1953). Narrower absorptions around the Si II 6347 line are of telluric origin.

The UVES spectrum covers the range from 310 to 1060 nm. In the blue region, not observable with Heros and Feros, various strong and again very narrow shell lines can be attributed to Ni II, most notable at 3514, 3577, and 3769 Å. Fig. A.9 presents such shell absorptions for five different ions.

The star is part of a visual multiple system, with periods of the order of at least millenia (Abt & Cardona 1984). Since this cannot have influence on the Be star, it is not listed as binary in Table 1. The core velocities of the sharp shell absorptions are stable in all our data as well as in the UVES spectrum and agree well with published values for the systemic velocity.

27 CMa (= HR 2745 = HD 56 014) has one of the strongest metallic shells among early-type Be stars. In most of our spectra there are almost no uncontaminated stellar lines. Of the shell stars listed by Slettebak (1982) it has the lowest $v \sin i = 150\,\mathrm{km\,s^{-1}}$, indicated as uncertain, however. The rotational velocity could, therefore, be underestimated. Indeed, recent spectra

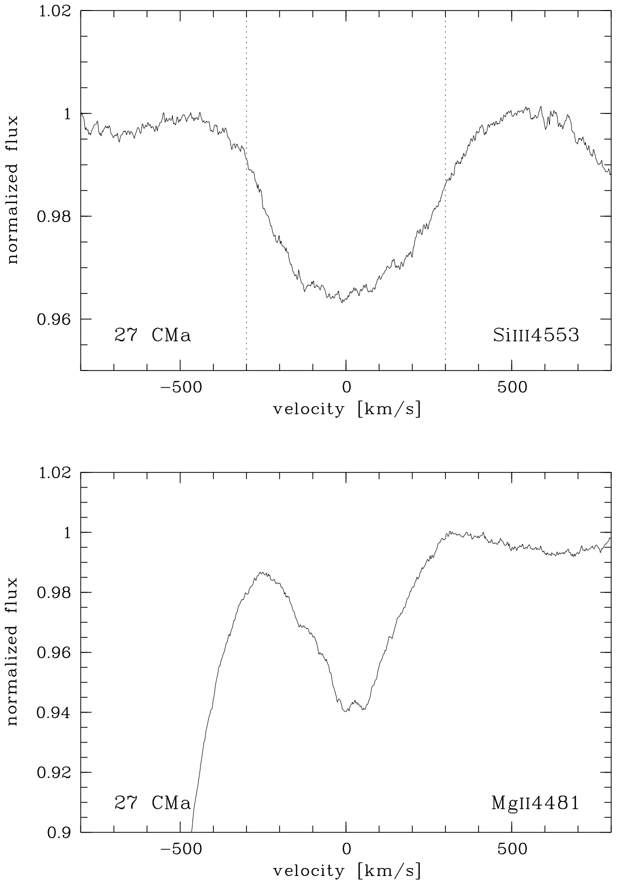


Fig. A.10. Averaged profiles of spectral lines of 27 CMa in 2000. An almost uncontaminated line, indicative of a stellar $v \sin i$ of at least $300\,\mathrm{km\,s}^{-1}$ is shown in the upper panel. The lower profile has intermediate shell contribution, a typical CQE can be seen.

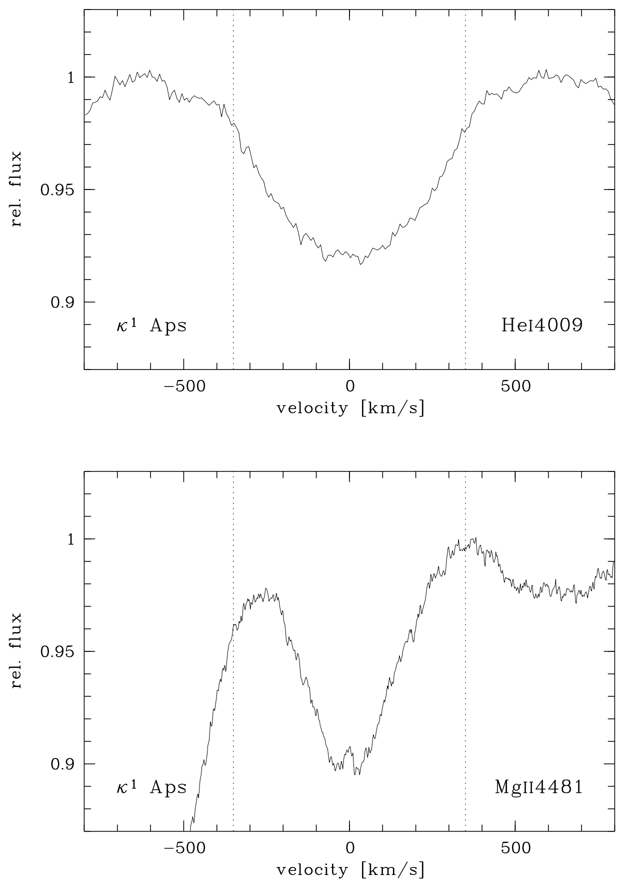


Fig. A.11. Photospheric profile (upper panel) and sample CQE (lower panel) of κ^1 Aps in the 1999 season. $v \sin i = \pm 350\,\mathrm{km\,s}^{-1}$ is indicated by dotted lines. Lower $v \sin i$ values may have resulted from the contamination by narrow shell absorptions.

taken with Feros do reveal a few lines hardly affected by the shell, like C II 4267, N II 3995, and Si III 4553. These profiles have a full width of about 600 km/s (Fig. A.10, upper panel), favouring about twice as fast an equatorial rotation as estimated during a strong shell phase. Chauville et al. (2001), too, derived a $v \sin i$ of $280\,\mathrm{km\,s}^{-1}$. Some weaker shell lines, like several Fe II transitions or Mg II 4481, show a clear CQE signature (Fig. A.10, lower panel).

HR 4123 (= HD 91 120) is confirmed as a shell star (first reported by Hanuschik 1996). The circumstellar Fe II lines show a typical shell profile, with the absorption cores being below the ambient stellar continuum. The S/N of the spectra is not high enough for an unambiguous detection, but some Fe II lines might have CQE-type profiles.

HR 4221 (= HD 93 563) possesses a shell only slightly stronger than that of HR 4123. The Fe II lines do not have CQEs but show flat-bottom profiles, which are intermediate between classical shell absorptions and CQE-type profiles (for theoretical and observational examples see Hanuschik 1995 and Rivinius et al. 1999, respectively).

39 Cru (= HR 4823 = HD 110 335) exhibits strong Balmer and Fe II emission. The central absorption core of the Fe II lines is only marginally below the local continuum. The object was classified as a shell star by Hanuschik (1996).

κ^1 Aps (= HR 5730 = HD 137 387) is an obvious shell-type star, with CQEs in most He I and some other lines, like Mg II 4481 (Fig. A.11, lower panel). The star was observed quite intensively in 1999 (49 spectra taken May-July). But the peculiar variability in line width between 250 and $350\,\mathrm{km\,s}^{-1}$ described by Slettebak (1982) was not present. The photospheric profiles affected least by emission favour the higher $v \sin i$ of $350\,\mathrm{km\,s}^{-1}$ (Fig. A.11, upper panel).

θ CrB (= HR 5778 = HD 138 749) was extensively studied with IUE by several investigators (e.g. Underhill 1985; Doazan et al. 1986). This B6 III star became particularly interesting when the shell signature due to the circumstellar matter faded and finally disappeared in 1980.

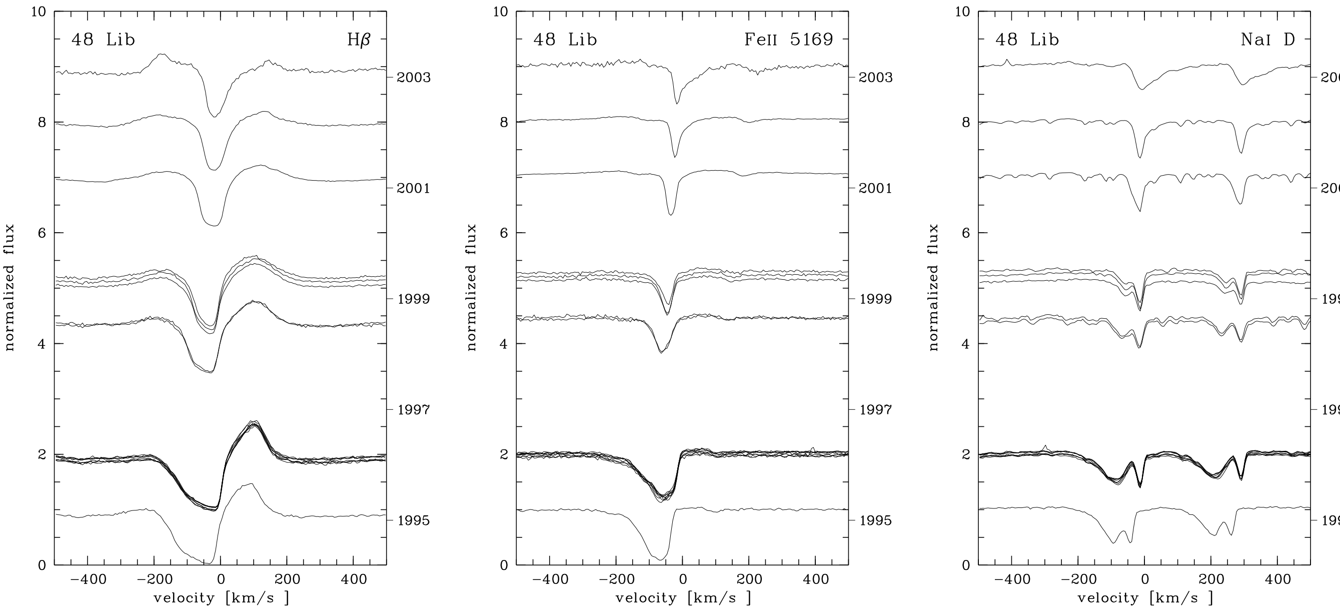


Fig. A.13. Evolution of Hβ, Fe II 5169, and Na I D shell absorption in 48 Lib between 1995 and 2002.

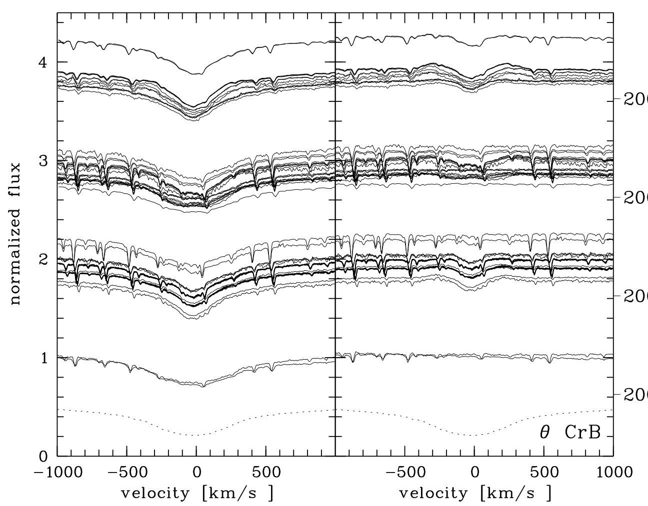


Fig. A.12. Evolution of the Hα profile of θ CrB from 2000 to 2003. A vertical offset of one flux unit corresponds to one year. The first spectrum was taken May 16, 2000, the last one on Aug. 11, 2003. The mean of the 1991 Tautenburg data is shown as a dotted line for comparison. The apparent absence of telluric lines is due to the lower resolving power of R=12 000 of this spectrum instead of 20 000 as in the later data. In the right panel the residuals are plotted w.r.t. the Tautenburg 1991 data, which is repeated for comparison.

Since then, the star has been in a stable B-star phase, in the UV and optical spectral range indistinguishable from a normal rapidly rotating B star. Several, mostly photometric monitoring projects covered θ CrB in case it became active again (e.g. Fabregat & Adelman 1998; Percy & Bakos 2001).

θ CrB was observed from Tautenburg in 1991 and 1992 with FLASH, with the Ondřejov coudé instrument 1993 to 2000, and with HEROS from Wendelstein in 2000 as well as from Ondřejov since 2001. The Tautenburg, Ondřejov coudé, and Wendelstein data show the purely rotational Hα profile present since 1981. By 2001 February, the spectrum had developed a weak shell signature with a rather broad core. This signature remained stable until May, then disappeared in July. In March, 2002, a weak and broad CQE-type signature was present in the core of Hα. This signature finally disappeared in April, 2002 (Fig. A.12). In February, 2003, however, a circumstellar contribution is visible again. Only Hβ showed a similar, but weaker shell effect, while no other line reflected this brief and weak shell episode.

Although the disk signature is feeble and only transiently present, it seems that the star has restarted its circumstellar activity (see Panko & Tarasov 2000, for comparison with *o* And). It remians to be seen if θ CrB will develop a stable shell or if the current observations show a failed attempt at disk build-up. Photometric monitoring in the 1999–2002 period did not reveal any changes (Adelman 2002) so that the amount of accumulated material was probably too small to reduce the continuous light by a measurable fraction.

4 Her (= HR 5938 = HD 142 926) Koubský et al. (1997) published an extensive investigation. They showed that Hα V/R and its shell radial velocity as well as the RVs of other shell lines follow a 46.18 d period. They interpreted it as a binary period and derived orbital elements. However, they concluded that a Roche-lobe filling secondary, even as cool as 3500 K is ruled out. The spectral coverage of their data did not permit them to look for a hot sdO companion similar to that one in ϕ Per.

Our data (the Ondřejov spectra partly overlapping with the ones of Koubský et al. 1997) confirm the 46.18 d periodic variations of the shell and emission line characteristics. Just the emission had decreased from $W_\lambda \approx -6$ Å at the end of the observations of Koubský et al. (1997) in early 1997 to $W_\lambda \approx -1$ Å in mid 1999, only to climb again to $W_\lambda \approx -5.5$ Å in the following season, then having remained unchanged at least until March 2003.

A search for similarities to other stars with confirmed or suspected sdO companions remained unsuccessful also in our data. Our blue Heros spectra allowed us to search for a He II 4686 line of the suspected sdO secondary. Due to the much lower temperature of 4 Her, compared to ϕ Per and 59 Cyg, the detection of He II 4686 should have been easier. However, even in the phase-averaged Heros spectra of 4 Her, no trace of such a He II 4686 feature could be found. The orbital interpretation of the 46.18 d variability in 4 Her as well as the nature of its secondary component still needs to be further investigated.

48 Lib (= HR 5941 = HD 142 983) has a very strong shell, rendering the determination of the spectral type uncertain. In the past decade, the strong and unusually broad shell absorption observed in 1995 has weakened and narrowed (Fig. A.13). This broad absorption was not present in observations by Hanuschik et al. (1995, taken 1985 to 1993), but only in 1995 and 1996. The absorption reached velocities as high as -200 km s^{-1} projected against the stellar surface in the line of sight, with a similarly large dispersion (Fig. A.13, lowermost panel). During these years, additional moving narrow absorption components were observed by Hanuschik & Vrancken (1996).

In the past 50 years, 48 Lib underwent long-term V/R cycles of 11.8, 6.8 and recently 9 years (Okazaki 1997). The current cycle started 1990 at $V = R$, with $V > R$ until 1994, as reported by Hanuschik et al. (1995). After that, the red peak was dominant for almost eight years (see Fig. A.13). In particular, in the beginning of 2003 the $V/R_{\mathrm{H}\alpha}$ was still larger than 1, but decreasing, while $V/R_{\mathrm{H}\beta}$ was already less than unity. This points to a very asymmetric V/R cycle, or to a change in cycle length.

88 Her (= HR 6664 = HD 162 732) possesses a strong shell with relatively narrow absorption lines, mainly seen in hydrogen and Fe II. The shell absorbs up to 30 % of the stellar flux in the strongest Fe II lines of multiplet 42. Shell absorption is weakly apparent in Si II or O I. The red peak in Hα is slightly higher than the violet one.

ϵ Cap (= HR 8260 = HD 205 637) was reported by Rivinius et al. (1999) as double with a possible period of 95 d derived from shell-line radial velocities. In the first half of 1999, 28 additional spectra were obtained with Heros and Feros. Re-analysis of the radial velocities of the absorption core of Hδ and the addition of more recent data show that a period of $P = 128.5$ d

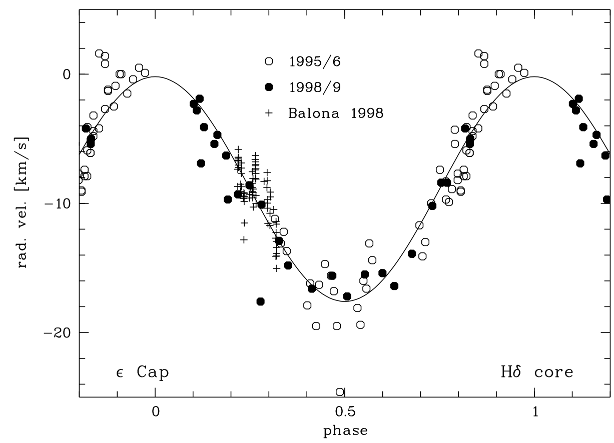


Fig. A.14. Periodic radial velocity variations of the Hδ absorption core of ϵ Cap, sorted with $P = 128.5$ d. The parameters for the plotted radial velocity curve are compiled in Table A.1 (Veloc solution). Additional points were measured by us in 76 spectra taken over two weeks in Sep. 1998 by Balona (2002).

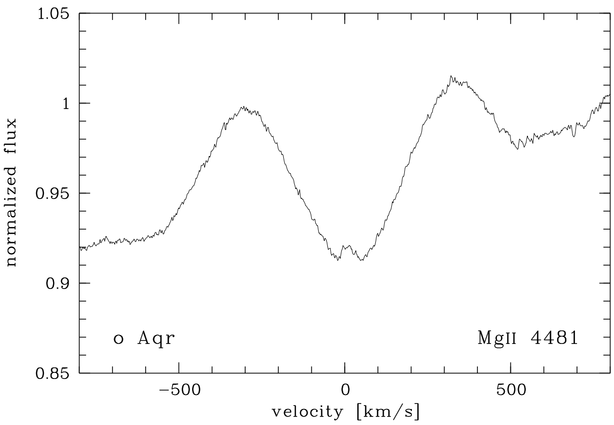


Fig. A.15. CQE in the Mg II 4481 profile of o Aqr in 1999.

sorts the data better; 96.3 d is a seasonal alias (Fig. A.14 and Table A.1). Since part of the RV curve is not well covered by our observations; the uncertainty might be as high as ±2 d, although the formal error is smaller (Table A.1). The radial velocities of the CQEs in ϵ Cap trace well the RV curve of the shell absorption cores. This confirms that CQEs are markers of the stellar radial velocity (Rivinius et al. 1999).

o Aqr (= HR 8402 = HD 209 409) displayed remarkably narrow and deep shell lines of Fe II already in 1993 (Hanuschik 1996). Between then and 1999, the disk seems not to have undergone any changes. In addition to the narrow shell absorption, Mg II 4481 shows a clear CQE (Fig. A.15).

EW Lac (= HR 8731 = HD 217 050) was observed a few times with Heros and more than 60 times with the Ondřejov coudé spectrograph. Similar to o Aqr, the Fe II multiplet 42 shell-absorption lines are too narrow to be resolved with Heros. The hydrogen shell absorp-

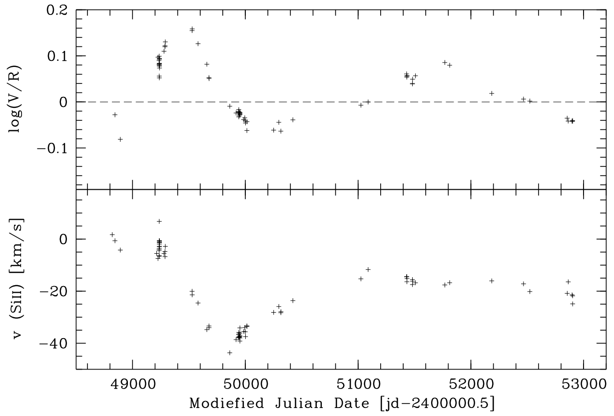


Fig. A.16. V/R ratio of Hα and radial velocity of the Si II 6347 shell absorption of EW Lac. Note the strong cycle-to-cycle variations of amplitude and cycle length.

tion reaches zero intensity even for the higher Balmer lines up to H10.

The star is a weak V/R variable. The cycles are strongly different from each other in length and amplitude (Fig. A.16). The $\pi/2$ phase shift between the radial velocity of the Si II shell line and the Hα V/R ratio is explained well by a global density wave (cf. model computations by Hummel & Hanuschik 1997).

***o* And (= HR 8762 = HD 217 675)** had strong and broad metallic shell lines in 1998 (Rivinius et al. 1999). They were absent in 2000 to 2002, although CQEs were still seen in, e.g., Mg II 4481; Balmer emission was generally weaker than in 1998. The results of an ongoing, more in-depth investigation will be published elsewhere.

Appendix B: Stars with emission ⇔ emission & shell transitions

***γ* Cas (= HR 264 = HD 5394)** went through a cycle of shell phases in the 1930s (see Hummel 1998, and references therein). The so-called "giant outburst" of γ Cas in the mid 1930s was part of this pattern, with the emission peaks highest outside the shell phases (Underhill & Doazan 1982). Since then, γ Cas was not observed to show shell behaviour.

Recently, Harmanec et al. (2000) have shown the star to be a single-lined spectroscopic binary with a low amplitude of about 5 km s^{-1} and a period of 203.59 d. Harmanec (2002) analyzed the photospheric wings of the He I 6678 line and gave a $v \sin i$ of 380 km s^{-1}, while Chauville et al. (2001) derived even $v \sin i$ = 432 km s^{-1}.

In our data, taken between 1996 and 2003, the presence of the above orbital period is confirmed, as is the large width of He I 6678. The star continued its long-term V/R cycle (Fig. B.1). No line in the observed wavelength range would have justified a shell classification in this period. As in other stars (see Baade 1985, for a summary) the V/R cycle undergoes phase lags between different lines, which is seen best when V/R changes from R-dominated to V-dominated (and vice versa) in some lines earlier than in others (Fig. B.2). In the frame of the global density wave pattern such phase lags are explainable by a (trailing) spiral geometry (Okazaki 1991 was the first to propose a spiral pattern; later McDavid et al. 2000 suggested it to explain phase lags in 48 Lib). The density pattern is, then, not at the same azimuth for all radii, so that the bulk of (e.g.) He I 6678 emitting plasma, close to the star, crosses the line of sight earlier than the bulk of Hα emitting plasma does, farther away from the star. A similar behaviour is apparent for 28 Tau (Fig. B.3) and 48 Lib (Appendix A, 1998 data).

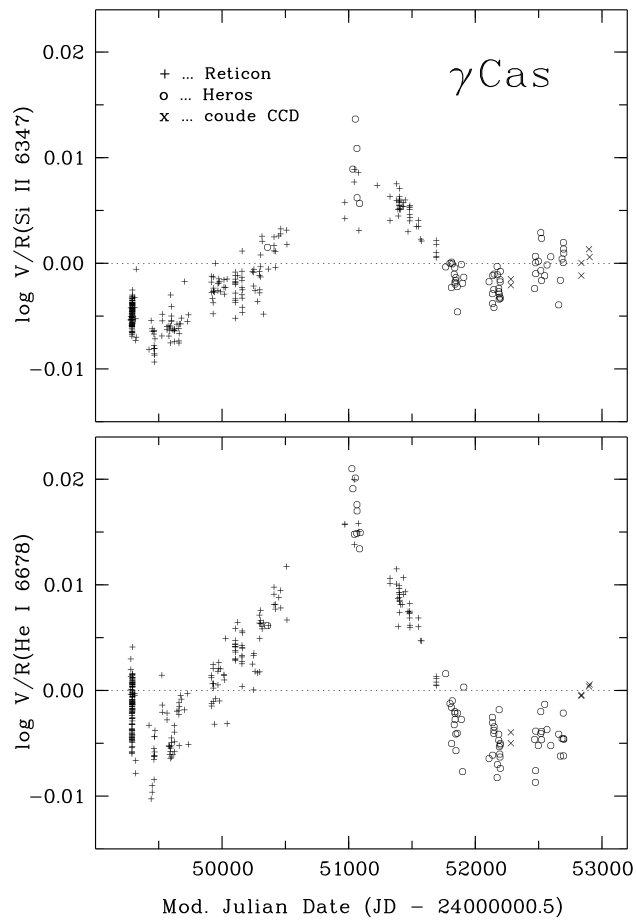


Fig. B.1. V/R peak height ratios observed in Si II 6347 and He I 6678 of γ Cas.

28 Tau (= HR 1180 = HD 23 862 = Pleione) is a well-observed Be star. The last shell phase ended in 1988 (e.g. Ballereau et al. 2000), although absorption was still visible in our FLASH spectra taken 1991 in a few Fe II lines, but not all of them. Because of their limited wavelength coverage of the Hα region only, the available 32 Ondřejov coudé spectra obtained between 1994 and 2000 do not permit the disappearance of

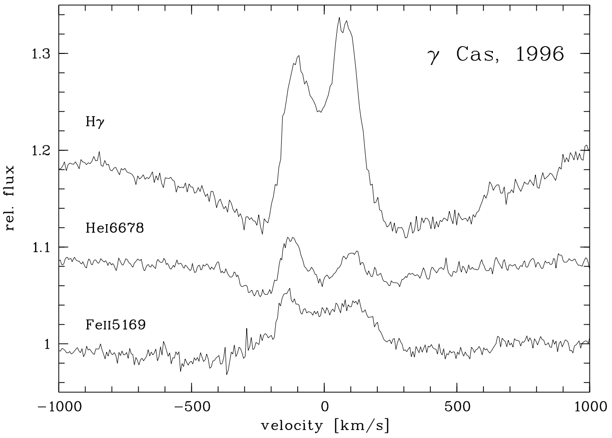


Fig. B.2. A spectrum of γ Cas on JD=50358, showing different V/R ratios in different lines. This indicates a trailing spiral structure of the density wave causing the V/R variations (see Appendix A about γ Cas for detailed explanation). The red absorption wing of Hγ is blended with another Fe II emission line

these Fe II shell absorption remnants to be traced. But a set of Heros spectra obtained in 1998 unambiguously showed that the shell signature had completely vanished.

In addition, Pleione is subject to a very strong cyclic V/R variability that affects not only the peak heights but even the filling-in of the absorption wings of the Balmer lines (Figs. B.3 and B.4). Inspection of He I and metal lines does not show their radial velocities (RV) to be variable. This excludes orbital motions as the cause of the variability of the Balmer line wings.

The 218-d period reported by Katahira et al. (1996) could not be confirmed from the present data. Therefore, 28 Tau is not listed as a binary in Table 1.

The long-term trend of the Hα emission reported by Pollmann (2003) is confirmed by the present data. But they do not cover the claimed sudden breakdown and recovery of the line emission. On the other hand, only 10 days before Pollmann's measurement of $W_\lambda = -5$ Å (JD=51585.36), we observed $W_\lambda = -29$ Å (JD=51575.28, last profile taken in 2000 in Fig. B.4). Since a Keplerian disk cannot dissipate in so few days, an independent confirmation of the unusual behavior of Pleione as reported by Pollmann (2003) is needed.

59 Cyg (= HR 8047 = HD 200 120) exhibited two shell phases in the mid-1970s (Hummel 1998, and references therein). The phenomenology of these shell phases was the same as in γ Cas, and also very similar to the one of Pleione. The star was observed by us in 1998 and from 2000 to 2002. In addition, about 30 Ondřejov coudé spectra were taken between June 1994 and November 1999.

The published $v \sin i$ values range from 260 km s^{-1} (Slettebak 1982), 379 km s^{-1} by Chauville et al. (2001) to 450 km s^{-1} by Hutchings & Stoeckley (1977), con-

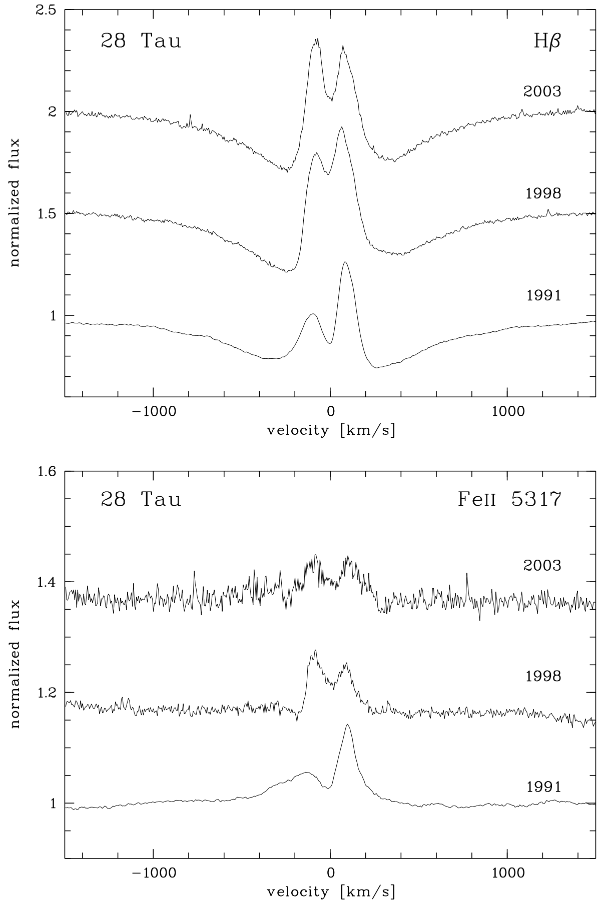


Fig. B.3. The changes of the emission profile of Pleione between 1991 and 2003. Note the strong variable asymmetry of the Balmer absorption wings vs. the V/R ratio of the emission, which in Fe II is ahead of Hβ, while in Hα the red peak even in 2003 is till higher than the blue one (Fig. B.4).

firmed by Harmanec et al. (2002b) and Maintz (2003). For Table 1, 379 km s^{-1} was adopted as a lower limit.

59 Cyg underwent strong V/R variability in the past, which was still weakly present in 1998, but had completely ceased by 2000. Since then, the profiles have been symmetric, except for variability phase-locked to the orbit.

The binarity was confirmed by Rivinius & Štefl (2000), who found a period of about 27.17 d and an RV amplitude of 27 km s^{-1}. Because of striking phenomenological similarities to ϕ Per, the companion was proposed to be an He-sdO star. Harmanec et al. (2002b) improved the period, gave a smaller amplitude and put the nature of the companion into question. However, Maintz (2003) meanwhile detected a He II 4686 absorption. Because of its radial velocity variations it can undoubtedly be attributed to a very hot, small companion; the larger RV amplitude of the primary is also confirmed. A detailed publication is in preparation.

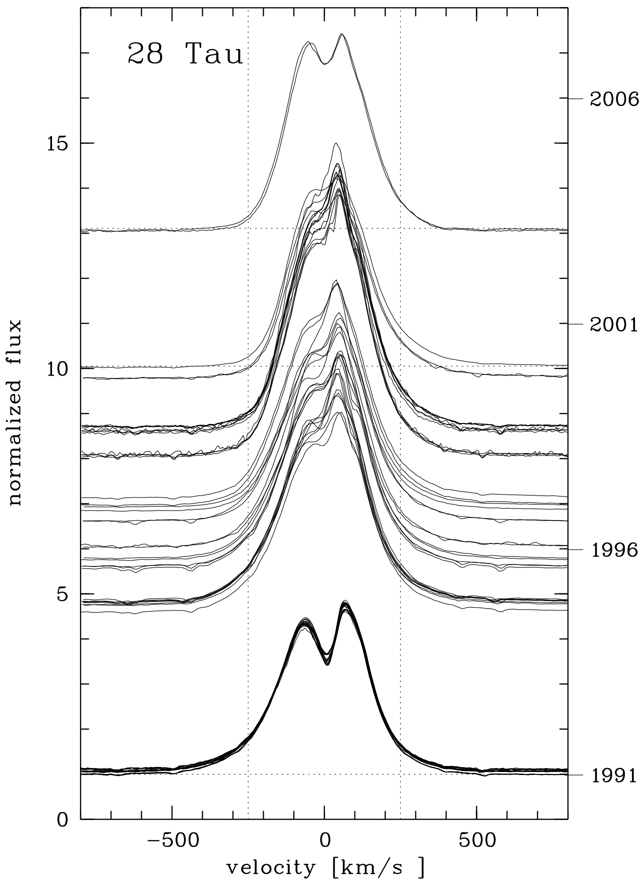


Fig. B.4. Hα line profiles of 28 Tau. A vertical offset of one flux unit corresponds to one year. The first spectrum was taken Jan. 8, 1991, the last one on Feb. 15, 2003. Horizontal lines mark the continua of the first and last spectra, and the one with the most pronounced red displacement of its base. Vertical lines at $\pm 250\,\mathrm{km\,s^{-1}}$ are to visualize the secular shift of the emission base towards the red.

Appendix C: Bn stars with weak disk absorption signature

The search for rapid line profile variability included 19 Bn stars, i.e. rapidly rotating B stars without a record of line emission.

In three of these stars observed in 1999, namely 1 Sco, 2 Sco, and possibly also η Aqr (Fig. B.5), subtle distortions of the Hα line profiles were observed that are reminiscent of CQEs. Similar weak CQEs are seen also in the Balmer lines of classical Be shell stars, when the disk is about to form (e.g. o And, Doazan 1976, Panko & Tarasov 2000; and η Cen, Baade 1983), or when it simply is extremely weak (θ CrB, Fig. A.12).

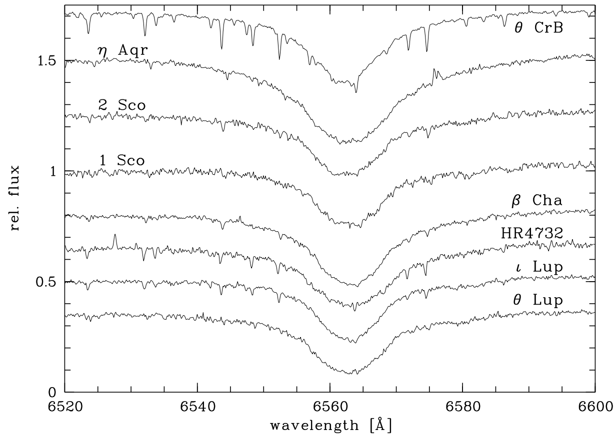


Fig. B.5. The Hα lines of the Bn stars 1 Sco, 2 Sco, and η Aqr observed 1999. The line cores show a CQE-like deformation, which is known also from Be stars in a weak disk state (cf. θ CrB, Fig. A.12). Several Bn stars with normal Hα profiles are plotted in the lower part for comparison, a spectrum of θ CrB showing such a profile distortion in the upper part.