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Central quasi-emission peaks in shell spectra and the rotation of disks of Be stars*

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Abstract. New high-resolution echelle spectra are presented for all 6 B-type stars currently known to exhibit so-called central quasi-emission peaks (CQE's). Empirical requirements are derived on the circumstances which favour the appearance of such features. The presence of a circumstellar disk seen edge-on is the most important. Furthermore, the disk should be optically thin in the continuum, have a small spatial extent, and show little line broadening.

Both this set of conditions and the observed line profiles are compared to a model by Hanuschik (1995) for the formation of shell lines in circumstellar disks with Keplerian rotation. This model predicts not only the existence of CQE's, but also the same actual circumstances of their occurrence. They result from the local minimum at zero radial velocity in the fraction of the stellar disk that is occulted by circumstellar gas in Keplerian orbital motion, i.e. by gas moving perpendicular to the line of sight. In particular, CQE's are in spite of their name not related to any emission process but are a pure absorption phenomenon. All currently available observations of CQE's are consistent with this model, which appears to have considerable diagnostic potential for the understanding of the structure and dynamics of Be star disks. Only one of the 6 stars (ν Pup) was not previously known to ever have displayed shell or only emission lines. But the new Hα and Hβ profiles clearly show the presence of variable amounts of circumstellar matter. Previously suggested photospheric explanations for CQE's are nevertheless briefly examined.

In a given star, CQE's seem to appear with the highest probability at times when the innermost regions of the disk are being re-supplied with matter.

With the success of Hanuschik's model, CQE's furthermore become one of the most important indicators of rotational support of disks of Be stars. Together with other evidence for rotation compiled from the literature, this leads to the conclusion that models for the formation of disks need to include a mechanism for sufficient angular momentum transfer. In the context of Hanuschik's model for CQE's, the considerable acceleration inherent to wind-compressed disks (WCD's) presents an additional difficulty for the WCD model in its basic form.

Key words: line: profiles – line: formation – stars: emission-line, Be – stars: circumstellar matter – stars: mass-loss

1. Introduction

In the past two decades, snap shot observations of B and Be stars have revealed that a few of them exhibit a special type of line profiles, in which the central part of the line core exhibits a weak local flux maximum. These so-called central quasi emission peaks (CQE's) were as a distinct phenomenon first noted by Baade (1990).

Five of the six stars, in which CQE's have been found to date (cf. Table 1), are known Be stars. But there is also one object, namely ν Pup, that did not so far have a record of observed emission or shell lines. Furthermore, the features were first identified in lines of He I (early-B sub-types) and of Mg II (late B stars) considered to be primarily of photospheric nature. Therefore, all previously mechanisms suggested for their formation assumed a photospheric origin of the CQE's, which is unrelated to the Be nature (Baade 1990, Jeffery 1991, Zorec 1994).

These models are based either on the variation of local line strengths caused by the equator-to-pole variation of effective gravity and temperature in the presence of rapid rotation (Baade, Jeffery), which is a distinctive property of Be stars, or on differential rotation (Zorec). However, in his detailed model atmosphere calculations, Jeffery could reproduce CQE's only with the additonal assumption of thermal polar caps, for which there is presently no physical justification. Differential rotation would be less of an *ad hoc* ingredient but has not so far been required for the explanation of other observations of Be and shell stars. These early models (see also Baade 1990 had already in common that they did not seek an explanation of CQE's in terms of line emission but rather hypothesized a local deficit in absorption.

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A first hint, that the search for an explanation of CQE's should probably be extended beyond the photosphere, was given by 4 Her: In this star, CQE-like features were observed only in shell lines (Koubský et al. 1993). However, whether the two phenomena can be identified with one another, so far remained open.

Since the detection of CQE's requires relatively large spectral resolution, most of the available small datasets only cover few spectral lines. Accordingly, they probe a limited range of atmospheric conditions and do not permit a full assessment of the possible origin(s) of CQE's. Therefore, series of new cross-dispersed echelle spectra were obtained of all 6 stars currently known to display these features; they are described in Sects. 2 and 3. Empirical criteria for the occurrence of CQE's are established in Sect. 4. Since it turns out that a proper calculation of line transfer in stellar disks in the presence of rotation is essential for their understanding, the introduction of the model (Hanuschik 1995) used for this purpose is deferred to Sect. 5. Sect. 6 adds in other indications from the literature that disks of Be stars are, in fact, rotationally supported, and Sect. 7 briefly examines this point and the significance of CQE's in connection with models for the formation of Be star disks. The main conclusions are summarized in Sect. 8.

2. Observations

In several seasons (see Table 1), the six CQE stars were observed with the HEROS dual-channel cross-dispersed echelle spectrograph of the Landessternwarte Heidelberg. Via a fiber link, it was used with the ESO 50-cm telescope on La Silla, Chile and with the 1.23-m telescope on Calar Alto, Spain. HEROS covers more than the entire Paschen continuum (3450 Å to 8600 Å) at a resolving power of 20 000. The instrument was described in detail by Kaufer (1998). For the main program stars η Cen, ϵ Cap, and o And, the spectra were taken typically every other week, during a few runs also daily or even more frequently. For comparison, a few spectra were obtained also of well-known proto-typical shell stars.

Further spectra were exposed in November, 1998 during the commissioning period of the newly built FEROS spectrograph at the 1.52m ESO telescope (Kaufer et al. 1997, 1999) and in January, 1999 as part of the guaranteed time observations. The coverage of FEROS ranges from 3700 Å to 8900 Å with a resolving power of 48 000. Since the configuration of the CCD system was not yet fully optimized at the time of these observations, the spectra are affected by relatively numerous bad columns. However, owing to the large number of lines simultaneously observable with FEROS, this does not in any way compromise the significance of the results reported below.

All spectra were reduced according to the procedures described by Stahl et al. (1995) and Kaufer et al. (1997, 1999). Since the CQE's turned out not to be variable on time scales of a few weeks, all spectra of a given observing run (lasting from a few weeks to a couple of months) were averaged in order to increase the signal-to-noise ratio (S/N, in Table 1 given for the range from 4800 Å to 4820 Å).

Table 1. Journal of observations of CQE stars. HEROS, FEROS, and CES observations are marked with H, F, and CES, respectively. The aperture of the telescope used and the observatory (ESO and Calar Alto) are also indicated. Spectral type and $v \sin i$ were adopted from Simbad, where available; for ω Car and ν Pup $v \sin i$ was taken from the Yale Bright Star Catalogue (4th edition)

Object Sp. type $v \sin i$	Observing season	 station	No. of obs.	S/N of ave.
ϵ Cap	July 2 85	ESO 1.4 CES	1	330
B3Ve	Nov. 94	ESO 1.4 CES	4	950
274 km/s	Feb.-May 95	ESO 0.5 H	6	200
	Jan.-June 96	ESO 0.5 H	61	350
	Aug.-Oct. 98	CA 1.23 H	4	115
	Nov. 20 98	ESO 1.52 F	1	271
η Cen	Feb.-May 95	ESO 0.5 H	46	320
B1.5Vne	Jan.-June 96	ESO 0.5 H	294	700
300 km/s	Jan.-Mar. 97	ESO 0.5 H	80	420
	Jan. 6 99	ESO 1.52 F	2	260
o And	Aug.-Oct. 98	CA 1.23 H	104	280
B6IIIpe				
330 km/s				
4 Her	Aug.-Oct. 98	CA 1.23 H	2	70
B9pe				
350 km/s				
ω Car	Feb.-May 95	ESO 0.5 H	1	170
B8IIIe	Jan.-Jun. 96	ESO 0.5 H	10	370
225 km/s	Jan.-Mar. 97	ESO 0.5 H	7	200
	Jan. 99	ESO 1.52 F	4	650
ν Pup	Feb.-May 95	ESO 0.5 H	1	150
B8III	Jan.-Jun. 96	ESO 0.5 H	8	350
228 km/s	Jan.-Mar. 97	ESO 0.5 H	7	290
	Jan. 4 99	ESO 1.52 F	1	418

Additionally, data obtained at La Silla by DB and ŠS with the 1.4-m Coudé Auxiliary Telescope (CAT) and the Coudé Echelle Spectrometer (CES) were used. The data reduction was described by Štefl et al. (1995) in detail.

3. Observed properties

3.1. ϵ Capricorni

ϵ Cap (HD 205 637, HR 8260) is a well-known shell star with a considerable record of long-term variations, cf., e.g., Porri & Stalio (1988) who were also the first to report central quasi-emission features in He I$\lambda\lambda$ 4471, 5876, 6678, and Mg IIλ 4481 in observations obtained in Aug./Sept., 1986. Hα exhibited emission at a peak height of 1.3 in units of the local continuum, while the absorption core reached a normalized flux of only 0.45.

HEROS spectra from 1995 show similar structures in these lines, except that the CQE was hardly visible in Mg IIλ 4481. The features are seen in most, but not all He I lines. CQE's were not at all detected in He I$\lambda\lambda$ 3927, 4009, 4121, 4144, 5047, and hardly in He Iλ 4388. But in He I$\lambda\lambda$ 3820, 4026, 4471, 4713,

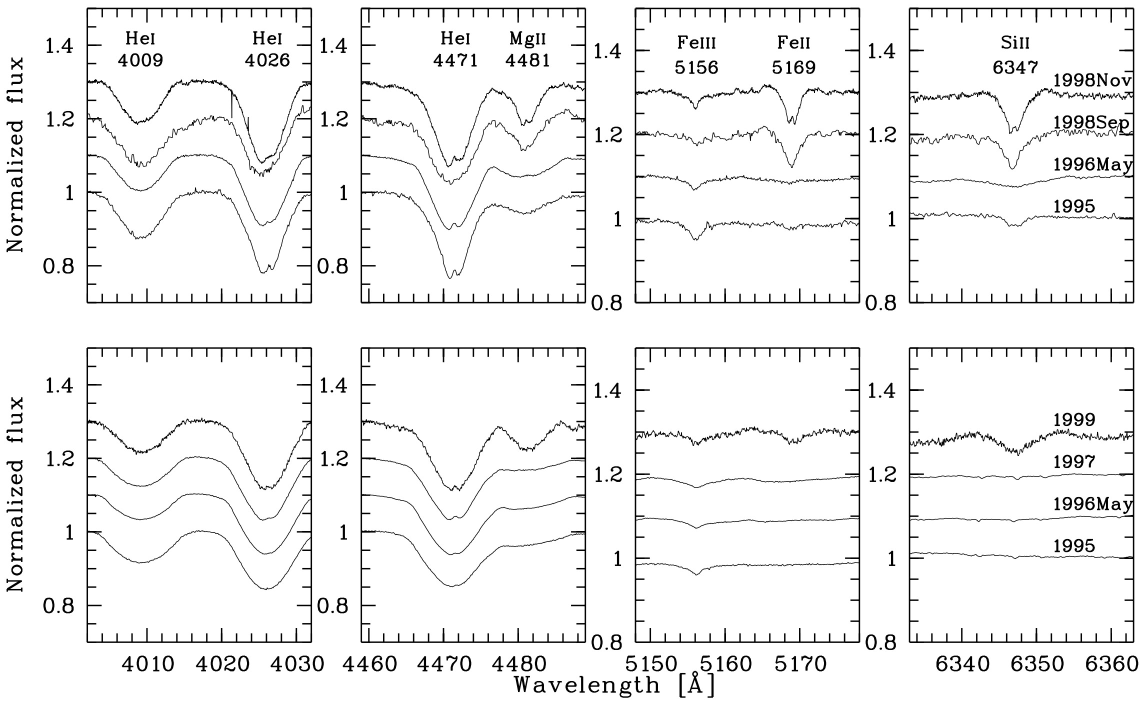

Fig. 1. Different spectral regions of ϵ Cap (*upper panels*) and η Cen (*lower panels*) in several observing seasons as indicated on the right side. Average profiles are shown for HEROS data (cf. Table 1), whereas the uppermost profiles are single spectra taken with FEROS at the ESO 1.52-m telescope. Note the presence of CQE's, which appear as small central reversals especially in He I$\lambda\lambda$ 4026, 4471 and partially also in the lines of Mg II, Fe II and Si II. Profiles of additional lines are shown in Fig. 2

4921, 5015, 5876, 6678 and 7065 they were well visible. (cf. Figs. 1 and 2 for examples). While the lines without CQE exhibit purely rotationally broadened profiles, those with CQE display some unmistakable circumstellar contribution, especially in the line wings. Pure shell lines were found in Fe III$\lambda\lambda$ 5127, 5156, Si II$\lambda\lambda$ 6347, 6371 O Iλ 8446, and weakly also in Fe II. Shell absorption is as well seen in Ca II and Na I lines, in addition to the sharp interstellar absorption cores. No photospheric wings were apparent in Paschen lines. The Si II$\lambda\lambda$ 6347, 6371 absorptions showed a remarkable profile that is described best as a broad, shallow trough with flat bottom (Fig. 1, right panel). No CQE could be detected in typical *bona fide* photospheric lines such as Si IIIλ 4553, C IIλ 4267, or S IIλ 5454.

In 1996, the strength of the Hα emission and the shell signature but also the CQE's were weaker. The remnants of these features, seen best in He Iλ 4471, are now shallow and broadened. However, the Mg IIλ 4481 line seems to have developed the CQE only now, although it is very weak and extremely broad compared to He I. In Fe III$\lambda\lambda$ 5127, 5156, and to some small extent also in Si IIλ 6347, broad line emission has developped. Photospheric wings now do appear in the Paschen lines.

By 1998 September, the spectrum had changed rather drastically. While Fe III absorption was nearly absent, shell lines of Fe II had become strong. Other probable shell lines (cf. above) also returned, but the CQE had vanished completely, so that all He I lines showed purely rotationally broadened profiles. The shell absorption of Hα was weaker, while the photospheric absorption wings were filled up by line emission.

Only two months later, on November 20, the absorption core of Hα was again deep. As the shell absorption lines strengthened, the CQE's not only returned in the He I and Mg IIλ 4481 lines, but for the first time in ϵ Cap they were also seen in purely circumstellar lines such as Si II and Fe II lines. Quantitative data are given in Table 2.

HEROS and FEROS data, together with unpublished spectra with a resolving power of 70 000 or higher obtained with the CAT/CES on La Silla in July, 1985 and November, 1994 illustrate the long-term evolution of the CQE in He Iλ 6678 over many years. They are shown in Fig. 3. In this line the CQE's can exceed 4 % of the continuum flux and their strength is variable on a time scale of months to years. Both the visual inspection of the profiles and our quantitative measurements show a clear correlation between their strength and the depth or FWHM of the parent absorption profile. The CQE is stronger when the absorption line is deeper and narrower, i.e. when the envelope's contribution to the absorption is larger. A similar trend can be seen also in Mg II and He I in both ϵ Cap and η Cen.

Three CAT/CES profiles from 1983 June of He Iλ 4471 also exhibit CQE's (in Mg IIλ 4481 even the main absorption is barely recognizable).

The decrease in the Fe III/Fe II ratio suggests a change in temperature (Fig. 1). If the concommittant increase of the Hα line emission (Fig. 2) is due to a replenishment of the disk, the disk would be cooler when denser. This could be plausible but can be concluded with some justification only if a more detailed modelling has ascertained that the lines due to the two

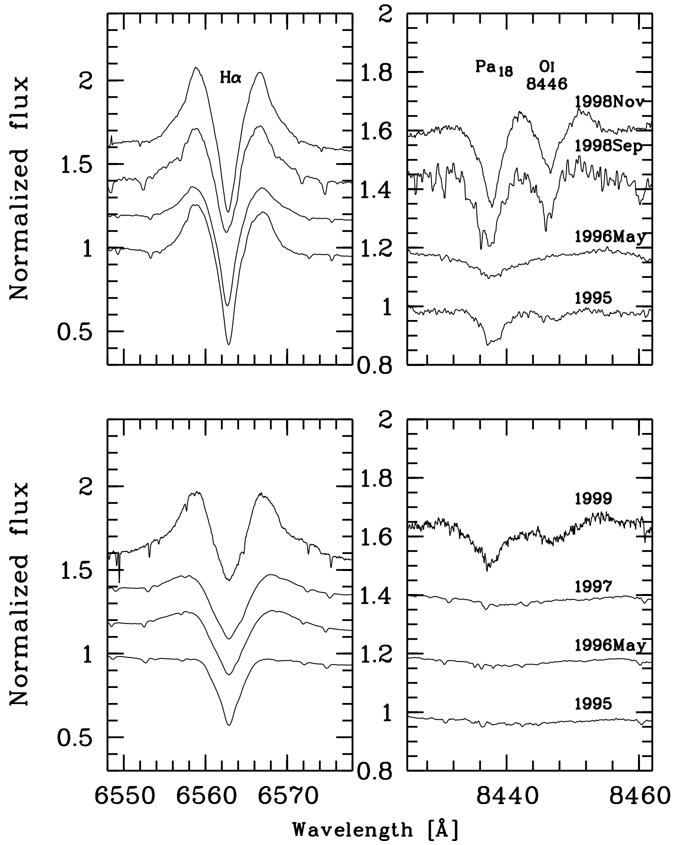

Fig. 2. Same as Fig. 1 except for different spectral regions

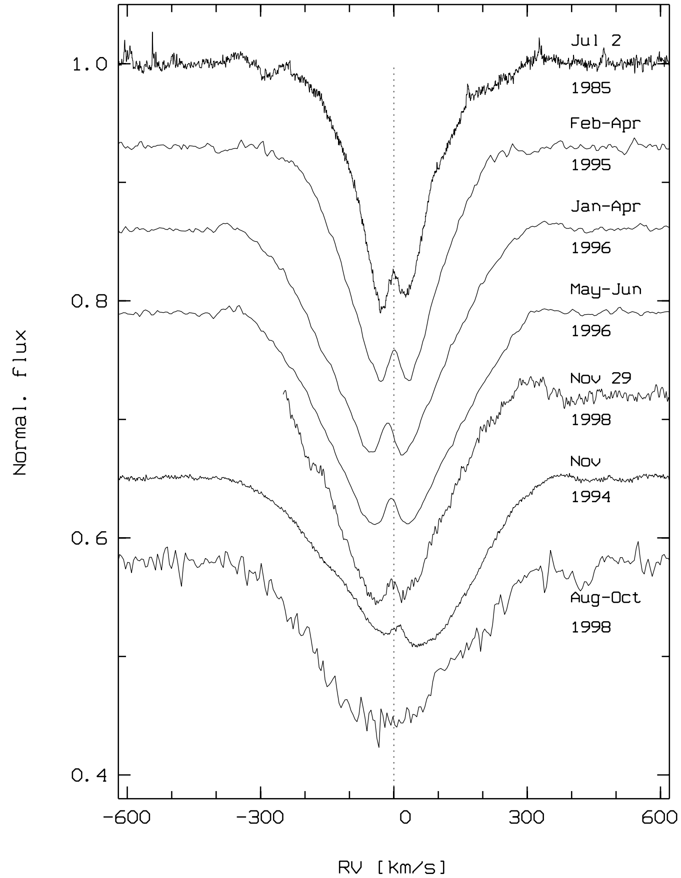

Fig. 3. Appearance of the CQE and the parent profile of He Iλ 6678 in ϵ Cap in different seasons. Profiles are arranged by decreasing depth and increasing FWHM of the absorption (from top to bottom). Note that this corresponds to decreasing strength of the CQE. The spectra from 1995 until Aug.-Oct., 1998 were obtained with HEROS, the 1998 November one with FEROS (the blue side is not plotted because it is strongly affected by bad columns of the CCD), and the others with the CAT/CES. The vertical dotted line shows the mean position of the CQE's

ionization stages do not originate from different locations at different times.

ϵ Cap is believed to be a binary with an estimated period of about 0.3 years (Abt & Cardona, 1984). The combination of all 72 spectra spanning 3.5 years supports this and indicates a period of roughly 95 days. The estimated peak-to-peak amplitude in radial velocity as derived from the CQE's is about 20 km/s.

A meaningful determination of the orbital parameters, however, is complicated by the shell-type line profile variability on similar time scales and is beyond the scope of this paper. Because of the underlying long-term variability, all measured quantities provided in Table 2 therefore refer only to a single high-quality FEROS spectrum obtained on Nov. 20, 1998.

3.2. η Centauri

The first CQE in η Cen (HD 127 972, HR 5440) was reported by Baade (1983). However, as in the case of o And (see below), they were detected in a Balmer rather than in a metallic line. Furthermore, rapid variations seemed to be present. Sorting the published data with the photometric period of 0.6424 day (e.g., Štefl et al. 1995), however, does not contradict the hypothesis of an intrinsically stable feature merely reflecting the underlying photospheric variability.

In the present data, η Cen is almost a twin of ϵ Cap (cf. Figs. 1 and 2). Before 1999, the CQE's were best visible in He I lines, in which also some shell contribution can be recognized in the line wings. The strongest shell line is Fe IIIλ 5156 in which also weak genuine emission is detected. Measurements of the temporal development of the CQE in He Iλ 4471 are compiled in Table 3.

In January, 1999 the Hα emission had become stronger. Similarly to ϵ Cap, lowly ionized shell lines of Fe II and Si II had developed (see also Table 2).

3.3. o Andromedae

o And (HD 217 675 HR 8762) was the first star for which CQE was reported (Doazan 1976) but at the time taken to be genuine emission. These features were seen in Balmer lines and rapidly variable. As in the case of η Cen, it is not clear if the structures were intrinsically variable or reflected underlying stellar variability. No subsequent study reported such features. However, shortly after Doazan's observations of CQE's, the star entered into a new shell phase (Fracassini et al. 1977).

CQE's can be recognized again in the spectra taken in 1998. But this time they are present in shell rather than in Balmer lines (see Fig. 4, right panel). The weak Hα emission with a peak height of about 1.1 looks similar to that in ϵ Cap or η Cen (Fig. 2). The absorption core drops as low as 0.2 of the ambient continuum. Lines of the Balmer series can be detected up to H26 at 3666 Å in the high-quality, averaged spectrum.

As part of a long term-monitoring programme at Ritter Observatory, K. Bjorkman (1999, private comm.) observed o And in fall 1997 and fall 1998 and found both narrow shell absorption and emission peaks. In late 1998, the emission strengthened somewhat. Peters (1999, private comm.) concluded from observations of the Hδ and Hβ regions that "a weak shell was present in mid-January" (1999). Noteworthy is also a recent report by McDavid (1999), who within only a few months of the present observations measured the highest linear polarization ever published for this star.

Previous shell episodes are known to have started in 1966, 1975, 1983, 1988 (cf. Sareyan et al. 1992), and 1994 (Harmanec 1994). For the latter event it is also known that it was accompanied by a similar rise in polarization (McDavid 1995) as observed recently. Therefore, it seems possible that a new shell phase, or an enhancement of shell characteristics, started only a short while ago. Since shell phases of o And typically last a few years, observations in the next observing season should easily confirm or reject this hypothesis.

o And is the star in which a further typical property of CQE's can be seen best. Although the absorption component of the various parent lines may have different radial velocities, the CQE's always occur at one radial velocity common to all CQE's (see Fig. 4 and Table 2).

The multiplicity of o And (Hill et al. 1988) has most probably negligible physical influence on the phenomenon. The 33-d period only concerns companion B which orbits the Be star and another, much fainter companion a, in about 30 years at least. The period of component a is still of the order of 4 years. Therefore, averaging spectra over some weeks to months does not grossly affect any conclusion about the CQE's of the Be star. Only for measurements with very high precision do the values of the derived parameters depend on the disentangling of the component spectra and would require a dedicated study.

3.4. 4 Herculis

The first report on CQE's in the shell star 4 Her (HD 142 926, HR 5938) was given by Koubský et al. (1993), a more detailed description by Koubský et al. (1997). Being visible in many shell lines, these features are present at the beginning of new shell phases, when the star is faintest. They vanish when the Hα emission strengthens. It should also be noted that the shell lines are reported to be unusually broad. Compared to classical shell stars such as ζ Tau or EW Lac (cf. Sect. 3.7), this is true of all CQE stars.

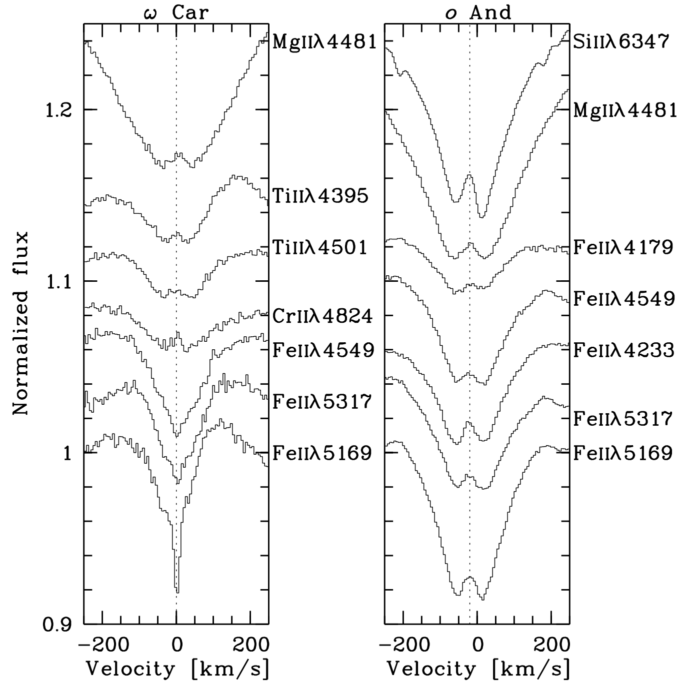

Fig. 4. Selected profiles of lines with circumstellar contributions in ω Car (*left,* 1996 data) and o And (*right,* 1998 data). The dotted vertical lines indicate the mean radial velocity of the CQE's. Note the good alignment of all CQE's even though the parent absorption profile varies rather significantly

Koubský et al. (1997) do not report any indication for a relation between the 46 day period of the probable companion and the appearance of the CQE.

In the two HEROS spectra of 1998 August, CQE's are not detectable. However, it can hardly be judged if this is so as a result of the limited S/N or because they have really disappeared (cf. Fig. 6).

3.5. ω Carinae

Central quasi-emission peaks in ω Car (HD 89 080, HR 4037) were first found by Baade (1989) in his search for line profile-variability in late-type B stars.

The Hα profile was stable during the monitoring from 1995 to 1999. Of the stars investigated here, ω Car has the strongest emission with an Hα peak height of 2 in units of the local continuum. The central absorption is rather deep, but the minimum flux is still above the continuum. CQE's are seen in partly photospheric lines like Mg IIλ 4481, being broadest there, as well as in shell lines of Ti II and Cr II. However, in Fe II, the most typical shell lines of Be stars, only deep pure absorption cores are visible (Fig. 4, left panel). Strengths and widths of the CQE's as observed with FEROS are given in Table 2.

3.6. ν Puppis

ν Pup (HD 47 670, HR 2451) was also one of the stars investigated by Baade (1989). It exhibited a CQE quite clearly in

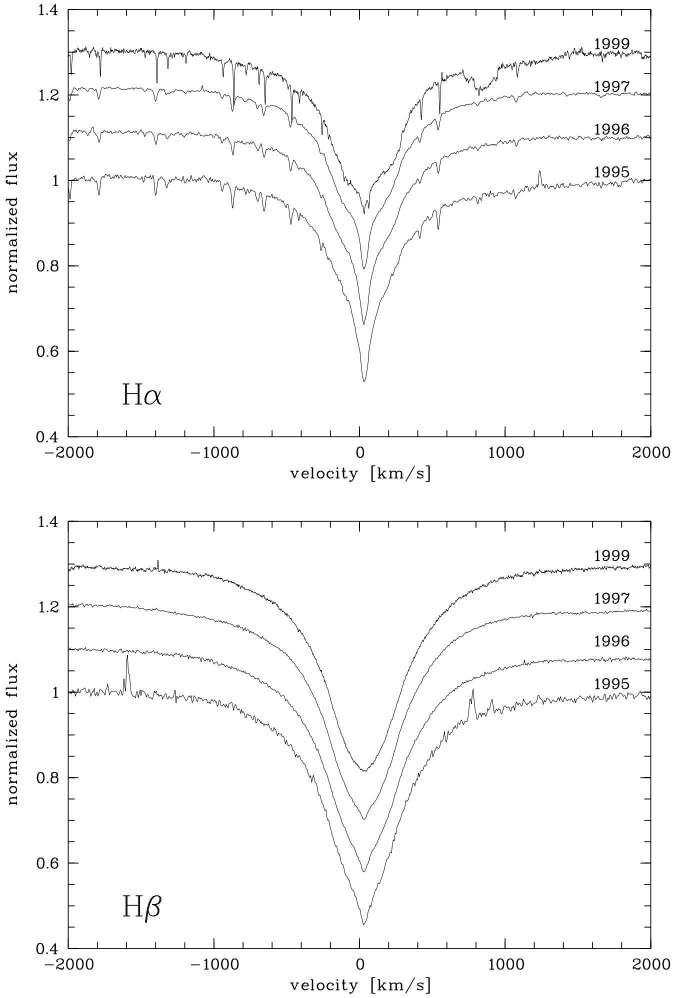

Fig. 5. Hα (*upper panel*) and Hβ (*lower panel*) profiles of ν Pup in 1995, 1996, 1997, and 1999 (from *bottom* to *top*). In addition to numerous narrow telluric absorption lines, the FEROS Hα profile at the top is affected by bad CCD columns. The temporal evolution clearly shows the presence of varying amounts of circumstellar matter

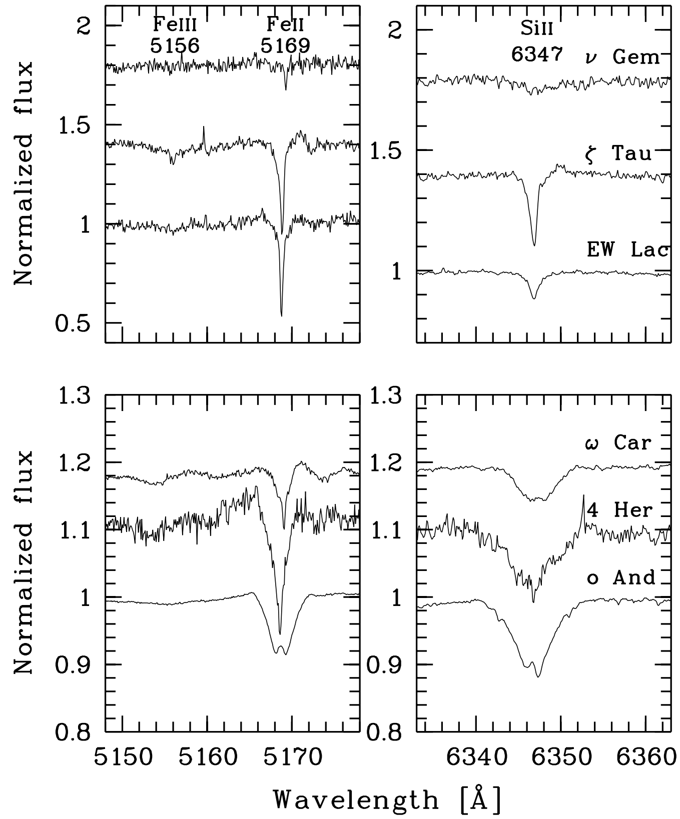

Fig. 6. Typical shell lines of late-type Be stars without CQE's (*upper panel*) and of stars with CQE's (*lower panel*). The tendency towards broader and shallower absorption in stars with CQE's is well visible

Mg IIλ 4481. No indication of circumstellar matter was, however, found in previous studies.

The HEROS and FEROS observations do not show any trace of CQE's. In comparison to the earlier spectra of Baade, it is, however, not excluded that the Mg IIλ 4481 line was deeper during his observations due to additional shell absorption, similar to, e.g., the one in ϵ Cap and η Cen (cf. Fig. 1) or to He Iλ 6678 in ϵ Cap (Fig. 3). But this could also be the result of imperfect normalization. Nevertheless, there is strong evidence that this star is a not previously recognized bright Be star. The variations of the Hα profile observed from 1995 to 1999 clearly point towards a variable amount of circumstellar matter (cf. Fig. 5); this indication is weaker but still significant in Hβ.

3.7. Comparison with other well-known shell stars

In order to permit a comparison with other, partly more intensively studied shell stars to be made, a few additional spectra were obtained during the Aug.-Oct., 1998 observations from Calar Alto. The spectra of EW Lac and ζ Tau show Balmer line profiles with nearly black absorption cores. The Fe IIλ 5169 absorptions reached down to only 0.5 of the local continuum and were very narrow but still resolved. Compared to the CQE stars, the other shell lines were also more strongly developed (cf. Fig. 6)

In contrast, ν Gem hardly shows any shell signature except in the Balmer lines and the lines of Fe II multiplet 42 ($\lambda\lambda$4925, 5018, 5169). These Fe II lines are too narrow to be resolved. The shell lines of the CQE stars are broader, incl. the Fe IIλ 5169 absorptions of EW Lac and ζ Tau (cf. Fig. 6, left panel)

The comparison with the CQE stars reveals that, although CQE's are intimately linked to shell absorptions, CQE's are not detected in all shell stars. On the one hand, this is probably due to temporal variability as not even the known CQE stars display CQE's at all times. On the other hand, CQE's, if present, could not by the current observations of EW Lac, ζ Tau, and ν Gem have been detected because their shell lines were not resolved.

Unpublished observations (by DB) at a resolving power of 100 000 and a S/N of better than 300 with the CAT/CES on La Silla of various small wavelength regions in 48 Lib (1982 July and 1983 June) do not show traces of CQE's in the shell lines contained in these spectra, nor do unpublished HEROS spectra. Similar observations of the same star in 1989 June by Floquet

Table 2. Parameters of CQE's in different stars and lines observed with HEROS and FEROS. Strength denotes the CQE peak height above the lowest point of the parent absorption profile in units of the local continuum. The peak heights are accurate to about 0.2 percentage points, the FWHM's to about 5 km/s. The error estimate of the radial velocities (RV) is about 10 % of the respective FWHM. *Note* that in ω Car, the *sharp absorption core* of Fe IIλ 5169 was measured that replaces the CQE's in Fe II profiles. The RV of the broad absorption was derived by measuring the wings at about half-depth of the profile

Line	Strength [%]	FWHM [km/s]	$v_{\rm rad,CQE}$ [km/s]	$v_{\rm rad,ABS}$ [km/s]
ϵ Cap, 1998 Nov., FEROS				
He Iλ 4471	2.1	28.2	−0.2	−27.9
Fe IIλ 5169	1.6	20.3	−2.4	−1.6
Si IIλ 6347	1.5	28.3	−0.9	−6.2
Mg IIλ 4481	0.8	30.1	5.9	−8.2
o And, 1998, HEROS				
Si IIλ 6347	2.5	38	−25	−17.9
Si IIλ 6371	2.3	37	−24	−18.7
Fe IIλ 5169	1.3	30	−21	−17.1
Fe IIλ 4233	1.2	28	−21	−18.9
Mg IIλ 4481	0.9	30	−21	−13.9
Fe IIλ 5317	0.8	31	−23	−12.3
ω Car, 1999, FEROS				
Mg IIλ 4481	1.0	36.8	4.7	+12.4
Ti IIλ 4395	0.7	26.7	−0.1	−11.7
Fe IIλ 5169	−8.4	9.5	1.4	–

Table 3. The temporal evolution of the CQE of He Iλ 4471 in η Cen

Season	Intens. CQE [%]	FWHM CQE [km/s]	$v_{\rm rad}$ CQE [km/s]	$v_{\rm rad}$ ABS [km/s]	Hα peak height
1995	0.4	34	20	−16.6	0.96
1996 Jan. – Apr.	0.5	40	15	−14.9	1.07
1996 May/June	0.4	27	10	−13.2	1.06
1997	0.8	40	10	−15.6	1.08
1999 (FEROS)	1.7	39	5	−3.1	1.35

et al. (1996) and in 1995 by Hanuschik & Vrancken (1996) are consistent with this finding.

By contrast, the Fe II profiles for some of the stars observed in 1990 February by Ballereau et al. (1995) do include indications of a marginal CQE. Therefore, a small survey of very narrow-lined shell stars at very high spectral resolution would still be worthwhile.

4. Synopsis

4.1. Empirical conditions for the occurrence of CQE's

From the database described above, it appears that several conditions are important for the occurrence of CQE's:

- The star possesses a circumstellar disk.
- The orientation is such that the star is seen equator-on and the disk edge-on.
- The continuum opacity of the disk is low, while the shell lines are opaque.
- The outer radius of the disk is small.
- The intrinsic width and turbulent broadening of the shell lines are low.

The observational evidence is, point by point, summarized in the following:

Orientation: All six stars showing CQE's are shell stars which are characterized by narrow absorption lines mostly of singly ionized metals superimposed on the spectrum of a broad-lined B star. This is now commonly accepted to be due to the combination of a rapidly rotating star with a circumstellar equatorial disk viewed edge-on. Sect. 6 elaborates more on the disk nature of the circumstellar envelope of Be stars.

Shell nature: The new observations show clearly that CQE's occur only when shell features are also present. Often they appear in typical shell lines (ϵ Cap, ω Car, o And), but also in photospheric lines with circumstellar contributions such as, e.g., emission components in the wings of He I lines of ϵ Cap in 1995. In 1998 September, the latter star provided an even more significant indication of the circumstellar connection, when the CQE's in He I lines disappeared simultaneously with the circumstellar emission components.

Dimensions of the disk: At the time of visibility of CQE's in ϵ Cap, η Cen, and o And, their H α emission was relatively weak, which is indicative of a comparatively small spatial extent of the disks from where it originates. For 4 Her it is known (Koubský et al. 1993, 1997), that CQE's are present only when the disk is in the beginning of its formation process, but they disappear later. For η Cen, Coté et al. (1996) conclude from the analysis of *IRAS* far-IR data, which were obtained when the Hα emission probably was weak, that this star's envelope was at that time, too, small.

The strength of the Balmer emission of ω Car suggests that its disk is probably the most extended one of the observed sample of stars. However, either its intrinsic density or the column density along the line of sight (or both) do not seem to be high, judging from the strengths of the shell lines. Moreover, CQE's appear with a range of prominence in different shell lines, as is demonstrated in Fig. 4 for ω Car. In this object the Fe II lines, which are supposed to be formed over the greatest range of parameters among the metal shell lines, only show narrow, pure absorption cores. Among the Fe II lines, these cores are strongest in the transitions belonging to multiplet 42, which is the one most commonly observed shell line in Be stars. By contrast, the lines of Mg II, Ti II, and Cr II, which are probably formed in a more limited region, i.e. closer to the star, do exhibit CQE's.

Thermal width: The above description of the observations shows unambiguously that CQE's are seen more easily in lines with higher atomic weight, i.e. lower thermal width. This is demonstrated best for ω Car and o And in Table 2, where the FWHM, and by implication also the potential visibility, of CQE's changes from He I to Fe II. That is, the

FWHM of CQE's in He I or Si II is larger by about 10 km/s than in Fe II. Therefore, in He I or Si II lines a CQE may appear in the form of a flat bottom of a profile rather than a local flux maximum separated clearly from the absorption wings. In a smaller number of lines this trend in FWHM can also be confirmed for ϵ Cap. To some extent, such a behaviour can also be seen in Fig. 5 of Koubský et al. (1997), comparing Mg II to the neighbouring Ti II and Fe II lines. When CQE's were reported in H I lines (ϵ Cap, o And), it was always at the very beginning of a shell phase in these lines, when the density and radius of the disk were still rather low.

Line strength: Similarly, CQE's occur preferentially in the relatively strongest shell lines, i.e. when the line opacity is high.

It is evident from the above that either this set of conditions overconstraints the formation of CQE's or the available observations are still incomplete or both. But it does provide solid, empirical guidelines for an attempt to understand CQE's in the framework of shell line formation.

4.2. CQE's and disk phase transitions

Many shell stars are known for phase transitions from a shell- to a pure Be-, sometimes even plain B-, and then again shell-type appearance (e.g., Hubert-Deplace & Hubert 1979). The typical time scale for such cycles is close to a decade. But there are also less spectacular changes in the appearance of the circumstellar spectrum, often on shorter time scales. It is likely that many of these variations are linked to the replenishment and subsequent dilution of the circumstellar disk (see also Sect. 6).

From the rather scattered observations of CQE's it is difficult to establish a temporal profile of their life cycles. But the time scales of their variability are not incompatible with those of disk phase transitions. Moreover, the cases of ϵ Cap, η Cen, o And, and 4 Her suggest that CQE's are more likely to occur around the early phases of the build-up of a new disk or when the inner disk is re-filled with matter. They would weaken and eventually disappear, once the disk has reached more sizeable dimensions and greater density. Therefore, the initial speculation (Baade 1983) that CQE's are early tracers of the recurrence of a shell is still only a conjecture but now better justifies a more systematic follow-up.

5. Comparison with models for CQE's

The above description of the observations does not by necessity lead to the conclusion, that all 6 stars owe CQE's to the same mechanism. It even leaves open the possibility, that the CQE's observed in one and the same star, but different lines, have different origins. Especially the CQE's observed in lines with or without significant photospheric contributions may form differently. However, the homogeneity of the parameters shown in Table 2 is rather indicative of a common origin. For the sake of simplicity, such mixed stellar and circumstellar explanations are not considered here. Because of the unquestionable circumstellar origin of at least some of the CQE's, the main focus will in Sect. 5.2 be on such an explanation. However, since only stellar models have been considered in the past, the next subsection first briefly re-visits some purely photospheric models.

5.1. Photospheric origin of CQE's

Jeffery's (1991) Table 2 provides specific criteria for observational tests of his model. CQE's should hardly be seen in He Iλ 4026 for any model, whereas they should be most prominent in Si IIIλ 4553, N IIλ 3995, and C IIλ 4267 for early B-type stars. However Fig. 1, left panel, shows that He Iλ 4026 is particularly likely to exhibit CQE's. By contrast, in none of the other candidate lines identified by Jeffery CQE's could be detected in any of the program stars.

In the absence of rotationally induced gradients in effective gravity and temperature (von Zeipel's theorem), Zorec's (1994) model predicts the same profile for all lines with the same intrinsic width. This is not observed. By combining differential rotation and latitudinally varying atmospheric properties, a much larger range of sets of line profiles can be generated for an otherwise fixed set of parameters. However, as was pointed out by Baade (1990) and Jeffery (1991), this would still only work for stars with intermediate inclination angles. More specifically, Jeffery states that only $\sin i = 0.2$ to 0.8 is a possible range for the formation of CQE's, the best being 0.4 to 0.6 for most models. The fact, that six out of six CQE stars are also shell stars, effectively excludes both Zorec's and again Jeffery's model since there is ample evidence that the shells around Be stars are equatorial, disk-like structures (cf. Sect. 6).

A final possibility to produce CQE's in the photosphere is a reduced polar chemical abundance of all elements showing CQE's (cf. Baade 1990). Over the broad wavelength range of the HEROS and FEROS spectra, there is no evidence of major chemical peculiarities. A still more severe problem is that, of a given ion, some lines may and others may not show a CQE. Finally, the restriction of CQE's to lines much narrower than those from the photosphere at large cannot be construed as evidence of a circumpolar origin. Fig. 3 shows that the width of a given line may vary as a consequence of the *shell* contribution to this line. Moreover, such an interpretation would be at variance with all else that is known about the formation of narrow lines in Be shell stars (cf. Sect. 6)

In summary, the present observations of CQE's do not invalidate the principles of any of the photospheric models proposed so far. But these models simply cannot account for the observations, which evidently require a circumstellar explanation.

5.2. Circumstellar origin of CQE's

Hanuschik (1995) has computed the iso-radial velocity contours of a gaseous Keplerian disk viewed edge-on and the associated fraction of the stellar disk that is occulted by gas having a given line-of-sight velocity. The scattering and absorption of stellar photons in an opaque spectral line formed in the circumstellar gas is roughly proportional to the obscured fraction of the stellar disk. This area reaches a maximum at a radial velocity $|v|_{\rm K,d,limb} = v_{\rm K} R_{\rm d}^{-1.5}$, that corresponds to the orbital Keplerian velocity, $v_{\rm K}$, at the outer disk radius, $R_{\rm d}$, projected on to the line of sight towards the stellar limb. Since geometry and velocity field are symmetric with respect to the orbital axis, two such maxima exist, namely one each at $+v_{\rm K,d,limb}$ and $-v_{\rm K,d,limb}$. Accordingly, a local minimum in absorption develops at zero velocity, which corresponds to a local maximum in flux, very much alike the CQE's. The principle is demonstrated in Hanuschik's Figs. 3 and 9; examples of the resulting line profiles are shown in his Fig. 8.

The local minimum in geometrical occultation by gas with zero radial velocity always exists in a Keplerian disk seen edge-on. Whether it leads to an observable CQE depends mainly on two basic circumstances:

Outer disk radius: Because $v_{\rm K,d,limb}$ decreases with increasing outer disk radius as $R_{\rm d}^{-1.5}$, the two line profile minima are the more separated the smaller the disk is. That is, a CQE can still be resolved even in the presence of some line broadening if the disk is small. However, if the size of the disk increases beyond some critical dimension, the separation of the two absorption maxima becomes smaller than the intrinsic line width. Then, the CQE disappears and a pure absorption core with a width corresponding to the intrinsic line width will appear instead. Since the ionization structure of the disk may change radially, "outer disk radius" actually denotes the outer radius at which a given line is formed. To some extent, this covers also the case of disks of finite thickness but not viewed exactly edge-on.

Turbulence and thermal broadening: Obviously, these two quantities need to be small in order not to reduce the contrast between a CQE and its adjacent minima beyond detectability. Lines of heavier elements are, therefore, more likely to display CQE's.

Finally, the zero-velocity condition with respect to the stellar photosphere also implies that CQE's occur at the stellar systemic velocity. Accordingly, they would supply a very reliable means of measuring variations of the latter even in the presence of other variations.

These theoretical conditions form an almost exact match of the empirical criteria for the occurrence of CQE's derived in Sect. 4.1. Because the inclination angle of all six stars considered will be somewhat different from 90 degrees and their vertical disk structure may not be the same as assumed by Hanuschik, the conclusion that the explanation for circumstellar CQE's is given by Hanuschik's model becomes even more robust.

However, although Hanuschik's model is very successful in reproducing CQE's (and shell line profiles in general), it is not physical in that it only assumes Keplerian rotation but does not predict it. This point, therefore, requires further scrutiny, which is the subject of the following section. Before that, a very abbreviated example of the practical usage of CQE's for the diagnosis of the structure of Be star disks, and especially their variability, is given in the following sub-section.

5.3. CQE's as a means to probe the disk structure

Hanuschik's (1995) Eq. 23 offers rather straightforward access to the radial disk structure, if the positions of the local minimum cusps blue- and redwards of the CQE are measured. This can be demonstrated well for the example of η Cen in 1996, when a similar outburst–relaxation sequence as in μ Cen was observed (Rivinius et al. 1998a).

Hanuschik (1995) normalized the equation to $v \sin i$. Even assuming $\sin i = 1$, the rotation velocity of the disk at $R_{\rm d} = 1\,{\rm R_{star}}$ is unknown. For a Keplerian disk this is the critical velocity, rather than the stellar rotational velocity as for a disk conserving angular momentum. As estimate $v_{\rm crit} = 600$ km/s is taken, being a plausible value for such an early B-type main sequence star. The cusp separation was measured for He Iλ 6678. These numbers were derived from data secured just after an outburst and six weeks later, just before the following outburst event. The separation of the minimum cusps $\Delta v_{\rm cusps}$ is related to the distance from the star $R_{\rm abs}$ up to which the lower levels of the respective transitions are populated. For He Iλ 6678, this is the $2^1P^0 - 3^1D$ singlet transition from 21.13 to 22.97 eV. He Iλ 6678 moreover shows weak emission peaks, that can be used to probe the radius $R_{\rm emi}$ up to which the upper level is populated sufficiently to produce net emission. Similarly, the Hα peak separation can be used to derive an estimate of the dimensions of the Hα-emitting disk. In the case of Keplerian rotation the respective equations are

$$R_{\rm abs} = \frac{\Delta v_{\rm cusps}}{2 v_{\rm crit} \sin i}^{-2/3} \tag{1}$$

and

$$R_{\rm emi} = \frac{\Delta v_{\rm peaks}}{2 v_{\rm crit} \sin i}^{-2} \tag{2}$$

The disk radius derived from the CQE as well as from the emission became larger during our observations 1996. It grew from 6.2 to $6.8\,{\rm R_{star}}$ for He Iλ 6678 absorption (CQE's) and from 7.3 to $8.7\,{\rm R_{star}}$ for the Hα emission. On the other hand, the emission radius derived from He Iλ 6678 emission started at 2.8 and grew to $4.8\,{\rm R_{star}}$. The higher outbound velocity at smaller radii is consistent with the conclusions drawn already from μ Cen (Rivinius et al. 1998a), that part of the ejected material after a burst migrates slowly outwards as a ring of enhanced density, visible as migrating emission peaks. There it merges with an already present, relatively stable disk at larger radii. It should be noted that these values are derived on the basis of simplifying assumptions, as $\sin i = 1$, and only estimated critical velocity, but the relative changes of the numbers should be reliable.

6. Keplerian rotation of disks around Be stars

The question whether disks of Be stars are rotationally supported is still considered an open issue by many. Truly mysterious appears the mechanism which would supply the necessary angular momentum transfer to the disk, since even the most rapidly rotating Be stars do not seem to reach much more than ∼70% of the break-up velocity (e.g., Porter 1996). Two reasons may explain why this matter has for a long time perhaps not been given the emphasis that it deserves. One is the realisation that Struve's concept of a purely rotational instability is not supported by the actual distribution of equatorial velocities (cf. Porter 1996). The other one is the discovery that Be stars do lose mass in a high-speed wind (cf. Prinja 1989) that is more prominent at higher stellar latitude.

However, a fair amount of at least circumstantial observational evidence that disks of Be stars are rotating has been mounting during the past couple of years, often as a by-product of other work:

Polarisation and geometrical flatness: The very presence of a disk-like, as opposed to spheroidal, geometry is with the least number of additional assumptions attributable to rotational flattening. This has for long been inferred from the intrinsic polarisation of Be stars (Poeckert et al. 1979). The constancy of the polarisation angle through all phases of disk transformation (e.g., Hayes & Guinan 1984) shows that the plane of the disk around single Be stars is constant in space and probably corresponds to the one of the equator. The final proof of the disk geometry has come from direct interferometric imaging (Quirrenbach et al. 1994).

Stellar $v \sin i$ and width of emission lines: The clear correlation between the stellar $v \sin i$ and the width of circumstellar emission lines (Slettebak 1976, Hanuschik 1989) is also most easily reconciled with an equatorial rotating disk model.

Emission line profiles: Symmetric Hα emission lines of relatively low equivalent width often show a V-shaped central absorption. Hummel & Vrancken (1999) have modelled the absorption by the circumstellar shell, taking into account the velocity shear in the shell, obscuration of the shell by the star, and the finite size of the stellar disk. They conclude that the depth of the central absorption (and consistency with interferometrically measured shell radii) requires that the parameter j in the shell velocity law $v_{\rm rot}(r) = v_{\rm rot,*} r^{-j}$ (where r is the distance from the center of the star and $v_{\rm rot,*}$ denotes the rotational velocity at the stellar surface) is on average less than 0.65 in their small sample of stars (incl. η Cen). The value $j = 0.5$ corresponds to a Keplerian disk.

Outbursts: Rivinius et al. (1998a, 1998b) have constructed a detailed temporal profile of the line emission outbursts of the Be star μ Cen, which are events of mass ejection and related to the beating of nonradial pulsation modes (Rivinius 1999, Baade 1999). It shows that matter is ejected at super-equatorial velocity which, after allowance for the relatively weakly constrained inclination angle and for plausible values of stellar mass and radius, comes at least close to the critical velocity. Kroll and Hanuschik (1997) studied somewhat less complete observations of outbursts of the same star. They find that inclusion of viscosity in the simulation of the orbital evolution of ballistically ejected matter (by some arbitrary mechanism) leads to the formation of a Keplerian disk from some fraction of the ejecta.

V/R variability and disk oscillations: Numerous Be stars undergo cyclic variations of the ratio in strength, V/R, of the violet and red components of their emission lines with cycle lengths of the order of a few years (cf. the compilation in Okazaki 1997). Okazaki (1996, 1997) and Savonije and Heemskerk (1993) have modelled this general behaviour in terms of, respectively, retro- and pro-grade global one-armed oscillations of the disk. Actual line profile variations based on such dynamics were calculated by Hummel & Hanuschik (1997). The prograde-mode version was recently given strong observational support by interferometric observations of ζ Tau (Vakili et al. 1998) and γ Cas (Berio et al. 1999) at different V/R phases. This matter is of relevance in the context of this paper as the disk oscillation models by necessity require (quasi-)Keplerian rotation.

Tilted/warped disks: Hummel (1998) recently suggested that particular peculiarities in the long-term emission-line variability of γ Cas and 59 Cyg at certain epochs may be caused by a temporary tilt or warping of a precessing disk. This explanation, too, would require the disk to be rotating.

It would be premature and, given the observed spectrum of variabilities and the importance also of non-gravitational forces, probably even wrong to conclude from the above enumeration that the azimuthal velocity law in Be star disks is strictly Keplerian. But there can be no doubt that the disks (i) are rotating and (ii) do so sufficiently much in a Kepler-like way that Hanuschik's model is based on a reasonable approximation. Accordingly, this model does provide the correct qualitative explanation of CQE's: they are due to the line transfer in a rotating gaseous envelope and the finite size of the disk of the central star.

The inverse reasoning is also valid: Since Hanuschik's model explains CQE's, it re-inforces independent conclusions that rotation plays an important role in supporting disks of Be stars against gravitational collaps. With respect to CQE's alone, this is, more strictly speaking, correct only for weakly developed disks. But, e.g., the explanation of long-term V/R variations by disk oscillations is not subject to such a limitation. Because the issue of rotation in disks of Be stars has prior to the work of Hanuschik, Hummel, and co-workers for quite some time not been very explicitly addressed, the velocity law may in some areas have been used almost as a free parameter. This may have possible repercussions. An important topic, that is worthwhile to re-visit in this connection, is the formation of disks around Be stars. This is the subject of the following section (for a recent review see also Bjorkman 1999).

7. Implications for disk formation

The transfer of matter to the disk with higher specific angular momentum than the one of matter co-rotating at the stellar equator remains unexplained by all of the above conjectures. In the case of outbursts *à la* μ Cen (Rivinius 1999, Baade 1998, 1999), it must form part of the still unknown outburst mechanism. Osaki (1999) has made a first qualitative suggestion based on the breaking of waves in the non-linear regime of nonradial pulsation. But μ Cen may not be representative of all Be stars, and even in μ Cen not all mass accumulated in the disk may be due to outbursts only. Therefore, other physical processes need to be considered that can build up disks around single stars in a more continuous fashion.

One of the few models that have attempted this to date is the wind-compressed disk (WCD) model by Bjorkman & Cassinelli (1993). It is based on the presumably line-driven, high-velocity wind which for long has been detected in UV resonance lines of Be stars viewed at a smaller inclination angle than shell stars (e.g., Prinja 1989). In the presence of rapid rotation, wind stream lines are deflected towards and concentrated about the equatorial plane. From there, part of the matter flows inwards back to the star but much of it leaves the star, so that a quasi-stationary disk-like concentration of circumstellar matter develops. However, as was pointed out before by Owocki (1997, private communication; 1998; see also Owocki et al. 1996 for a more complete assessment of the WCD model), this does not solve the angular momentum problem posed by Kepler-like rotating disks. The severity of the problem is only further emphasized by the explanation of CQE's by Hanuschik's model.

The sharpness, contrast, and degree of centering within shell lines of the CQE's should also put limits on any outflow in the disk. In a numerical simulation of the WCD model, Owocki et al. (1994) obtain an outflow velocity profile in the plane of the disk, which becomes positive (i.e., outward directed) about 1 photospheric radius above the star and accelerates roughly linearly to 400 km/s at a distance of 5 stellar radii. By contrast, the IR excess observed in numerous Be stars by the *IRAS* satellite has been used to infer an expansion velocity at the level of 10 km/s or less (Lamers & Waters 1987). A break in the energy distribution towards the mm domain suggests a truncation of the disk or a re-acceleration of the disk matter only at very large radii (Waters et al. 1991).

The ubiquity of V/R variations and inferred oscillations of Be star disks probably require that the observations cover at least one V/R cycle before the degree of centering of CQE's within the shell profiles can be properly quantified. But the sharpness and contrast of the CQE's suggest already that any acceleration within the radial range of formation of the lines concerned should not be by more than $\sim$20 km/s when CQE's are present. Otherwise, the visibility of CQE's would be much reduced by the outflow velocity gradient in the line of sight similar to the effects of turbulence or other line broadening mechanisms.

With a typical pole-to-equator outflow velocity contrast of $\sim$1000 km/s vs. $\sim$100 km/s, the bistability model of Lamers & Pauldrach (1991) might in this respect face a similar problem as the WCD model. This model is based on a rather sharp boundary in effective temperature near 19 300 K, above and below which winds are, in the Lyman continuum, optically thin and thick, respectively. In the presence of rapid rotation, the two domains could occur in one and the same star but in a region above and below, respectively, a critical stellar latitude.

However, as Lamers & Pauldrach emphasize, this model is not by itself able to produce a disk, because the equatorial velocities of Be stars are too small. Therefore, there are no detailed numerical simulations that could be used to judge whether disk outflow velocities as low as required by CQE's and suggested by the far-IR excess are possible. If the extra mechanism necessary to (a) make the bistability model applicable to Be stars and (b) provide the angular momentum transfer were co-rotating magnetic fields or nonradial pulsation-driven outbursts, the angular momentum problem could possibly be solved at the same time. But a high disk outflow velocity would still require attention. A rotating magnetic wind model has been proposed by Poe & Friend (1986).

In all chains of observations attributed to and models developed for the formation of disks one or more links are missing to make them fully self-sufficient and -consistent. But the one missing between (a) the unknown mechanism that leads to outbursts as the result of some temporary increase of the nonradial pulsation amplitude and (b) the *ad hoc* mechanism assumed by Kroll and Hanuschik (1997) presently appears to be one of the smallest ones. Moreover, at the moment, this chain is one of the very few ones that would produce a *Keplerian* disk in a relatively uncontrived way.

8. Conclusions

Central quasi-emission features seen in the absorption lines of some Be stars can be understood as being formed in the circumstellar disk. Purely photospheric models fail to reproduce the available observations. Both application of Hanuschik's (1995) parametrical model for shell line formation in a Keplerian disk and a mental principal components- and correlation-like analysis of the known properties of Be stars suggest that several circumstances strongly favour the exhibition of CQE's: The disk should be viewed edge-on, be optically relatively thin in the continuum, and have a small outer radius and little line broadening over and above the thermal width.

Under these conditions, CQE's are qualitatively explained as a line transfer effect in a rotating gaseous disk when also the finite size of the stellar disk is properly taken into account. CQE's only look like emission lines but in reality are due to the circumstance that in a rotating disk there is less line absorption and scattering at zero velocity than at slightly higher or lower velocities. Such a model and its application to CQE's has the potential for a quantitative tomography of the dynamics and structure of disks of Be stars. A promising target would be ω Car, where in different shell lines CQE's were seen at different levels of prominence.

Another worthwhile extension of the present work would be towards stars with very narrow shell lines at very high spectral resolution in order to assess the degree of commonality of the CQE phenomenon to all Be shell stars. The narrowness of the lines certainly implies a difference in geometry or size of the disk itself or in its orientation with respect to the line of sight, or both. But there could also be dynamical differences. Since, in a Keplerian disk, very narrow shell lines require a large outer disk radius, Hanuschik's model does not generally predict CQE's for such stars, unless a line is formed only in the inner regions of the disk.

The apparent applicability of a Keplerian rotation-based model to CQE's also suggests two corollaries of more general relevance:

1. Previous, often more indirect, inferences are re-inforced, that the disks of at least some Be stars are largely rotationally supported.
2. Models for the formation of such disks, that do not include the necessary star-to-disk angular momentum transfer, are incomplete.

Furthermore, the large outward acceleration in wind-compressed disks is incompatible with the explanation presented above for CQE's and could pose an additional difficulty for the WCD model in its basic form.

Finally, the times when CQE's are present in a given star may be linked to phase transitions in the evolution of the circumstellar disk. CQE's seem to be more likely to occur during the early replenishment of the innermost regions of the disk.

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