Be STARS AS NONRADIAL PULSATORS*

(Review Paper)

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Abstract. The observational status of the ubiquitous rapid variability of Be stars is summarized. The most comprehensive interpretation is obtained with a traveling velocity field and associated temperature variations. But neither the available observations nor theoretical predictions presently allow an unambiguous mode determination of these nonradial pulsations. In addition to rapid rotation, an NRP mode of low azimuthal order, $m \approx 2$, seems another prerequisite for a B star becoming a Be star. The amplitudes of these modes are variable and have been observed to decrease with some delay after an outburst. For low-order sectorial modes, NRP's therefore have the potential of explaining the three oldest unsolved problems of Be stars: the difference between Be and Bn stars (the latter do not usually have a low-order mode), the episodic component of the mass loss from Be stars, and the equatorial density maximum of their winds. Mechanisms for the transfer of energy to the atmosphere and its transformation into the kinetic energy of an outburst are discussed.

1 *INTRODUCTION*

Two major constituents make an Oe/Be system: a central OB star and an envelope around it. Already with the first Be-star model (Struve 1931) an attempt has been made (which later has not always been pursued) to explain the characteristics of the envelope as a *consequence of the properties of the central star*. Unfortunately, as we know today, Struve's assumption of the central star rotating *at* critical velocity was not correct (see Slettebak 1976). However, even without this defect, Struve's model is incomplete as it does not explain the pronounced episodic character of the mass loss from Be stars (see, e.g., Hayes 1986, Doazan 1986). Other models have therefore been suggested. But only with the recent discovery that very many Be stars show rapid photometric and/or spectroscopic variations, a new observational property of the central stars has been detected which has the potential of also explaining Be systems. The identification of this variability with nonradial pulsations (NRP's) may eventually even pave the way to identifying the proper place of Be stars among the other groups of OB stars since NRP's are fairly ubiquitous in the upper left corner of the H-R diagram (cf. Baade 1986a).

If the properties of the central stars play a decisive role, a single model probably cannot explain all B stars in which Hα line emission has ever been seen. At least initially, chemically peculiar and strongly magnetic stars as well as close binaries must be excluded in order to avoid confusion. From open clusters it is known (Mermilliod 1982, Slettebak 1985) that the majority of the remaining emission-line B stars are little to moderately evolved main-sequence stars. It is this group of stars – often referred to as the classical Be

*Based in part on observations collected at the European Southern Observatory, La Silla, Chile

stars – with which the present paper is concerned; γ Cas (B0.5 IVe; all spectral types are from Slettebak 1982) and o And (B6 III) are among their most prominent representatives. Before the implications of NRP's in these stars can be discussed (Section 5), a brief description of the general properties of the sample (Section 2) is useful in order to identify areas lacking explanation (Section 3), and a presentation of the evidence of NRP's (Section 4) is a necessity. To achieve consistency, these three steps plus the selection of the sample must be iterated because none of them can be isolated from all others. Further iterations will therefore have to follow the one attempted in this paper.

2 *GENERAL OBSERVATIONAL PROPERTIES OF Be STARS ...*

Deconvolutions have shown for different samples (Lucy 1974, Balona 1975) that the distribution function of the $v \sin i$'s of Be stars is consistent with the assumption that *all* Be stars are characterized by large equatorial velocities. However, as has been stressed by Slettebak (1976), neither the observed $v \sin i$ distribution nor individual values give rise to the suspicion that Be stars are rotating *at* critical velocity. The frequency of Be stars relative to non-supergiant B stars rises between B0 and B2 to $\geq$20 % and then decreases more slowly towards later types.

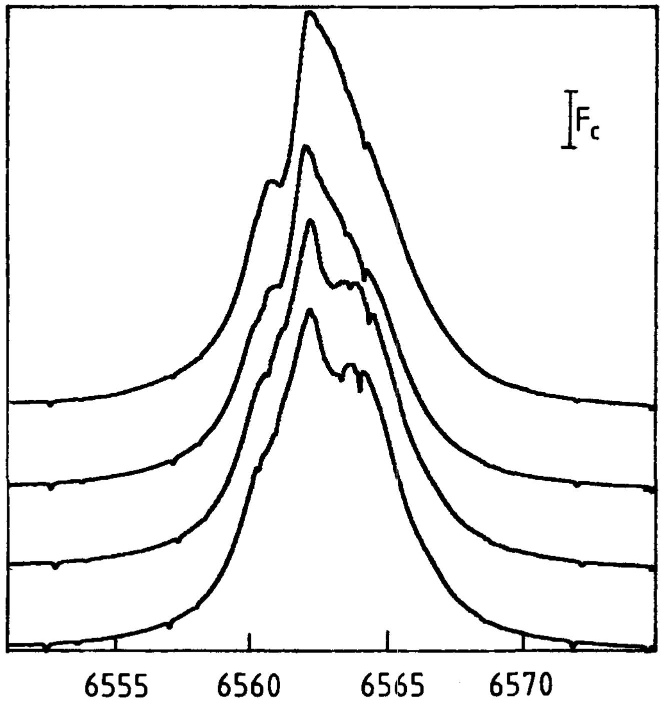
Substantial broadening characterizes also the emission lines formed in Be star envelopes. The work by Andrillat (1983) has finally established the correlation between the widths of emission and stellar lines. Oegerle & Polidan (1984) furthermore confirmed from *Copernicus* data long-existing ground-based observations that the occurrence of narrow shell absorption lines is limited to stars with the broadest lines. The high-density regions of Be-star envelopes are therefore flattened. The constancy of the polarization *angle* independent of all other variations as demonstrated by Hayes in long series of measurements of ω Ori (Guinan & Hayes 1984 and references therein) and γ Cas (Hayes 1986) additionally shows that the plane about which the envelope matter as well as most of the mass loss are concentrated maintains its orientation for years and is therefore almost certainly perpendicular to the rotation axis.

Detailed model line profiles have been calculated only for flat rotating and expanding disks (Poeckert & Marlborough 1978). Except for stars seen equator-on, the overlap of the ensemble of model profiles with the range of observed profiles is very encouraging in view of that model being mainly based on *ad hoc* assumptions. As a special case, Fig. 3g of Poeckert and Marlborough may be mentioned which for a low inclination shows an Hα emission profile with indications of *two* weak reversals. They are due to self-absorption in the near and the far half of the disk and appear at different radial velocities because of the assumed radial expansion of the disk. Fig. 1 (other examples are given by Hanuschik 1986) shows that such profiles, which are clearly difficult to reconcile with spherical symmetry, in fact exist and have considerable long-term stability. Assuming $i = 30°$, the Hα emitting envelope of δ Cen (B2 IVe) expands with $40/\sin i$ km s^{-1} = 80 km s^{-1}.

Estimates for the masses of Be-star envelopes range from 10^{-10} to 10^{-8} $M_{\odot}$. The largest Hα equivalent widths reach about 50 Å. Variations by several Å within a few months are not uncommon, which in stars with small envelopes means a variation by 100 %. Polarimetry has shown that the rise times of mass loss events are often much shorter than the phases of decline (Guinan & Hayes 1984 and references therein) and that the distribution of these events probably consists of few strong and many much weaker ones (Baade 1986c).

UV-resonance lines in Be stars often have blue edges with velocities several times faster than the ones known from optical spectra of the Hα emitting envelope. They clearly

Figure 1: Hα profiles of δ Cen observed (from top to bottom) in 1984 March, 1985 January, and 1986 January and April. The vertical bar indicates the local continuum flux. Note the two inflection points and their variability. Compare this figure with Fig. 3g of Poeckert and Marlborough (1978).



exceed the escape velocity (Snow 1982, Marlborough 1982) but usually are much smaller than those found in O stars and OB supergiants. The mass-loss rates derived *in the UV* appear to continue the general mass loss–luminosity relation of more luminous stars (Snow 1982). But while Be star winds are eventually also line-driven, stellar wind theory (Abbott 1984) is not firmly decided whether they are also *initiated* by radiation pressure. From *IRAS observations* even up to two orders of magnitude larger mass loss rates have been inferred (Waters 1986) so that Be stars would then *not* simply continue the sequence defined by OB supergiants. The assumption of an expanding disk, which is fundamental for this interpretation of the *IRAS* data, appears justified since at larger distances from the star an even faster expansion is in fact observed (cf. Fig. 1).

Be stars also show the phenomenon of discrete high-velocity components in UV resonance lines. In non-supergiants with spectral types later than ~B2, these features have been found only among the Be stars (Henrichs 1984). For Be stars, their occurence is restricted to stars with $v \sin i > 150$ kms^{-1} (Harmanec 1983b, Henrichs 1984), and like in most other stars they are substantially variable (see Henrichs 1984, Doazan 1986). The contribution of the narrow components to the total equivalent width of wind features is on the average larger in Be stars than in more luminous stars. Narrow components are mostly observed (cf. Marlborough 1982) in lines of so-called superions (i.e., ionization stages beyond the limits of photoionization by the photospheric radiation; superions are

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also well known from O stars). Recent work by Pauldrach (1986) indicates that super-ionization will eventually find its explanation in the proper NLTE treatment of the *cool* wind so that coronal temperatures, Auger effect, shock-induced collisional ionization, etc. are either excluded or only of secondary importance. From the comparison of 72 Be stars with 82 B stars without Hα emission, Barker *et al.* (1984) find that CIV $\lambda\lambda$ 1548,50 Å is seen in Be stars up to much later spectral types than in B stars (B8 versus B2).

3 ...*AND WHY THEY ARE NOT WELL UNDERSTOOD*

The Be phenomenon is evidently closely related to rapid rotation, and even though the rotation rates are too low to lead to mass loss by themselves, a fair number of processes have been suggested which in the presence of rapid rotation would be more efficient in driving mass loss. However, the existence of the Bn stars which are equally numerous as high-v sin i Be stars shows that the conditions are not in all rapidly rotating B stars such that the stars may display Be characteristics (problem I). However, not even a Be star looks always like a Be star. While the temporary absence of emission lines may be ascribed to a change of the ionization balance in the envelope, the disappearance also of shell absorption lines strongly suggests substantial variations also in the amount of circumstellar matter. This may be combined with the variability of UV resonance lines at super-escape velocities to conclude that the mass-loss rates of Be stars are variable and that at least part of the mass loss takes place in individual events (problem II).

Discrete mass loss events have also been suggested as an explanation of the narrow UV components (see Henrichs 1984) but the instabilities of line-driven winds - either intrinsic or induced by stellar variability - are another possibility (Rybicki 1986 and references therein). Regardless how they are produced, the restriction of their occurrence to stars with v sin i > 150 kms^{-1} combined with their relatively large contribution to the total equivalent widths of wind features suggests that a major *component* of the wind is confined to low and intermediate latitudes. Considering further the net intrinsic polarization, the polar directions form a zone of *partial* avoidance all the way from the stellar surface to the high-velocity region of the wind.

Perhaps, and this is strongly supported by the IRAS observations, the density of the wind decreases relatively smoothly, though rapidly, from the equator to the poles. At the same time, since the number of UV photons available for driving the wind is rather limited in B dwarfs, the terminal velocity would strongly decrease from the poles to the equator as it apparently is observed. Because of the increased density, the equatorial wind would not be driven by resonance lines but by numerous weak metal (mostly FeIII) lines as proposed by Lamers (1986) for P Cygni. (The question whether the disks of Be stars are basically a special case of a line-driven wind was independently raised by Lamers [1986, private communication] and Marlborough [1986, oral presentation of the paper included in these proceedings].) If superions are an NLTE effect, no separate region needs to be foreseen for their formation (as was done by Poeckert 1982). Barker *et al.* (1984) in fact do not find a dependence of the occurrence of the CIV $\lambda\lambda$ 1548,50 Å doublet on v sin i. - The non-spherical structure of the wind forms the third major problem posed by Be stars.

4 *OBSERVATIONAL EVIDENCE FOR NRP's IN Be STARS*

4.1 *Basic properties of stellar nonradial pulsations*

Not considering magnetic fields, there are three major restoring forces, pressure, gravity and rotation, which control the return to equilibrium of a star after some perturbation, and accordingly pulsation theory distinguishes p-modes, g-modes (these two

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are also known as spheroidal modes) and Rossby waves or r-modes. They differ in their period spectra (p-modes: generally shorter, g-modes generally longer than the radial fundamental mode, r-modes: rotational time scale) and in their velocity fields. For short-period p-modes, the ratio of horizontal to vertical amplitude, k, is small, whereas for long-period g-modes the two are comparable (see Cox 1980). Rossby waves have no vertical velocity component at all and therefore do not transport information between different radial zones of the star; they can be described as large eddies (see Saio 1982). Unfortunately, this classification system is based on the assumption that the rotation rate of the star is negligible (and that the pulsations are linear and adiabatic). This is definitely not true of any Be star. Osaki (1986b) has suggested that the eigenmodes of rotating stars may be a mixture of g- and r-modes. But concrete solutions which could be compared with the observations are not yet available.

The eigenfunctions of nonradially pulsating stars are usually separated into an angular and a radial part (cf. Osaki 1971). Only the angular part is more or less directly observable (see Sect. 4.3.1), whereas the radial one needs to be inferred from model calculations and the star's intrinsic pulsation period, i.e., the one that would be measured in the corotating frame, which requires knowledge of the rotation rate. At present it is very unlikely that the radial eigenfunctions of Be stars will soon be identified with any certainty. The angular part of the eigenfunctions is usually expressed in spherical harmonics. Photometry and spectroscopy place partly independent constraints on them. Unfortunately, very few simultaneous observations are yet available.

4.2 *Photometry*

4.2.1 *Observations*

Comprehensive descriptions of the relevant photometric properties of Be stars have been given by Harmanec (1983a) and Percy (1986a, see also 1986c). They can be abstracted to the following enumeration:

1. Most Be stars between B0 and B6 show short-term variations; a not-exhaustive list is included in Percy (1986a). At the hot end, variability almost certainly extends into the O-star domain whereas a decrease in the amplitude and/or incidence of NRP's towards later spectral types would be in line with observations of B stars without emission lines (Baade 1986a). The amplitudes are typically a few 0^m01 but may occasionally exceed 0^m10.
2. Whenever the observations allowed a period search, at least strong indications of periodicity were found (combine Harmanec 1983a with Harmanec 1984a,b). The period determination is severely hampered by the periods being in the range between 0.3 and ~2 days, by underlying long-term variations which often require adjustment of the nightly mean magnitudes, and by variable light curves.
3. Amplitudes and shapes of light curves can change substantially on time scales between one day (e.g., EW Lac [B3:IV:e-shell]: Walker 1953, Stagg 1986, Pavlovski 1986; λ Eri [B2 III(e)p]: Percy 1986b) and years. These changes do not follow any systematic pattern so that at least beating of only two periods is not the cause.
4. Harmanec (1984b) first recognized that the light curves of some Be stars show a reduced scatter about the mean if they are assumed to consist of two rather than one wave. This phenomenon has since been confirmed in many more Be stars (Balona & Engelbrecht 1986b, see also Percy 1986a).

Three important points need to be added to this list. (a) There is no convincing case yet where two photometric periods have been found to be simultaneously present, and (b) in the few stars with observations spanning many years the same period has been found to dominate at all times (e.g., o And [B6 III]: Harmanec 1984a; HR 9070 [B4Ven]: Percy 1983; λ Eri [B2 III(e)p]: Percy 1986b; EW Lac [B3:IV:e-shell]: Pavlowski 1986). Finally,

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(c), most observations have been made only in one pass band. But where more than one filter was measured (e.g., Walker 1953, Percy 1983) only small or even no color variations were found. It is probable, however, that as in many other variable OB stars (cf. Waelkens and Rufener 1985) a detectable wavelength dependence of the amplitude begins only shortward of the Balmer jump. An example of this is EW Lac (Lester 1975).

4.2.2 *Discussion*

Rotation of an inhomogeneous surface brightness distribution (as advocated by Balona & Engelbrecht 1986a,b, see also Harmanec 1984b) and nonradial pulsation are the only explanations which seem consistent with the length and the stability of the periods. However, the claimed consistency is in neither case trivial. The rotation hypothesis (star spots) appears to work only if most short periods (< 0.6 day) can in fact be doubled so that the light curves are double-waves. At rotation periods shorter than this, most B dwarfs would be unstable so that the implied high velocities are only *phase* velocities, i.e., no transport of matter is associated with them. Also, with a factor of five, the range from the shortest to the longest periods may otherwise exceed the combined widths of the distributions of equatorial velocities (in Lucy's [1974] deconvolution, it is very peaked) and stellar radii, which can be estimated for cluster members from the spread in visual magnitude at constant T_{eff} (Mermilliod 1982, Slettebak 1985).

In the classification scheme for slowly rotating stars, the pulsation modes can only be of the g- or r-types or a mixture thereof because the intrinsic frequencies would be extremely low (corresponding to the small difference between observed and rotation period) and thereby rule out p-modes. However, normal Rossby waves without vertical component would not be photometrically detectable; the g-mode spectrum is dense at such long periods (cf. Cox 1980), while always only one mode is found to dominate the observations; and the properties of possible mixed modes are not well known.

4.3 *Spectroscopy*

Rotationally broadened spectral lines are one-dimensional velocity maps of the stellar disks. With this dimensional restriction, direct observations of the velocity fields characteristic of NRP's are possible (cf. Osaki 1971, Vogt & Penrod 1983) but very high spectral resolution ($\geq$20,000) and S/N ($\geq$200) are needed. Moving patterns have been detected in the line profiles of quite a few Be stars (Walker *et al.* 1979; Baade 1979, 1982a, 1984a,b; Bolton 1982; Ninkov *et al.* 1983; Vogt & Penrod 1983; Smith & Penrod 1984; Penrod 1986a,b; Smith *et al.* 1986; see also Fig. 2). It is actually difficult to find a Be star whose line profiles, at least over a few years, are not rapidly variable: Penrod (1986a) reports that he has detected NRP's in all Be stars observed by him; my experience with more southern Be stars is the same except for the late B-types. The main observational to be analyzed in the following subsections results can be summarized as follows:

1. At least occasionally, the stellar line profiles show periodic asymmetry variations. Often also several narrower bumps are seen traversing rotationally broadened lines.
2. The strength of the bumps can vary (i) with relative position from one to the other, (ii) with observer's perspective from the blue to the red wing of the underlying profile (i.e., across the stellar disk), (iii) with time from one year, month or week (maybe even day) to the following, and (iv) also from one spectral line to the other. This variability does not cause the mean period to be violated.
3. There are V/R variations of double-peaked emission lines with the same period as the asymmetry (low-order) variations of the stellar lines.
4. In a given star, the strength of the Hα emission and the amplitude of the profile modulation often are anticorrelated. In a small number of cases and stars, the

modulation amplitude has been observed to slowly decrease after an outburst (Smith and Penrod 1984, Penrod 1986a,b).

4.3.1 *The steady line-profile variations*

Several circumstances impede the analysis of line-profile variations in Be stars: (a) Because of the need for high spectral and time resolution at low noise, the fast rotation of Be stars reduces the observable spectral lines to the very strongest ones most of which are not very good atmospheric diagnostics. (b) The short length of modern detectors furthermore mostly precludes the simultaneous observation of two different unblended lines. (c) The problems with periods in the vicinity of one day are amplified by transient variations on a similar time scale. (d) At a S/N of several hundred, many line profiles are contaminated by circumstellar features. (e) Paschen continuum emission of the envelope may additionally reduce the contrast of the stellar lines and renders the usual normalization to the adjacent continuum a doubtful basis for quantitative work.

With a typical uncertainty of $\pm$ 1, the number of azimuthal sectors of the variability pattern is determined from the number of traveling bumps seen (times two, to account for the invisible hemisphere). For the identification of NRP modes, this fixes the azimuthal quantum number, m. It also provides a lower limit on the mode degree, ℓ, since m can take on the $(2\ell+1)$ values from $-\ell$ to $+\ell$ (cf. Osaki 1971). A simple description of ℓ is that $\ell - |m|$ is equal to the number of node lines with constant stellar latitude. Because the rotational Doppler effect does not provide information on any structure perpendicular to the equator, ℓ can thus only indirectly be inferred. $\ell - |m|$ should be small since the effects on the observed profiles of adjacent bands (defined by the node lines parallel to the equator) tend to cancel each other because they are one-half cycle out of phase. In practice, sectorial modes ($\ell = |m|$) are usually found to reproduce the mean line profile variations quite well. Their pulsation amplitude varies with stellar latitude, ϕ, as $\cos^m\phi$ so that the width of the equatorial maximum decreases rapidly with m.

Mode degree, mode order, amplitude, and horizontal-to-radial amplitude ratio must be extracted from the line-profile variations. For this, global parameters such as $v \sin i$ and macro- and microturbulence need to be determined from the same profiles. If the waves are not very gentle (points (a) and (b) of Sect. 4.3.3, see also 4.3.2) the microturbulence will vary across the stellar disk. Since the effects of NRP's on line profiles depend on the inclination, some knowledge about i is useful. Compression and rarefaction of the atmosphere will lead to temperature variations and thereby also change the local line strength. The phase angle between velocity and temperature field is not really a free parameter but also needs to be determined. Any photometric predictions by the line-profile analysis must of course fit the photometric observations. Finally, effects of the pulsation on the structure of the atmosphere (Sect. 4.3.2, cf. also 4.3.3) must at least be distinguished from the more basic variations mentioned here, and time series must be long and dense enough to recognize possible transient variations (see Smith 1986a). It should also be remembered that a complete description of a mode by a single spherical harmonic is only possible in the limit of linear adiabatic pulsations of non-rotating stars.

With so many parameters, the mean line-profile variations of Be stars can be quite well fitted. But since satisfactory solutions are often already achieved with the simple sectorial modes, a suitable periodic modulation of virtually *any* parameter will reproduce the observed mean line-profile variations similarly well (see, e.g., Balona 1986) if it affects the strength or position of the local line. Therefore, successfully fitted line-profile variations alone do not *prove* that the variability was correctly identified. The importance of fitting line profiles lies mainly in the provision of a *quantitative* description. But the longer the wavelength (on the stellar surface) of the variations is, the more important are also the qualitative constraints set by the line-profile variations. It clearly makes a difference *whether to the rotational velocity field another vector quantity – such as an NRP velocity* field – or a temperature field is added (which however because of limb darkening does not quite behave like a scalar field). Fig. 2 includes some line profiles which after the steep ascent from the core do not simply merge smoothly and slowly with the adjacent continuum but show a distinct knee beyond which they approach the continuum level via a straight ramp-like wing. As Fig. 2 shows, such ramps can occur in either wing. Variable ramp-like line wings were first described by Smith (1985) for Spica, and he demonstrated that they can be easily reproduced with a large azimuthal velocity component. As mentioned above, for low-order line-profile variations, simultaneous photometry is essential to further narrow down the range of acceptable solutions.

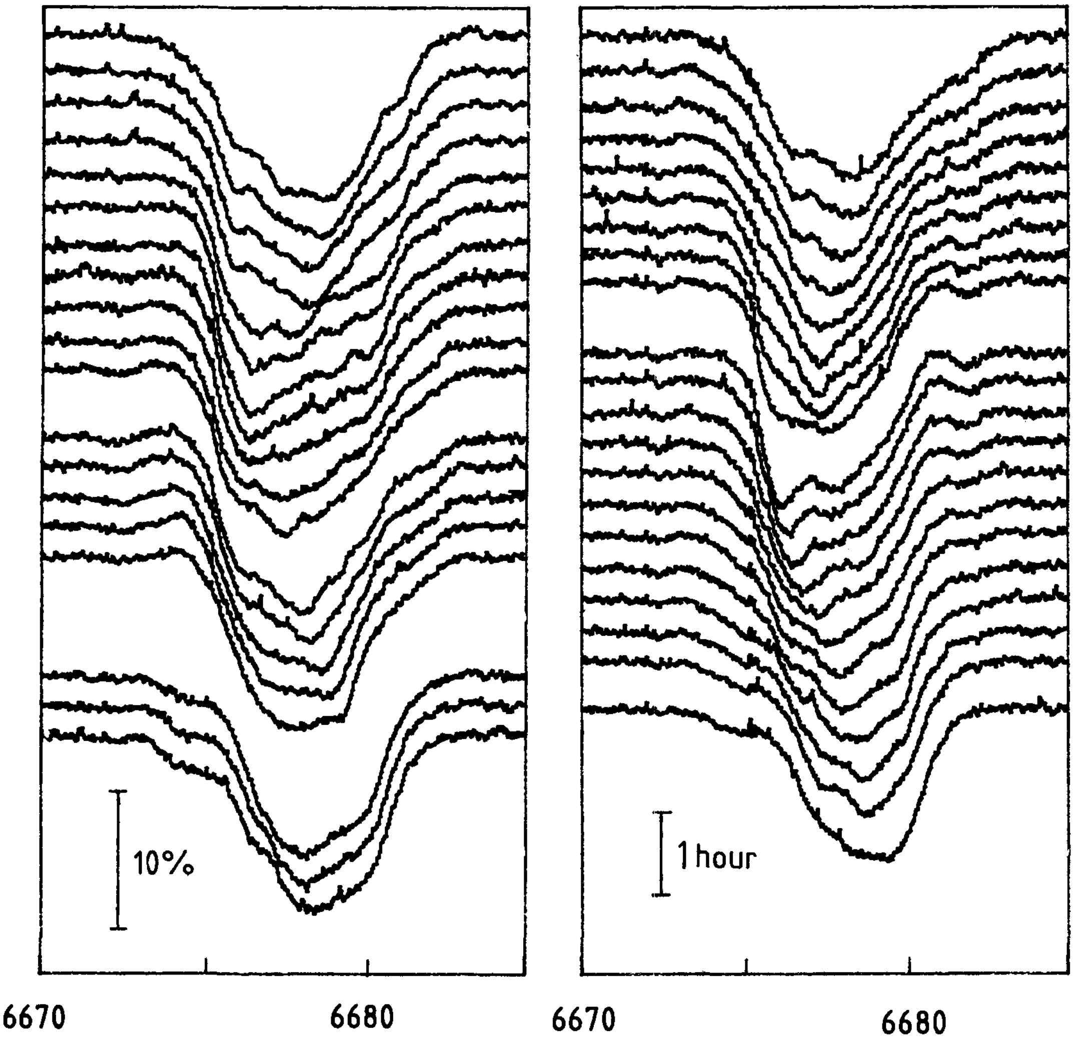
The problem of the non-uniqueness of the velocity field inferred from a single star may also be partly overcome by postulating that, statistically, the solutions obtained should not depend on inclination. Osaki (1985) has given an example how a spheroidal and a toroidal sectorial mode can lead to indistinguishable line profile variations. The assumed purely vertical velocity field of the spheroidal mode in his example does not have a node line parallel to the equator. His toroidal, purely horizontal velocity field however does have such a node line, namely where the line of sight is perpendicular to the stellar surface. At the inclination angle of 30° assumed by Osaki, this node line occurs at high stellar latitude where the velocities (not only the line-of-sight component) are small. This is not so for stars seen equator on where the effects of the latitudinal velocity component partly cancel for the two hemispheres. By contrast, the integrated line-of-sight component of the spheroidally pulsating star considered by Osaki is maximized if viewed equator on. It is still too early to utilize this criterion in practice; but the potential evidently exists.

As one of their arguments against the NRP interpretation of Be stars, Balona & Engelbrecht (1986a,b) mention the lack of multiperiodicity due to m-mode splitting, etc. But owing to the simultaneous low- and high-order line-profile variations, most Be stars are nevertheless clearly multiperiodic. It has been suggested (Baade 1984b) that in a given star the superperiods of all modes may be the same and that the modes would therefore be resonantly coupled. (If P_m is the difference in arrival time between two consecutive bumps associated with a pattern of m sectors, $P_{super} \equiv m \times P_m$ is the time for one full revolution of the whole pattern.) But since it now seems that the superperiods are very close to the rotation periods, the apparent equality of the superperiods may only be an illusion because differences between the very slow phase speeds in the corotating frame (Sect. 4.2.2) effectively vanish in the observer's frame where the effect of the much faster rotation is added. Similar observations in slowly rotating OB stars (see Smith 1986, Baade 1986b) indicate that this is not necessarily so in all stars. However, if superperiods are different for different patterns, certainly not all patterns can be due to star spots.

4.3.2 *Periodic effects on the atmosphere*

Sect. 4.3.1 has considered only effects that do not alter the structure of the atmosphere. With this approach, some observed profiles can only poorly be reproduced with standard velocity fields alone (and certainly not with simple two-dimensional star spots). This was first noted by Baade (1984a) with regard to narrow absorption spikes which occurred periodically in the line wings of 28 CMa and HR 4074 (B3 IIIp). Such spikes are also evident from Fig. 2 (μ Cen). Similar features in Spica were attributed by Smith (1985) to large azimuthal velocities of a tesseral ($|m| \neq \ell$) Rossby wave. But in 28 CMa and HR 4074 the azimuthal component should not be of much importance because they are almost certainly seen at inclination angles $i < 20°$. Large line-to-line

Figure 2: Line-profile variations of HeI λ 6678 in μ Cen observed on April 9 (left panel) and 10 (right panel), 1986. Time increases from top to bottom. Vertical bars provide the scales of time and local continuum flux.



differences of the spikes's proportionate equivalent widths strongly suggest that they are only indirectly due to a velocity field. It has been proposed (Baade 1984b) that local line-broadening mechanisms such as the Stark effect may offer an explanation. However, observations of the CII doublet $\lambda\lambda$ 6578,83 Å (cf. Fig. 3), even though contaminated by telluric lines, rule this out because the share of the spikes in the total equivalent width would require velocity amplitudes which are physically unreasonable and incompatible with the other lines (for this reason, the ℓ=2 pulsation amplitude derived for μ Cen by Baade [1984b] is grossly in error). On the other hand, the spikes are clearly part of the general line-profile variability as they repeat with the same period. The lines in which spikes have been seen in Be stars occasionally also show emission components (MgII

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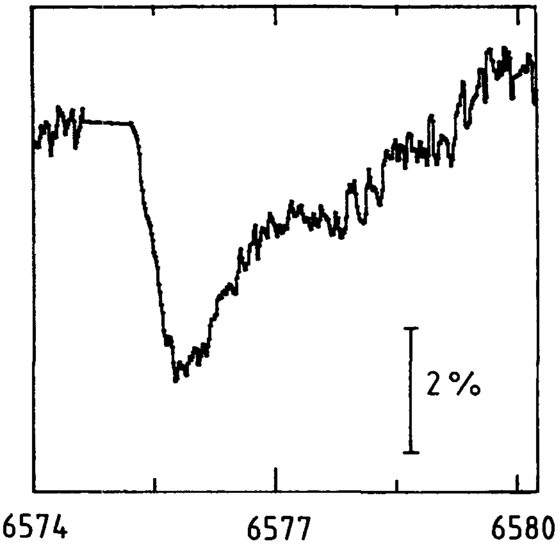
Figure 3: CII λ 6578 in μ Cen. Just shortward of the stellar line, a strong telluric absorption has been chopped off. The scale for the local continuum flux is provided by the vertical bar. The line is situated in the far wing of Hα; the corresponding slope of the adjacent quasi-continuum has not been corrected for. This observation was obtained on April 10, 1986, in the gap of the time series shown in Fig. 2 (right panel). Note the very much larger relative strength of the "spike" (cf. text) in this line than in HeI λ 6678.



λ 4481 Å: Baade 1984a, HeI λ 6678 Å: Fig. 2, Penrod 1986a) or are pressure sensitive (CII $\lambda\lambda$ 6578,83 Å: Young *et al.* 1981). The spikes therefore bear some resemblance to ordinary shell lines. A plausible explanation is thus that they form in low-density regions of the atmosphere. This would also account for their occurrence in the line wings because at the stellar limb the column density would be largest. On this basis, one should expect that spikes are on the average stronger at low inclination angles than for equator-on situations.

A glance at Fig. 2 shows that the major features traverse the profile from blue to red, i.e., they are prograde in the observer's frame. Closer inspection reveals also red-to-blue moving features which thus mimic a retrograde mode. It seems likely that they led to the claimed detection (Baade 1984b) of retrograde NRP modes in μ Cen. This identification now appears quite doubtful as the *phase speeds of both prograde and retrograde features are about equal in the oberserver's frame.* The simplest explanation is that after having crossed the stellar hemisphere (in azimuth) facing the observer the features producing the bumps are still visible in the far hemisphere where their phase velocity is of course the same except for the sign so that in the line profiles the bumps then move from red to blue. The phenomenon should therefore only be seen at low inclination. Under this assumption, it can be simulated with a velocity field if it is dominated by a tangential equatorial-polar component at a suitable stellar latitude. However, a pulsationally modulated atmospheric stratification can in lines that are sensitive to such effects (cf. the discussion given above of the spikes) lead to the same phenomenon. It in fact seems necessary in order to produce prograde and retrograde bumps of roughly equal strength (cf. Fig. 2). However, since perhaps also in the much broader-lined star λ Eri (Smith *et al.* 1986) the phase speeds of prograde and retrograde features are about the same, a totally different interpretation may be required.

The low-order line-profile variability of 28 CMa and HR 4074 falls into the same category. The spike in, e.g., MgII λ 4481 Å also returns, at reduced strength and sharpness, to the red wing before starting the next "normal" blue-to-red tour. This is also seen from the sinusoidality of the RV curve of these features (Baade 1982a). It is interesting that in contrast to, e.g., μ Cen, 28 CMa and HR 4074 have been observed to display a single spike at nearly all phases. Nevertheless, Stagg's (1985, private communication) photometry shows *two* fairly different waves when plotted vs. phase of the spectroscopic period, i.e., the one of the spike. Since the narrowness of the spikes cannot be reproduced with standard low-order NRP velocity fields, the sinusoidality of their RV curves is probably not to be confused with a similar effect described by Osaki (1971, also for low inclinations). – The right-hand panel of Fig. 2 shows also for μ Cen an initial gradual shift of the line's center of gravity to short wavelengths from where it swings back to the red.

4.3.3 *Periodic effects on the envelope*

At low S/N and/or spectral resolution, the best criterion for the detection of NRP's in Be stars is the rapid V/R variability of their emission lines (Baade 1984a; examples can be found in Baade 1982a, 1984a, Baade *et al.* 1984, and Penrod 1986a, see also Fig. 2). Because of this variable asymmetry, the line emissivity must depend in a similar fashion on the azimuth as does the stellar low-order variability because both are observed to have the same period. This identifies the ***stellar variability as the cause of the circumstellar V/R variability***. Under the assumption of NRP's, three different processes are conceivable which could accomplish this: (a) shocks, (b) local density enhancements due to matter lifted above the photosphere (cf. Sect. 4.3.2), and (c) the response of the circumstellar gas to an inhomogeneous surface radiation field (Smith & Penrod 1984). The variable emission component must in any case form close to the star as is shown by the variable emission also in HeI λ 6678 Å and the high velocities. Nevertheless, if the star is rotating near critical velocity, it may happen that the V/R variability is only due to corotation of a physical state of the matter, not of the matter itself.

Application of Poeckert and Marlborough's (1978) model to (c) predicts that temperature minima and emission strength maxima have the same stellar azimuth. Under the assumption that T_{eff} is maximal when the radius is minimal (i.e., adiabaticity!), the observations of the Balmer lines in 28 CMa (Baade 1982a) pass this test. However, the phase dependence reported for the emission in HeI λ 6678 by Penrod (Smith & Penrod 1984) for other stars is the same, and in μ Cen the V/R variations in Hα and HeI λ 6678 have been observed (Baade *et al.*, in preparation) to be in phase. In the context of model (c), this is somewhat surprising since HI is almost completely ionized while HeI is not. V/R variations are even observed (cf. Fig. 2, essentially the same was seen in simultaneous Hα profiles) without any underlying persistent emission. Assuming again model (c), this would imply that circumstellar gas around hot stars like μ Cen (B2 IV-Ve) does not always reveal itself by line emission. In the Balmer lines of 28 CMa (B2.5 Ve) it was further found (Baade 1982a) that the difference amplitude |V–R| increases with quantum number. But it requires detailed model calculations to decide whether this fact would favor any of the three models. Even though only a detail, the correct explanation of this V/R variability is not without interest since alternatives (a) and (b) could mean that some link between NRP and mass loss is directly observable.

During seven nights (two are shown in Fig. 2) of continuous monitoring of the HeI λ 6678 line in μ Cen in 1986 April, violet and red emission components were at no time seen simultaneously (Baade *et al.*, in preparation). Line emitting material therefore most probably existed only above *one* stellar hemisphere (in azimuth). The implied asymmetry also of the two hemispheres of the pulsation pattern ought to be the equivalent of the photometric doublewave phenomenon (cf. also the example of 28 CMa, Sect. 4.3.2).

4.3.4 *Rapid variability and mass loss events*

Bolton (1982) was the first to draw attention to the possibility that the amplitude of the short-term variability of λ Eri is smaller during phases of enhanced Hα emission. Penrod (1986a, Smith & Penrod 1984) succeeded subsequently in catching λ Eri during a Be outburst and so could verify that after the outburst the amplitude of the low-order line-profile variations decreased to a fraction of its previous value. The decline was slow, but it began sufficiently shortly after the outburst to be confident that the claimed correlation is real and not coincidential although λ Eri is a fairly active Be star. The same pattern has now also been seen in three more Be stars (Penrod 1986b). Since also the difference between the pulsations of Be and Bn stars (see Sect. 4.5) suggests that the low-order mode is the one that matters, the apparent correlation between Hα emission and $\ell = 8$ amplitude in ζ Oph (Vogt and Penrod 1983) is at least not the canonical case.

A spectacular event has been reported by Peters (1986) for μ Cen. During 1985/86 Hα emission often was undetectable in this star but also frequently seen to faintly return within as little as one day (Peters 1986; Hanuschik 1985; Baade *et al.*, in preparation, see also Fig. 2). The star thus was in a very active phase when Peters only 12 minutes after the previous observation detected a 90 mÅ equivalent-width feature blue-shifted by about 250 km s^{-1} with respect to the stellar HeI λ 6678 Å line. This velocity considerably exceeds both the observed stellar $v \sin i$ of 155 km s^{-1} (Slettebak 1982) and the velocity of emission components seen in this line at other epochs. Unfortunately, no additional observations could be made in that night in order to follow the subsequent development. However, a similar depression, much weaker and lasting for $\sim$2 hours but at a comparable position, is visible in Fig. 2, and Penrod (1986a) mentions this as a rather common phenomenon among Be stars. This seems to confirm the reality of Peters's observations although the acceleration required for that particular case is tremendous.

Although the observed velocities do not even come close to the escape velocity, the observations are suggestive of a mass-loss event (Penrod 1986a, Peters 1986). If, on the basis of their reported frequency (Penrod 1986a), such events are identified with polarimetric ones (cf. Guinan & Hayes 1984 and references therein) and their collinearity, the example of ω Ori (Baade 1986c) would suggest that they occur preferrentially (but, as the example of μ Cen with its $v \sin i$ of only 155 km s^{-1} shows, probably not exclusively) at low stellar latitudes. A relation also to the variable UV components appears possible since they, too, are low-latitude features. But at this moment, the details of such events and in particular their relation to NRP's are not well understood.

4.4 *Photometric/spectroscopic synopsis*

The pronounced amplitude variability usually forbids the combination of non-simultaneous photometry and spectroscopy. But it is important to emphasize that in stars with well determined photometric and spectroscopic periods these periods are the same. There are two examples which perhaps illustrate what the results of coordinated observations could be. In 28 CMa, the first example, spectroscopy had for 5 nights shown large-amplitude line-profile variations; but during the following 5 1/2 nights continuous photometry could not detect related light changes at the 0^m003 level (Baade 1982b). At other times, the light curve folded with the spectroscopic period had an amplitude of

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several 0^m01 (Stagg 1985, private communication). The second example concerns HR 9070. Over several years, this star has persistently displayed photometric variations with a period of 0.62 day (if the light curve is a double-wave) and a fairly constant amplitude of 0^m03 (Percy 1983, Harmanec 1986). Baade *et al.* (1984) measured two nights of photographic spectra for radial velocities and V/R ratios and recovered the photometric period. At a much better S/N, Penrod (1985, private communication) has however found no indication of line-profile variability.

With all due caution and keeping in mind that 28 CMa has an unusually low $v \sin i$, the two examples suggest that the *amplitudes of photometric and spectroscopic variabilities are at times very little correlated.* Since furthermore sudden drastic amplitude variations have so far been reported only for light curves but not for the low-order line-profile variations, the atmosphere probably responds to the pulsations differently at different times, i.e. the structure of the atmosphere cannot always be the same.

4.5 *Comparison with other rapidly variable OB stars*

In the H-R diagram, the Be stars are embedded (cf. Baade 1986a, Percy 1986c) in a general background (extending from mid-O to ~B8 and from supergiants to the main sequence) of nonradially pulsating OB stars. The extreme width (more than a factor of 3 in T_{eff} !) of the instability strip has led to the suggestion (Osaki 1986a) that the pulsations are driven by a core mechanism (such as the resonant coupling between the oscillatory convection of the core and a global stellar eigenmode) rather than an envelope mechanism (such as the κ mechanism). However, pronounced pulsational instabilities have so far been found in stellar models only after some parameters (e.g., opacities) had been arbitrarily altered. Empirically, it seems that the amplitudes and incidence of NRP's in B stars, like the Be phenomenon, reach a maximum near mid- to early-B spectral types.

The comparison of the short-term variations in Be stars with the general phenomenon of rapid variability in early-type stars is important for their identification with nonradial pulsations. (i) For the β Cephei stars in which NRP's have first been diagnosed (see Baade 1986a) the multi-periodicity, the frequency spacing, and the shortness of the periods not only rule out star spots but also positively identify NRP's as is acknowledged by virtually everybody *although* a driving mechanism has not been found yet. It is therefore surprising that essentially the same lack of understanding shall be an argument (Balona & Engelbrecht 1986a,b) that the quite similar – except for the periods – variability of Be stars is not also due to NRP's. (ii) In the even more similar line-profile modulations of OB supergiants, superperiods have been found (Baade 1986b and references therein) which are too short to be rotational and can only be understood as evidence of high *phase* velocities. (iii) Some long-period (1-2 days) line-profile variable B stars (e.g., 53 Per; Smith *et al.* 1984, Balona & Engelbrecht 1985) have two or more stable not commensurate periods which therefore cannot all be due to rotation.

It is striking that with the single exception of the β Cephei stars for which Smith (1981) has suggested a close interaction of the nonradial modes with a radial mode, the ranges of nonradial superperiods in all other sub-groups, i.e., slowly rotating B main-sequence stars, Bn stars, Be stars, and OB supergiants, are indistinguishable, or at least widely overlapping, although the evolutionary states are quite different and that they are indistinguishable in the *inertial* frame although the range of rotation rates is much larger. Maybe, this fact lends additional support to Osaki's (1986a) suggestion of a core model for the nonradial pulsations of OB stars. Smith and Penrod (1984) had proposed earlier that the sign of m may depend on $v \sin i$ and change at about 150 km s^{-1}. But the inclusion of the factor $\sin i$ of course introduces some arbitrariness.

If NRP's have any effect on the behavior and appearance of Be stars, there must be a difference between the pulsations of Be stars and those of rapidly rotating B stars without emission lines, the Bn stars, even though there would be no immediate explanation for this difference. Penrod (Smith & Penrod 1984) has indeed drawn attention to the fact that while NRP modes of higher order ($\ell \geq 4$) are equally ubiquitous in Bn and Be stars, quadrupole modes (ℓ=2) are much more frequent in Be stars, if not restricted to them (but note that low-order modes do occur in slowly to moderately rapidly rotating non-emission line B stars, see Smith 1986a). The same is apparent from a small survey (Baade, in preparation) of bright southern B stars with $v \sin i \geq 200\ km\ s^{-1}$. However, these Bn stars occasionally show narrow absorption spikes in their wings similar to those described in Sect. 4.3.2 for Be stars. Since in Be stars the spikes are associated with the low-order mode and because I have obtained too few spectra of the Bn stars to even estimate time scales on which the spikes occur in them, my observations do not exclude the possibility that Bn stars, too, pulsate in a low-order mode. This possibility also arises from indications of photometric time scales on the order of 1 day found in some Bn stars by Jerzykiewicz and Sterken (1982). The difference between Be and Bn stars would then be that the latter do not have a low-order mode with appreciable vertical component and asociated temperature variations. By contrast, this property seems the second necessary condition, in addition to rapid rotation, for a B star to become a Be star is nonradial pulsation in a low-order mode. Finally, the omnipresence of traveling bumps also in Bn stars lets appear the hypothesis (cf. Harmanec 1984a) that bumps are due to spokes of circumstellar matter very unattractive.

For some of the southern Bn stars mentioned, Hα profiles have also been obtained. They confirm the result by Furenlid & Young (1980) that the Hα profiles of rapidly rotating B stars display blue-depressed cores. Because the correlation is with $v \sin i$ (*not* with v), rapidly spinning stars appear to have higher mass loss rates than have slow rotators, and the extra mass loss is predominantly in the equatorial regions. This is in qualitative agreement with stellar wind theory refined to include rapid rotation (Friend and Abbott 1986). But in non-Be stars the enhancement of the mass loss rate does not increase the wind's density by so much that its velocity is small enough to form a detectable disk.

Proponents of the spotted star hypothesis often quote the magnetic Be star σ Ori E as an example. Kilo-Gauss magnetic fields are in fact the only established way of producing spots in a hot stellar atmosphere. But it must be noted that (a) dipole fields as in σ Ori E have not been found in any Be star down to the 100 Gauss level (see Barker 1986), that (b) strong and weak HeI lines are 180° out of phase in σ Ori E (Bolton *et al.* 1986) but in phase in 28 CMa (Baade 1982a) and other Be stars, that (c) the line profiles of σ Ori E do not have the ramp-like wings (Bolton *et al.* 1986) seen in so many nonradially pulsating B stars (cf. Sect. 4.3.1), and that (d) traveling bumps are not known for σ Ori E but have so far been detected in every Be star. Comparison with other nonradially pulsating B stars rather suggests that the strong magnetic field of σ Ori E efficiently suppresses the pulsations that one should otherwise expect from the star's position in the HRD. Speculations that σ Ori E might be the prototype Be star do not appear adequate.

5 *MODELING Be SYSTEMS WITH A NONRADIALLY PULSATING CENTRAL STAR*

5.1 *Models*

Willson (1986) investigated the effects of periodic isothermal shocks caused by the vertical component of the pulsation assumed to act like a piston. If shocks deposit energy in high-density regions of the atmosphere, this energy may not completely be

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radiated away, and the structure (scale height) of the atmosphere may change if strong shocks convey sufficient energy. Accordingly, the sonic point moves closer to the star. Further, the radius where the shocks become adiabatic increases with period because long periods leave more time for cooling. If the sonic point lies within this radius, shocked gas can cool, do work against gravity by expansion, and thereby initiate a cool, dense wind. A major Be outburst will probably reset the atmospheric scale height (but of course not necessarily to its value at the beginning of the cycle) so that via this self-regulation a cyclic behavior may develop.

Willson's (1986) work is an adaption to hot stars of a model developed by Willson and Bowen (1984) for the radial pulsations of Mira variables. Even in these very cool stars most of the energy dissipated in the shock is radiated away. But because of the shock-induced ionization of hydrogen and resulting increase of the opacity, the radiative losses do not amount to 100%. However, since hydrogen is completely ionized in B-star atmospheres, it is not clear how easily conclusions valid for Miras can also be applied to Be stars. If there is a way of avoiding quasi-instantaneous radiative loss of the shock energy, Willson's model could take advantage of the very long intrisic periods because, then, the radius beyond which the shocks become adiabatic would be particularly large in Be stars so that shocks would be more efficient in initiating a cool dense wind. Another effect of these very long periods is, however, that the available photometric data place very stringent limits of only a few km s^{-1} on the vertical velocity amplitude.

Castor (1986) has pointed out that the observed pulsation periods of OB stars are much longer than their wind flow times (1-2 hours) so that the wind should relatively easily adapt to the motions at its base. Since the periods of quadrupole oscillations in Be stars are several times longer than the periods of β Cephei stars, it might appear that pulsational effects on the winds of Be stars are even smaller. But this comparison ignores the important fact that the expansion velocities in the disk are by more than one order of magnitude smaller than the terminal velocities of 'normal' winds of OB stars. If the whole velocity law is scaled by a similar factor as the terminal velocities, the periods of Be stars might not be all that different from the wind flow time.

If under non-adiabatic conditions non-axisymmetric ($m \neq 0$) NRP waves are damped (dissipation, leakage), a small phase difference develops between the vertical and the horizontal velocity components of the pulsation, and the waves can transport energy and angular momentum to the damping zone. Osaki (1986c) therefore proposed that this could spin up the surface layers to the critical velocity. Once this process has initiated mass loss, the partial loss of the boundary by which adiabatic NRP waves would normally be reflected will lead to an even stronger energy leakage and so accelerate the mass loss until the pulsation is damped out or the reflecting boundary re-established. Essentially the same mechanism is also invoked by Ando (1986) but he extends it through the inclusion of a cyclic long-term variability. The latter makes use of the fact that prograde waves ($m < 0$) can transport positive and retrograde waves ($m > 0$) negative angular momentum. The interaction between NRP waves and stellar rotation could, then, lead to a situation where the star's rotation profile contains some wiggles about a straight line and undergoes quasiperiodic oscillations about the case of rigid rotation as the equilibrium state. Ando shows that the time scales are similar to the intervals between major emission episodes of Be stars. While Ando's model does not explain how NRP's in early-type stars are driven, it shows a way how perhaps part of the huge reservoir of stellar rotation energy may be tapped for other processes. Note that the amount of energy transported by NRP's does *not* depend on the pulsation amplitude but on the waves's phase speed.

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Observations raise several possible objections against the models of Osaki and Ando: (i) Be stars are not observed to rotate *at* critical velocity or any faster than Bn stars. (ii) Variable radial rotation profiles are not reconciled with indications that at least some Be stars have fairly stable periods. (iii) The surface phase velocities of NRP waves are very small. From the lengths of the observed periods it even appears probable that in at least some Be stars the modes are retrograde so that the proposed mechanisms would actually *decrease* the surface rotation rate.

The hysteresis-like long-term component in the mass loss from Be stars and the apparent lack of a pronounced dependance of the instantaneous mass-loss rate on pulsation amplitude is reminiscent of the release of overpressure by opening a valve. Since mass loss events are very frequent but certainly not caused by reaching critical rotation, the opening of the 'valve' may have to be accomplished by some atmospheric process. In Willson's model, periodic isothermal shocks change the atmospheric scale height and thereby govern the long-term variations of the mass-loss rate. On shorter time scales, it is likely that temporal disruption by shocks of the atmospheric reflecting boundary (cf. Osaki 1986c) will also cause pulsation energy to be dissipated. A rather wide range (in amplitude and duration) of mass loss events therefore appears possible.

5.2 *Further comparisons with observations*

The thought that large amounts of nonradiative energy are accumulated in the atmosphere and substantially change its structure appears rather bold. (But it is not alien to the model proposed by Doazan and Thomas [1982] which however attempts to perceive and explain Be systems in a totally different way.) On the other hand, recent measurements of the UV continuum flux of Be stars have been used to infer long-term temperature and perhaps also radius variations (Doazan *et al.* 1986a, but 88 Her be a binary [see Doazan et al. 1982 and references therein]; Peters & Polidan 1986) which seem to be correlated with the appearance of the envelope. Whether these observations really mean that the stellar temperature or even the bolometric luminosity are variable or whether only different layers are observed because of structural variations of the atmosphere, may be subject to some debate. But it is important that they have been obtained in the far UV because a correlation of flux variations with state of the envelope would inevitably lead to the suspicion that the altered flux distribution is due to the envelope rather than the star. Interestingly, *Voyager* observations have not so far detected (Polidan 1986, private communication) similarly large changes of the far-UV flux distribution in OB supergiants as in Be stars (Peters and Polidan 1986). This is consistent with the lack of significant long-term variations of O-star mass-loss rates (Prinja & Howarth 1986) even though some O stars are pulsating, too (cf. Baade 1986b). A long-term structural change of the atmosphere had also been inferred from apparent variations of the light-to-velocity amplitude ratio (see Sect. 4.4). The idea of global long-term variations of the atmosphere therefore at least seems to be compatible with independent observations which are not otherwise explained; the existence of such *local* variations is rather certain (cf. Sect. 4.3.2).

NRP models offer answers to the three classical problems of Be stars (Sect. 3): (i) Bn stars do not develop disks because they do not pulsate in a quadrupole mode with significant (vertical) amplitude . (ii) The distribution (in duration and amplitude) of mass-loss events is due to the combination of short- (instantaneous pulsation amplitude) and long-term (change of atmospheric structure) variations. The latter may or may not also be caused by the pulsation. In any case, they have an effect on the efficiency with which the pulsations contribute to the mass loss. (iii) The condition that the mass loss is maximal at the equator is trivial to fulfil once an NRP model works at all. With this

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anisotropy of the wind, a difference between the UV and IR mass-loss rate estimates is to be expected. If the discrete components of UV resonance lines are due to density enhancements, NRP's may also be responsible for them through either perturbations of the wind or discrete mass-loss events or both (see Rybicki 1986, Henrichs 1984, Baade 1986b).

When sometimes only striking UV variations reveal the Be nature of a star while its appearance in the visible is still the one of a 'normal' B star (Doazan *et al.* 1986b), NRP models explain this as a slightly enhanced variable wind which however is not dense enough to be slow and form a disk. A correlation between the equivalent width of $H\alpha$ emission and UV wind features (see Doazan 1986) is to be expected if NRP's enhance mass loss not only *at* the equator and *into* the equatorial plane. Because the atmospheric conditions for a big outburst are only slowly built up, one should further expect that smaller events are more noticeable before than after an outburst. This is one of the interpretations listed by Doazan *et al.* (1986b) for the variability of θ CrB (B6 III).

Several theoreticians have expressed doubts (e.g., Castor 1986) as to whether any effects of NRP's can couple to the wind. An important detail of the observations of ς Pup is therefore that the pattern of NRP-induced variable line profiles is still seen (Baade 1986b) in lines that have an appreciable blue shift (the so far most extreme case is $H\alpha$ at -100 km s^{-1}) and accordingly are formed in an expanding atmosphere, i.e., the base of the wind. Thus, some coupling does appear to take place. It is clear, however, that mass loss mechanisms due to NRP's alone must not be too efficient because β Cephei and slowly rotating OB stars which, too, show NRP's with considerable amplitudes, are not known for dramatically increased mass loss rates. This may be the point where the rapid rotation enters which however has not yet been addressed in detail by NRP-based models (but see Sect. 5.1 for a discussion of the implications of the resulting very long intrinsic periods).

5.3 *Model variants*

A term that is gaining some popularity in connection with mass loss from Be stars is 'mode switching'. It would be absurd to dispute without adequate observations that this may happen, but it must be emphasized that there is no well documented case where, in a Be star, an NRP mode has increased its amplitude *at the expense* of another mode. The change in pulsation amplitude is more likely to be due to damping, and the time scale is determined by the relaxation time of the atmosphere and the growth rate of the pulsation.

The mechanisms discussed in Sect. 5.1 implicitly assume that the pulsation modes of Be stars are spheroidal or at least have a strong spheroidal component while, for rapidly rotating stars, theory still finds Rossby waves easier to predict. Jupiter's Great Red Spot (GRS) bears some resemblances to Rossby waves (cf. Mayr *et al.* 1985), but nevertheless appears to differ in temperature (see Mayr *et al.* 1985 for references) and perhaps also in vertical extent (Kuiper 1972) from the ambient atmosphere, and it is an example of a long-lasting asymmetry in a large-scale atmospheric velocity field. This description of the GRS is not qualitatively in conflict with available observations of Be stars. It also introduces the possibility of an inversion of the causality between temperature field and velocity field. Since rapidly rotating stars are thought to have a non-spherically symmetric surface-temperature distribution which, on the one hand, may be reduced in amplitude by an independent horizontal velocity field such as NRP's and which, on the other hand, may itself induce a velocity field (meridional circulation, baroclinic instability, etc.; see Zahn 1983), the interplay of these two effects may perhaps assume oscillatory character and thereby lead to additional long-term variations. (I owe this thought partly to a discussion with Dr. Myron Smith.)

6 *CONCLUSIONS*

Given the stochastic nature of Be-star outbursts and the short-term irregularities of the wave propagation, only the concentration on a very small number of targets is likely to solve the cause-or-effect? riddle of the long-term component in the nonradial pulsations of Be stars. Technically, simultaneous photometry and high-resolution low-noise spectroscopy should be given high priority in order to find out whether and how a cross-calibration of the results is possible because there is no chance that a coudé spectrograph with modern equipment will be available for monitoring purposes. On the conceptual side, the long-term effects of NRP's appear also one of the most worthwhile subjects of further theoretical studies.

Because of the low pulsation amplitudes beyond spectral type B6, it is likely that the Be phenomenon extends to lower temperatures than significant NRP's do. The determination of the lower limit in temperature of NRP-based models could provide interesting insights into the existence and distinguishing properties of different populations of Be stars. Perhaps, binaries are more frequent among late-type Be stars. Depending on spectral type and magnitude difference, the presence of a companion could be most convincingly and maybe even most easily demonstrated by the direct detection in very low noise spectra of the intrinsic near-IR lines of a cool star.

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DISCUSSION FOLLOWING BAADE

Balona:

The main weakness of nonradial pulsations as an explanation of line profile variations in Be stars is that it explains too much, i.e. there are too many free parameters so that *any* line profile may be fitted by suitably choosing a combination of parameters. This makes the theory practically impossible to disprove. I believe any model for the short period variations should be able to explain the following observations for the so- called "low-order modes" in a natural way: 1) Only one period (comparable to the rotation period). 2) The frequent occurrence of a double-wave light curve. 3) The sometimes large "pulsation" amplitude (amounting to nearly 0.2 mag for EW Lac) and the changes in amplitude. 4) The wide spectral range (09-B8) in which such variations are found. At present it does not seem possible to explain any of these observations in a physical way by invoking nonradial pulsations. On the other hand, 1,2, and 4 may be more readily understood in terms of rotational modulation.

Baade:

I believe I have tried to be honest and fair to acknowledge all the problems that you are mentioning. One of the most basic properties of all physical systems is that they oscillate if they are disturbed. Nonradial pulsations are therefore not "unnatural". I do not understand how rotational modulation which has not yet been shown to fit the spectroscopic data can be thought to be a more physical explanation than nonradial pulsations that fit the observations. The only demonstrated way to produce rotational modulation is a B star seems to be a magnetic field. The comparison between the low-order line profile variations of σ Ori E (Bolton, these proceedings) and μ Cen shows that they have nothing in common and cannot be confused. Futhermore, σ Ori E does not display the effects of high-order modes which is true of virtually *all* early-type Be and Bn stars that I observed. This may be so either because line broadening effects prevent their detection or because the very strong magnetic field somehow quenches the pulsation.

Smith, M.A.:

Let me give a brief defense of the early history of the modeling of line profile variations with nonradial pulsations velocity fields. First, we have modeled the behavior of a number of alleged nonradial modes in many Be stars over the years, and we have found that certain patterns emerge in the choice of parameters we are forced to choose. It is not a question of a helter-skelter selection of nonradial modeling parameters as one proceeds from one case to another. One pattern is that the modes are consistently found to be sectorial modes (a "bulk property" of the line, the absence of radial velocities, sets this condition). Another is that there is a clear dichotomy of prograde and retrograde modes for slow and rapid rotators, respectively.

Second, the line profiles of many B stars include a large number of "Doppler resolution" elements - a lot of independent velocity information. So especially for the rapid rotator the issue of having a lot of free parameters is less critical than one might first think. In fact, the problem is well enough constrained that even modest departures from regularity betray themselves.

Third, there are sub-classes of β Cephei and δ Scuti stars thought to have nonradial modes, according to photometrically determined periods. These have been subjected to the same analysis techniques, and the results are that there are no surprises. The periods and the phases agree with the photometric ones, and within reasonable errors so do the amplitudes.

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But, fourth, let's admit up front that certain parameters one determines from line profile fitting techniques are softer than others, quite apart from the issue of uniqueness. Smith and Stern (1979) attempted to estimate the reliability of several observational parameters by means of a "single-blind" test with simulated data. In fairness, serious critics should perform such quality control tests anew or limit their critique to the errors defined by that study. Surely; if the advocates of a technique must quantify its limitations, so too should the critics phrase their objections in a quantitative way at some point.

Finally, yes, there are a variety of physical problems the line profile work has brought out, e.g. an assessment of temperature versus velocity contributions to the line profile, the appearance of the "K-problem" (where are the horizontal motions?). These are important questions and they are leading even now to creative observational tests. We haven't "forgotten" these effects - some of them we've just discovered. Its more a matter of planning the observing campaigns to resolve these problem areas step by step.

Koubsky:

Have you ever observed a Be star not showing these rapid variations?

Baade:

Yes, I have. I would divide these cases into two categories: (a) In none of ~ 3 Be stars of spectral type B8 or later (e.g. ϵ PsA) that I have observed were variable line profiles visible. (b) Stars of earlier type can be "dormant" for a long time. For example, I had to wait for almost three years before I could see nonradial pulsations in α Eri.

Furenlid:

The CII lines in the red wing of Hα($\lambda\lambda$ 6578 and 6582) are very pressure sensitive in the sense that they increase in strength as the pressure decreases. At the appropriate temperature they compete in strength with Hα in some supergiants. These lines may therefore serve as diagnostics of pressure variations in pulsating stars.

Baade:

I forgot to mention this point here but it is indeed in the written version of the paper.

Harmanec:

Have you checked that some of those (very weak) features you see in your line profiles are not simply weak lines belonging to other ions?

Baade:

In the continuum adjacent to none of the photospheric lines observed I have seen such moving features. It would be odd if they coincided only with the stellar lines.

Harmanec:

Periodic V/R variation is well established for several Be binaries. Could you explain why μ Cen cannot be a close binary?

Baade:

The periods of these variations are too short. This is best seen again from the example of ς Pup which seems to show V/R variations with a period of 8.5 hours.

Harmanec:

Every particular supergiant can potentially be a main sequence star (or a binary) inside an extended envelope, which shows that any argument we can use is not 100% convincing, I think.

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Baade:

This possibility clearly exists in general but is equally clearly excluded for ζ Pup.

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