Rotationally Modulated Winds of BA-Type Supergiants

Andreas Kaufer

Landessternwarte Heidelberg, Königstuhl 12, D-69117 Heidelberg, Germany

Abstract. Extended spectroscopic monitoring programs with high resolution and coverage in wavelength and time have revealed a new picture of the winds and the circumstellar environments of late B- and early A-type supergiants. Dramatic line-profile variations (LPV) of the wind-sensitive Hα line with characteristic cyclical V/R variations indicate the presence of deviations of the envelopes from spherical symmetry. Time-series analysis of these LPVs suggest that the wind variations are caused by rotating surface structures which modulate the lower wind region. Occasionally observed high-velocity absorptions (HVA) indicate the presence of rotating extended and dense streakline or loop structures in the envelopes. The potential use of these circumstellar features to determine the true stellar rotation periods is discussed.

1 Introduction

Based on extended spectroscopic monitoring programs with high resolution and coverage in wavelength and time a new picture of the winds and the circumstellar environments of late B- and early A-type supergiants (in the following BA supergiants) has emerged in the last years (cf. e.g. Kaufer 1998b).

In this contribution the observational evidence for rotational modulation of the winds of BA supergiants is discussed.

2 Signature and time scales of wind variability

The Heidelberg group has carried out extended spectroscopic monitoring campaigns on BA supergiants to examine their photosphere and envelope variability (cf. Kaufer 1998a for a description of the campaigns).

Their crucial finding about the complex wind variability patterns in *all* of the six examined program stars is that – independent of the timely average appearance of the most wind sensitive Hα profile – the variability pattern is localized symmetrically about the system velocity with the maximum power of the variations just beyond the $\pm v \sin i$ velocities of the star (Kaufer et al. 1996a). The variations are mainly due to additional violet (V) and red (R) shifted emission components superimposed on the otherwise constant underlying wind or even photospheric profiles. The amplitudes of the modulations were measured for all program stars in the corresponding 'temporal

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variance spectra' (TVS) and give equal amplitudes for the V and R peaks with values between 5% and 20% which are characteristic for the individual object. This characteristic V/R variability is highly indicative for deviations of the circumstellar envelopes of BA supergiants from spherical symmetry: a presumably equatorial concentration of the emitting circumstellar material is favored by Kaufer et al.

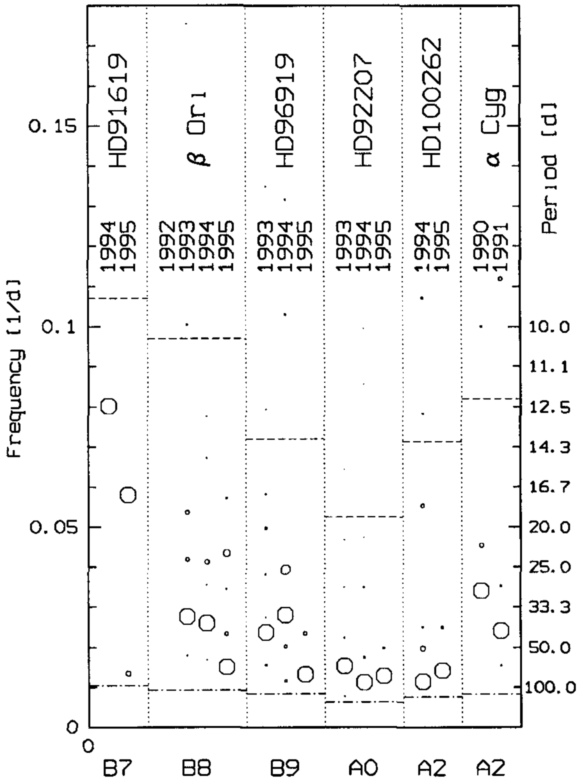

Fig. 1. CLEANed frequencies from Hα equivalent-width curves of the program stars of Kaufer et al. Horizontal dashed lines indicate the frequencies of expected photospheric radial fundamental pulsation modes $P_{\mathrm{rad,fund}}$ for $\log Q = -1.4$. Dot-dashed lines indicate the estimated lower limits for the rotational frequencies given by $P_{\mathrm{rot}}/\sin i$. Note that always one dominant period is found.

The measured equivalent-width curves of the variable 'excess' emission display best the cyclical variability of the wind profiles. Figure 1 shows the annual CLEANed frequencies from Hα equivalent-width curves of the six program stars in comparison with the frequencies of the expected photospheric radial fundamental pulsation modes and the lower limits for the rotational frequencies derived from $P_{\mathrm{rot}}/\sin i$. These time-series analyses of the equivalent-width curves reveal for all examined stars basically *one* dominant period, which is in all cases close to the rotational period as estimated from $v \sin i$

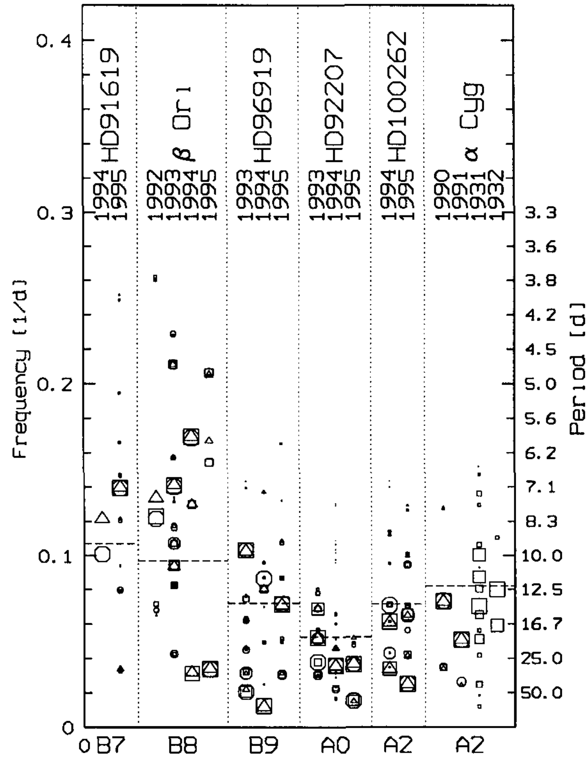

Fig. 2. CLEANed frequencies from the radial-velocities curves, which were measured with a cross-correlation method. The different symbols refer to the different groups of lines (triangles = weak, squares = medium, circles = strong); the size of the symbols represent the power (the significance) of the respective peaks in the periodograms. The horizontal dashed lines give $P_{\mathrm{rad,fund}}$ for $\log Q = -1.4$. Note the multiperiodicity and the variability from year to year of the frequency spectrum and the concentration around $P_{\mathrm{rad,fund}}$.

and the stellar radius. At this point it is worth to note that the values for $v \sin i$ of BA supergiants cannot be derived directly from the width of the photospheric line profiles since BA supergiants (as most of the evolved hot stars in the upper HRD) are known to show significant additional broadening mechanisms apart from rotation. The approach used by Kaufer et al. is to measure the width of the variable part of the profile by the use of 'temporal variance spectra' as suggested by Reid et al. (1993). The idea is that possible surface structures like spots or pulsation patterns which probably cause the LPVs are Doppler-mapped by the stellar rotation to a maximum velocity, which is to be identified with $v \sin i$. This method assumes that an azimuthal velocity component of the surface structures is small compared to the value of $v \sin i$. Apart from this, the even larger uncertainty for the estimate of upper limits for the rotation periods $P_{\mathrm{rot}}/\sin i$ of the program stars comes from the difficulties in the determination of their radii due to badly known distances and luminosities.

Even with keeping in mind these uncertainties and difficulties, the wind modulation frequencies shown in Fig. 1 give strong evidence for a rotational modulation of the lower circumstellar envelope of BA supergiants by stellar surface structures. Kaufer et al. suggest that an efficient coupling of the stellar rotation into the lower wind region could be provided by weak magnetic surface structures. From their detailed examination of the simultaneously recorded photospheric line-profile variability (Kaufer et al. 1997) they could rule out in first order e.g. non-radial pulsation patterns as modulating surface structures. Figure 2 shows the corresponding CLEANed photospheric frequencies to Fig. 1 as derived form radial-velocity curves. Multi-periodic NRPs are present in their data sets in form of low-order g-modes but occur on time scales distinct from the wind variability and are more coincident with the expected photospheric radial fundamental pulsation periods as indicated as dashed horizontal lines in Figs. 1 and 2.

Note that the pulsation periods in BA supergiants are clearly distinct from the rotation periods. However, in the case of the proposed non-radial g-modes, which are expected to display longer periods than the radial fundamental modes, this separation of time scales might shrink. On the other hand, Kaufer et al. report that the photospheric line-profile variations display prograde traveling pseudo-emission and pseudo-absorption features with crossing times from $-v \sin i \rightarrow +v \sin i$ of the order of the break-up rotation period and therefore, identify these features as NRP modes and not as rotating surface features.

Also the clear presence of multi-periodicity of the photospheric pulsations (cf. Fig. 2) could systematically shift the photospheric time scales towards longer time scales of the order of the estimated rotation periods by the beating of multiple periods. Recently, Rivinius et al. (1998) have presented strong observational evidence for mass-loss events triggered by the beating of closely spaced non-radial pulsation periods for the Be star μ Centauri. In addition to the multiplicity of the photospheric period spectra in BA supergiants, the variability from year to year of the period spectrum itself (see the periods from different years for the individual objects in Fig. 2) so far inhibits any precise determination of the pulsation modes, which would be required in order to test the tempting hypothesis of pulsation-driven mass-loss events in BA supergiants.

3 Repetition times of high-velocity absorptions

Temporarily the envelopes of BA supergiants display extraordinarily large and extended circumstellar structures which become observable as suddenly appearing, highly blue-shifted, and unusually strong absorption features; the so-called high-velocity absorptions (HVA) (cf. Kaufer et al. 1996b, Israelian et al. 1997). Both groups suggest localized regions of enhanced mass loss on the stellar surface to build up these extended circumstellar structures; Kaufer et al. favor rotating streak lines in the equatorial plane, Israelian et al. rotating loops, the latter supported by the observation of red-shifted absorption as indication of strong infall of material during an HVA event. In their picture the observed HVAs are the result of the *rotation* of these structures through the line of sight.

In two cases (HD 96919 and β Ori) it seems plausible that two extreme rotating circumstellar structures were strong enough to survive for several months and have been observed over several rotational cycles. This would allow for the first time a *direct determination of the (circum)stellar rotation period.*

In the case of the extremely strong and accidentally well-observed HVA event in HD 96919 in 1995, Kaufer et al. were able to derive directly a repetition time of 93 days from the reappearance of double-peaked emission components within one contiguous time series. With this 'period', the reappearance after four cycles of this very strong and therefore presumably quite time persistent HVA was predicted for March 22, 1996 (MJD 50164 = time of the maximum blue absorption) and indeed observed in a follow-up campaign at La Silla exact on the predicted date. The repetition time of 93 days is consistent with the estimated $P_{\rm rot}/\sin i = 119$ days for HD 96919 and therefore was identified as the true (circum)stellar rotation period.

In the second case of β Ori, the maximum blue absorptions of two comparatively strong HVAs in autumn 1993 and spring 1994 were observed 108 days apart. This interval is in excellent agreement with the estimated $P_{\rm rot}/\sin i = 108$ days for this star.

The crucial point about this direct determination of true (circum)stellar rotation periods is obviously the observational distinction between HVA events caused by the *same* circumstellar structure and HVA events caused by two individual, timely and spatially independent circumstellar structures. Basically, the latter can never be completely ruled out even not with a continuous (spectroscopic) monitoring of the object. From the observational material obtained so far, i.e., the two events described above, criteria for the identification of physically related HVAs might defined as (i) an integer cycle numbers between two events, (ii) similar characteristics of the line-profile and velocity signatures, i.e., the double-emission peaks, the depth and velocity of the maximum absorption, the slope of the rising branch of the equivalent-width curve of the event, (iii) a continuous weakening of the structure from cycle to cycle since the HVAs are observed to fade over several months until they disappear.

4 Discussion

The observational evidence for rotational modulation of the winds of BA supergiants has been presented in this paper.

The analysis of the line-profile variability of the most wind-sensitive line Hα has provided new insight in (i) the 'general' and always present wind variability of BA supergiants, which produces quite dramatic LPVs in Hα but a moderate 5 – 20% modulation of the integrated equivalent width, and (ii) the 'exceptional' variations as observed during the HVA events. Figure 3 illustrates the two intensity scales of the two types of observed variability.

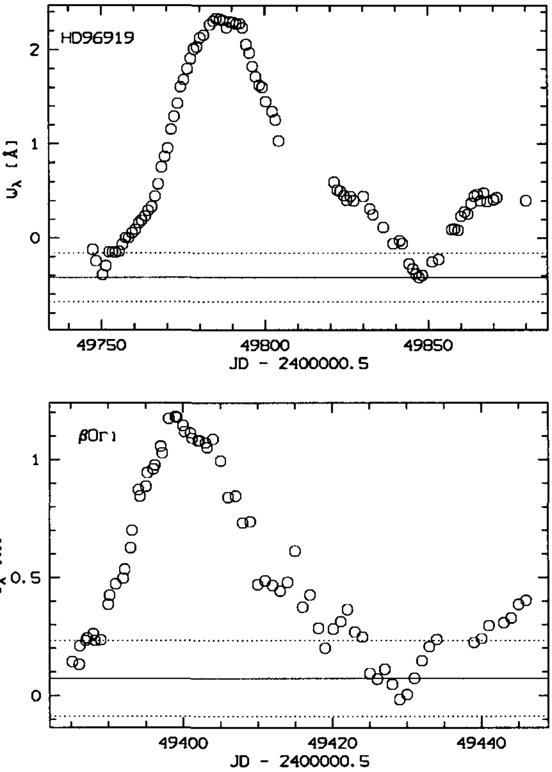

Fig. 3. Time development of the total Hα equivalent width during the HVA events of β Ori in 1994 (bottom) and HD 96919 in 1995 (top). For comparison the mean equivalent widths of the respectively preceding years (without HVAs) are indicated by full lines. The broken lines indicate the corresponding standard deviations representing the 'general' Hα variability. These statistics were computed from 86 spectra of β Ori and 83 spectra of HD 96919 obtained in 1993. Note the striking similarity in the run of the equivalent widths of two HVAs in two different stars.

Interestingly, both could be ***independently*** related the stellar rotation, (i) to rotating surface structures modulating the lower circumstellar envelope (based on time scale arguments), and (ii) to rotating extended circumstellar streaklines or loop structures also rooted to the stellar surface in localized regions of enhanced mass loss (based on the observation of the reappearance of the bona fide identical circumstellar structure).

For the so far two objects where both types of wind variability could be observed quantitatively, i.e., HD 96919 and β Ori, the corresponding dominant periods as found from (i) are *not* strict integer fractions of the directly determined periods from (ii). But in all cases the former are in the range of 0.5 – 0.3 times $P_{\rm rot}/\sin i$ whereas the direct periods are very close to the estimated rotation periods $P_{\rm rot}/\sin i$.

This leads to the conclusion that the 'general' rotational modulation of the winds of BA supergiants is caused by several ($\sim 2-3$) simultaneously present surface features, which are probably not located in equidistant stellar longitudinal sectors but are distributed irregularly. This is consistent with the on the first look definitely non-periodic appearance of the Hα LPVs. On the other hand, the 'exceptional' structures observed as HVAs are comparatively rare and have to be attributed to singular but therefore more extended and dense structures reaching up to several stellar radii (Israelian et al. 1997) into the circumstellar envelope. It seems plausible to speculate that individual of the always present surfaces structures could develop under certain – so far unknown – circumstances into strong and extended streaklines or magnetic loops.

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Discussion

H. Henrichs: I am puzzled by your remark that many of your stars have rotationally modulated winds and at the same time show different periods from season to season. Could differential rotation account for this ?

A. Kaufer: We do not find an obvious connection between rotationally modulated winds and photospheric pulsation. And it is the frequency spectrum of the photospheric variations which is found to vary from year to year. It looks to me like we have objects with rich period spectra, but only selected pulsation modes are excited; and the same modes are not necessarily excited each time we look at them.

T. Eversberg: Maybe I can add a reminder: such NRP mode variations are already known for δ Scuti stars observed by the Breger group in Vienna. They explained these quick changes by changes in the inner structure of the star.

S. Owocki: Could you clarify again why you say that the "High-Velocity Absorptions" (HVAs) you see are different from the "Discrete Absorption Components" (DACs) seen in UV wind lines? In particular, do you have the time resolution to rule out acceleration on the wind acceleration time scale? Also, a comment: the azimuthal speed declines so quickly outward, that it is difficult for material to be brought into the disk line-of-sight anywhere away from the surface. On the other hand, this does occur much more readily for rigidly rotating structures, as from, say, a magnetic structure extending to a stellar radius or so.

A. Kaufer: For a beta-type velocity law and typical stellar-wind parameters with $\beta \approx 0.8 \dots 1.5$ and $v_{\rm inf} \approx -200 \dots -300\,{\rm km\,s^{-1}}$, the flow time scales (defined as the time span for acceleration from $0.2\,v_\infty$ to $0.8\,v_\infty$) are on the order of 20 to 60 days; during a HVA event the blue absorption over the same velocity range grows to its maximum depth within some 1 to 5 days without any clear acceleration. This is why we favor the rotation of an existing structure into the line-of-sight as the model for the HVA. Concerning your comment: in our simple streakline model we had to include rigid rotation of the inner envelope up to about 1 stellar radius to account for the quasi-instantaneous deepening of the line-of-sight absorption over the full velocity range (cf. Kaufer et al. 1996b).

I. Appenzeller: Concerning the temporary presence and absence of pulsations in your stars, in spite of the fact that these stars seem to be in a stable region of the H-R diagram: the absence of instabilities does not mean that a star cannot pulsate. It only means that the pulsations are damped. But if the star gets a "kick" from some nonstationary process, it will pulsate for some time. The mode (temporarily) excited will depend on the symmetry (or asymmetry) of the "kick".