NONRADIAL PULSATIONS AND THE Be PHENOMENON*

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ABSTRACT. Following a summary of the observations which suggest that the outbursts of classical Be stars are caused by nonradial pulsations, properties, implications and requirements of a model based on this notion are evaluated. A preliminary analysis of new observations of μ Cen is presented which for the first time in a Be star reveals two relatively closely spaced non-commensurate periods. Such a result would render implausible speculations that the variability of Be stars is due to corotating surface features.

1. INTRODUCTION

Two extensive overviews (Percy 1987, Baade 1987a) of the numerous symptoms of the rapid variability of Be stars, their interpretation in terms of nonradial pulsations (NRPs), and the possible causal connection between NRP and mass loss have been given only recently. It suffices, therefore, if here only the main points are recalled:

- Observations of both the mass *loss* (resonance absorption lines extending beyond the escape velocity) as well as of indicators of the mere *presence* of circumstellar matter (Balmer emission, net continuum polarization, narrow 'shell' absorption lines, IR excess) show that the mass loss from many Be stars is highly variable. The mass loss spectrum of these stars probably consists of many minor and much fewer major events, and perhaps does not even include a significant continuous component.
- Because of this variability, rapid rotation alone is not likely the cause of the mass loss as Struve's (1931) model had assumed. This conclusion can be drawn more firmly from a simple analysis of the Bright Star Catalogue where for every Be star there is a Bn star with the same $v \sin i$ but without a record of observed Hα emission.
- High-S/N spectroscopy may have uncovered a more fundamental difference between Bn and Be stars: While both groups, like the overwhelming majority of all other early-type stars with sufficiently broad lines (*cf.* Baade, these proceedings), show a finestructure of pairs of quasi-absorption and -emission components which in time resolved observations move blue-to-red across the photospheric line profiles, only Be stars also show line profile variations on a coarser scale. This latter variability of their absorption lines may therefore be the defining characteristic of the classical emission-line B stars.
- The amplitude of the line profile variability (LPV) is variable with time; what few periods have been determined so far do not give rise to the suspicion that the periods, too, are variable. On a few occasions and in different stars, the amplitude has been observed to decrease with some delay (days, weeks) after a Be outburst.

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- The attribution of the LPV to NRPs, the similarity of the kinetic energy needed for a typical Be outburst and the energy contents of some NRP modes, and the ability of non–axisymmetric NRP modes to transport angular momentum and energy between different radial zones of a star have immediately led to the suggestion that mass loss episodes are *caused* by the pulsation. Because no dependence of the mass loss rate on the pulsation amplitude at the time of the outburst has been found, long–term effects of the pulsation appear to be the most important. It has therefore been conjectured that the long–term effect of low–order NRPs may be a secular change of the atmospheric scale height until a critical combination of scale height, rotation and pulsation is reached where the excess energy is released in an outburst with mass loss.
- Low–order NRP modes also occur in slowly rotating B stars, however without leading to mass loss. But, while the observed periods of the two groups show considerable overlap, the periods in the *corotating* frame are much longer in the Be stars, rendering their pulsations highly non–adiabatic, *i.e.* after each pulsation cycle the atmosphere may be in a slightly different state as required by the above picture of Be outbursts.

The self–consistency of this notion is quite satisfactory, but it is based on observational inferences that need to be well established.

2. CRITICAL CORNER STONES OF THE NRP MODEL

Four points have to be considered: first, the occurrence of large–scale line profile variations in Be stars but *not* in Bn stars, second, the discrimination between NRP and corotating surface features, third, the clear observational documentation of individual mass loss *events*, and, fourth, the unambiguous establishment of a correlation between mass loss events and amplitude changes of the pulsation. The critical details may be summarized as follows:

1.) Two independent samples of 10 Be and 10 Bn stars each (Smith and Penrod 1984, Penrod 1987; Baade 1986) have both shown that significant LPV on scales comparable to the line width is (a) restricted to Be stars and (b) one time or another occurs in all of them. Even though neither data have been published yet, there can be no doubt that the LPV patterns of Be and Bn stars differ dramatically. But a more detailed study is clearly in order to find out, *e.g.*, if the amplitude of large–scale LPV in Bn stars is zero or just at the detection limit and if there are no exceptions to the rule.

2.) Because of the failure of current techniques to detect magnetic fields in Be stars (Barker 1987, see also Vogt and Penrod 1983 on the 'spoke model') there is little dissense that the small–scale LPV is due to high order NRP; but the idea that the large–scale LPV can be explained by the same model meets much more resistance (Harmanec 1984, Balona and Engelbrecht 1986, Balona *et al.* 1987, Sareyan *et al.* 1987, Clarke and McGale 1987). The reason of the latter is rather simple: the observed periods are close to the typical rotation period of Be stars so that – considering only Be stars – the assumption of surface features corotating with the star appears the most straightforward explanation.

   However, this situation arises only in Be stars which are among the fastest rotators whereas LPV with the same 1 day timescale is in fact also observed all the way down to slowly rotating stars (Smith 1986). Among slower rotators, an excess of the phase velocities, v_{ph}, over the equatorial rotation velocities, v_{equ}, is implied that increases with decreasing rotation rate and eventually turns into compelling model–independent evidence against corotating surface features and in favor of NRP. Thus, does the near–identity of the two time scales in Be stars justify or even necessitate a second model for the same observational phenomenon? Note that Smith and Penrod (1984) even argue that in the most rapidly rotating B stars v_{equ} not only approaches v_{ph} but actually exceeds it so that in the corotating frame the putative spots or theirlike would propagate *opposite* to the direction of the rotation.

3.) As stated before, any effect NRPs may have on the mass loss should primarily have the character of a time *integral* because no evidence has been reported that at a given *moment* the mass transfer rate to the Hα emitting envelope and the pulsation amplitude are correlated. Furthermore, Osaki (1986) and Ando (1986) have shown that NRP induced changes of the mass loss rate with time may be relatively slow. The evidence that mass loss from Be stars is (partly) driven by NRP would then be rather circumstantial and depend mainly on the difference in the LPV of Be and Bn stars. However, if tight limits of the order of the star's dynamical time scale can be placed especially on the rise time of a mass loss episode, the need for an explanation other than by rotation, or radiation pressure, or static magnetic fields, *etc.* becomes much more pressing and the notion of the violent release of some extra energy more plausible.

   Examples of very short (~ day(s)) rise and much longer (~ week(s)) decay times of indicators of circumstellar matter have been given by Baade (1987a). Recent high-quality Hα observations of at least 3 small outbursts within 5 weeks in μ Cen (Baade 1987b, Baade *et al.* 1987) confirm the earlier conclusions and add an important new lower limit on the frequency of such events during active phases of a Be star.

4.) Existing conjectures about a link between NRP and mass loss in Be stars have so far only been qualitative, and nobody has worked out if a decrease in pulsation amplitude after an outburst as reported by Penrod (1986, 1987) is *necessarily* to be expected. If detailed calculations showed this not to be the case, one would again have to resort to more indirect indicators such as item 1 above. The possibility of a positive correlation is therefore certainly very appealing. On the other hand, there may be a rather basic problem with it. If, as has recently been observed (*cf.* point 3), the time between two successive outbursts becomes comparable to the typical time of decline in LPV amplitude, can one safely speak of a correlation? One possible way out is that the size of an event, the subsequent change of the pulsation amplitude, and the time needed by the atmosphere to return to the pre–outburst state are coupled quantities.

In summary, for 3 of the 4 issues discussed the observations either provide or firmly promise the necessary minimum of evidence that in Be stars mass loss events and photospheric variability on a timescale of one day are interconnected. The interpretation of the variability as NRP is more controversial, mostly with single–channel observers and some theorists. The latter are skeptical in part because the observations of so extremely rapidly rotating stars are outside the domain to which theories developed for non–rotating stars may be extrapolated. The former, not being directly confronted with the plethora of phenomena which at high S/N and spectral resolution become observable thanks to the rotational Doppler effect (*cf.* Baade 1987a), occasionally tend to integrate stellar disk-integrated data further into one number, 'the' period, and make it the key to the understanding of Be stars. One reason for this foreshortening are, paradoxical though it may appear, the available analyses of spectroscopic data which have not so far succeeded to detect multiple periods in the LPV which however a) are to be expected from NRPs and b) would eliminate corotating surface features from the model scene. (The ubiquitous presence of LPV with short spatial periods is usually discarded as evidence of multiperiodicity because the phase velocities of long- and short–wavelength patterns are often very similar.)

3. MULTIPERIODICITY

If the periodicity observed in Be stars is to be explained by surface features, these features must form a roughly periodic pattern on the stellar surface. For simplicity and following the same arguments as for NRPs (Baade 1987a), it can be assumed that to first order the pattern defines m identical sectors. If the polar axis of these sectors is inclined with respect to the rotational axis (Harmanec 1984, Clarke and McGale 1987), the corresponding segments of, *e.g.*, a light curve will be unequally long and have unequal amplitudes. Neglecting this possible complication, the relation between the frequencies in the corotating frame and the observer's frame is for m star spots as well as NRP with mode order $\pm m$:

$$f_{obs} = f_{corot} + |m| \times \omega \qquad (1)$$

where ω is the star's rotation rate. The formal difference between star spots and NRPs in this equation is that f_{corot} is zero for spots with a fixed location while for traveling waves it is not. Accordingly, only (two or more) spot patterns would have m–commensurate frequencies (or periods): $f_{obs,m}/f_{obs,n} = m/n$.

If the usual assumption for Be stars is made, that their range in ω is small, Equ. (1) shows that for small m ($m \approx 2$ is appropriate for the large–scale LPVs of most Be stars) the chances to find a star with large (absolute) f_{corot}, *i.e.*, where the distinction between the two models is the least ambiguous, are best for stars with extreme f_{obs}. One reasonable candidate is, therefore, μ Cen with its 0.505 day period (Baade 1984) which is one of the shortest periods known of Be stars (see the list compiled by Percy 1987).

Nearly 20 nights worth of observations have been obtained of this star in three different seasons. Typical nightly examples can be seen in Fig. 2 of Baade (1987a). Although there have been no dramatic changes of the amplitude and all nights look basically similar, there is not a single pair of nights or major sections thereof in which the large–scale LPVs were identical to within many σ of the noise. The residuals are almost certainly not due to small–scale ($m \approx 10$, Baade 1984) LPV, either, so that the beating of at least two large–scale LPV patterns, *i.e.* the existence of ***different*** periods, is a strong possibility.

The problem is to measure the presumably not very different periods of some processes which each modulate a series of one–dimensional data strings (line profiles) in a similar fashion. The least model–dependent method that furthermore utilizes the data to their full extent (Baade, these proceedings) is to separately analyse the flux in thin wavelength slices which extend over all observations (spectra) and together cover the entire spectral line observed. Such a study has been carried out for six nights of observations of He I λ 6678 Å in μ Cen obtained in 1987 April. The discrete Fourier transform (DFT) and the phase dispersion minimization method both gave nearly identical results. The wavelength series of DFT power spectra after deconvolution with the window spectrum by the CLEAN algorithm is reproduced in Baade (these proceedings).

The preliminary analysis confirms the 0.505 day period reported earlier (Baade 1984) and reveals a second set of peaks (mostly 1 c/d aliases) arising from a 0.391 day period. The difference of the period ratio from 5:4 appears significant. However, if Equ. 1 were to be simultaneously satisfied with both $m = 4$ and 5 and the observed frequencies, ω would have to be ~0.5 c/d. Assuming 5 $R_\odot$ for the radius of μ Cen (B2 IVe), this would translate into v_{equ} = 130 km/s, *i.e.* less than the observed $v \sin i$ of 155 km/s (Slettebak 1982) although the apparent retrograde propagation (Baade 1984, 1987a) of some features in the line profiles suggests that the star is seen at relatively low inclination (also consistent with the $v \sin i$ value which is low for a Be star).

Thus, μ Cen is almost certainly truely multiply periodic. A third period, either 0.305 day or its 1 c/d alias 0.440 day (the peak of the former is stronger, in the second case all three frequencies are, within the errors, equally spaced), is in fact likely. An unresolved puzzle, however, is the very strong variation of the Fourier power with wavelength (Fig. 1 in Baade, these proceedings). Gies and Kullavanijaya (1987) found a rather similar pattern in their analysis of ϵ Per. Insufficient sampling, especially of long beat periods, clearly is a possible explanation. But the vector character of NRP velocity fields may also play a role. This should be easy to verify from synthetic data.

4. CONCLUSIONS

The Be phenomenon is essentially one of variable mass loss. The timescales observed in indicators of circumstellar matter may be dominated by the time needed to disperse this matter (*e.g.* perhaps as a radiatively driven wind). More characteristic of the initial mass loss mechanism(s) are therefore the rise and repetition times of mass loss events. Recent observations have put fairly low upper limits on both timescales. Current evidence is furthermore consistent with the conclusion that the same process that causes the large-scale LPV of Be stars is involved in their mass loss which is neither otherwise explained nor for spectral types later than ~ B2 paralleled by other stars. The detection of genuine multiperiodicity with significant phase velocities in the corotating frame rules out star spots as an explanation of the LPV. Line profile fitting and analyses of more stars should permit a firm conclusion to be reached that Be stars are low-order nonradial pulsators and that they owe (much of) their mass loss and associated line emission to this property.

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DISCUSSION

VOGT My graduate student Don Penrod has observed a fairly large sample of both normal and emission-line B stars and finds the high order modes to be almost always present in both groups. However, only those rapid rotations which develop the l=2 mode ever exhibit Be mass loss outbursts. So, both the presence of an l=2 mode and rapid rotation seem to be required for Be outbursts. Hopefully, these results will be published within the forseeable future.

BOHANNAN The outbursts of Be stars are seen in the grossest ways. What signal-to-noise ratio spectra are required to detect the rotationally related line profile variations in the presence of longer period variations ?

BAADE If you want to detect small outbursts spectroscopically, you also need high spectral resolution (R ≈ 20 - 30 000) and low noise (S/N ≈ 200). More efficient, however, appears polarimetry. For the proper mapping of the line profile modulations the S/N should not be much worse than 300. But this number depends on the intrinsic amplitude and the $v \sin i$ because large line broadening reduces the contrast.