SOME OBSERVATIONS RELEVANT TO THE THEORY OF EXTENDED ENVELOPES

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ABSTRACT. Recent observations of S Dor variables and B[e]-supergiants are reviewed. These objects belong to the visually and bolometrically brightest stars in the universe. They have gained considerable interest for their exceptional stellar wind properties and represent rare cases of hot blue stars which form dust envelopes. S Dor variables are characterized by major outbursts. The ejecta have been spatially resolved in some cases. These luminous emission line stars are supposed to represent a short-lived phase in the evolution of the very massive stars prior to becoming WR stars.

## 1. INTRODUCTION

A great variety of objects which are topics of this symposium are characterized by extended circumstellar envelopes. I shall concentrate on observations of luminous blue stars which have been studied by our group within the SFB 132 (Baschek, 1987, this volume) over the past few years. Among the luminous blue stars are two groups which are particularly distinguished due to their strong emission-line spectra: the S Dor variables and the B[e]-supergiants. These stars which are supposed to represent a short-lived phase in the evolution of the very massive ($M \gtrsim 50\ M_\odot$) stars (cf. e. g. Maeder, 1983, Wolf, 1986, Zickgraf et al., 1986) form due to their particular wind characteristics cool extended shells. The main properties of these objects will be discussed in the following.

## 2. S DOR VARIABLES

The S Dor variables or Hubble-Sandage-variables are the visually (up to $M_V \approx -11$) and bolometrically brightest stars



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in the universe and were among the first stellar objects observed in other galaxies (Pickering, 1987, Duncan, 1922, Wolf, 1923).

S Dor variables are blue hypergiants with occasional eruptions of more than one magnitude on timescales of years to decades. From detailed spectroscopic observations, particularly of the LMC-S Dor variables R71 (Wolf et al., 1981) and of R127 (Walborn, 1982, Stahl et al., 1983) these luminous blue variables turned out to be OB supergiants. During eruption they exhibit spectra equivalent of later type (late B to A, F) formed in the expanding envelopes and characterized by strong P Cygni type emission of the Balmer lines and of lines of singly ionized metals. With an increase in brightness the stars become redder and their equivalent spectral type later. This behaviour was particularly well studied in the case of R127 (Stahl et al., 1983). This object had been classified as an Of/WN-transition type star during minimum. R127 had an outburst in the early 1980's and has since then still increased in brightness. In the beginning of 1986 it was the visually second brightest star in the LMC (V = 9.5). Its recent light curve is given in Fig. 1. Sections of spectra taken with CASPEC at the 3.6 m telescope of ESO, Chile, in 1984 and 1986, respectively, showing the spectral evolution of R127 are presentend in Fig. 2. Note that during the very bright phase in 1986 R127 exhibits a spectrum which is almost a clone of the spectrum of the prototype S Dor during outburst.

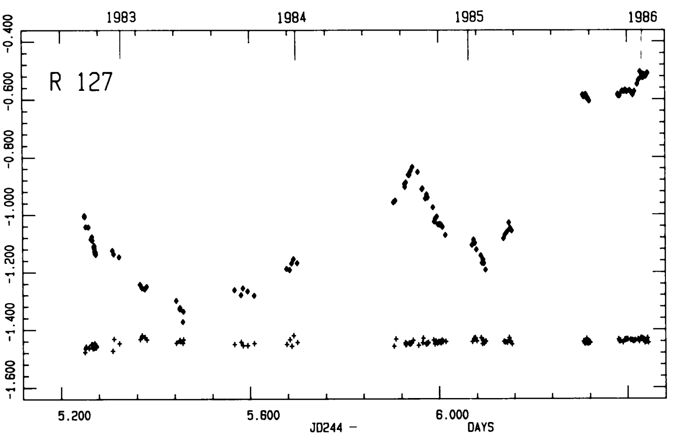


Figure 1. Visual (Strömgren y) differential light curve (◇) of R127. The y-magnitude of $C_1$ is 8.86. (+) denotes differences between comparison and check star. The observations are from the "Long-term photometry of variables" group, initiated by C. Sterken

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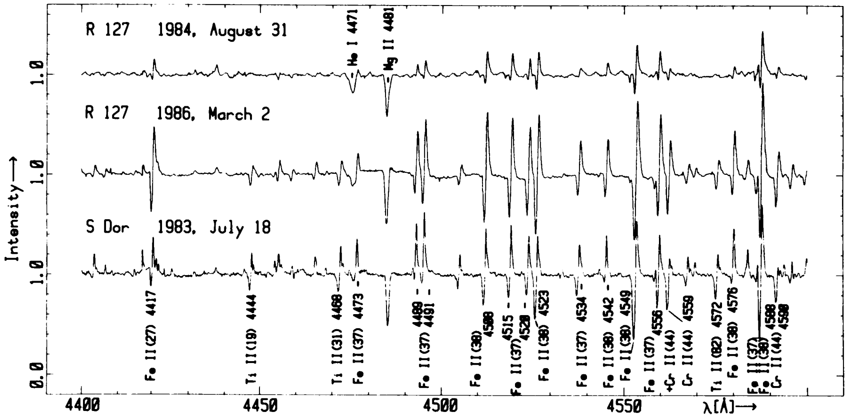


Figure 2. The spectral evolution of R127 and comparison with S Dor

A major finding by our group (cf. Wolf et al. 1981, Appenzeller and Wolf, 1982) has been that although the visual brightness during outburst increases by more than a magnitude the bolometric luminosity remains essentially unchanged. This former hypothesis has been recently observationally established in the case of the galactic star AG Car which was visually very bright in the early 1980's and about two magnitudes fainter in 1985 (for the light curve see Stahl, 1986). Its bright phase spectrum was shown by Wolf and Stahl (1982) to be of S Dor type during outburst whereas the spectrum in 1985 was shown by Stahl (1986) to be typical for Of/WN-stars. Since the launch of IUE in 1978 AG Car was monitored in the satellite UV. From these observations bolometric magnitudes were derived by direct flux integration (Cassatella and Viotti, 1986) showing that $M_{bol}$ remained practically constant inspite of the above mentioned visual brightness variations. As outlined in a series of papers by our group (cf. e. g. Wolf, 1986, and literature quoted therein) this behaviour can be understood by stellar flux redistribution due to strong density variations in the highly variable wind of S Dor types. The mass-loss rate is typically $5.10^{-5}$ $M_{\odot}yr^{-1}$ and is about a factor of ten lower than that during minimum.

A detailed study of the wind characteristics of the prototype S Dor during its bright phase has been recently carried out by Leitherer et al. (1985) on the basis of coordinated spectroscopic and photometric observations from the satellite UV to the infrared.

The high dispersion IUE spectrum is characterized by copious absorption lines of singly ionized metals formed in the expanding envelope. All lines are blueshifted against the systemic velocity and in addition the edge velocity

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$v_{edge}$ was found to depend on the excitation energy $\chi$; the edge velocity increases with decreasing $\chi$ from $v_{edge}$ = 50 km $s^{-1}$ (for $\chi$ = 5 eV) to $v_{edge}$ 150 km $s^{-1}$ (for $\chi$ = 0.0 eV). This dependence can be interpreted in terms of a depth-dependent temperature- and density-field where the velocity is increasing outwards. The edge velocity of the highly excited lines agrees resonably with the maximum outflow velocity as derived from the full width at zero intensity of the [Fe II]-lines which are best observed during fainter phases and which are formed at larger distances from the star. Modelling the observed IR-excess following the method discussed by Lamers and Waters (1984) yielded a smoothly increasing linear velocity law and a mass-loss rate of $\dot{M} \approx 10^{-4}$ $M_{\odot}yr^{-1}$. The velocity law derived in this way is very similar to the one found for P Cygni by Waters and Wesselius (1985) on the basis of infrared observations. This velocity law can not only account for the $\chi$-dependence of $v_{edge}$ of the UV lines but also for the prominent Balmer line P Cygni profiles. Particularly very sharp narrow emission peaks (about ten times continuum intensity in the case of $H_{\beta}$) indicate that a considerable fraction of the wind is at low velocities. Since even the typical high wind densities ($N_e \approx 10^{11}$ $cm^{-1}$) of S Dor variables during outburst require a large emitting volume to generate the observed high Balmer line flux, the velocity law has to be very gradual in order to produce the small Doppler velocities necessary for the narrow emission component. Both the extremely high value of $\dot{M}$ and the very gradual velocity law with a very low terminal velocity of only 150 km $s^{-1}$ indicate that a wind mechanism different from that of normal OB stars must be active.

S Dor like other luminous emission line stars of the LMC (cf. Stahl and Wolf, 1986a,Appenzeller et al. 1987) show also narrow emission lines of [N II] ($\lambda\lambda$6548, 6583, 5755) corresponding to flow velocities of only about 60 km $s^{-1}$. Hence at the distance where these lines form ($N_e$ < $10^5$ $cm^{-3}$) the flow velocity is significantly lower than the maximum velocity in the inner parts of the envelope. Presumably [N II] is emitted in a region of interaction between the wind of an earlier epoch and ambient interstellar matter. Then we observe in the [N II] lines of S Dor an unresolved "ring nebula" of the kind seen around AG Car (Thackeray, 1977) and around R127 (see below).

S Dor (like R127, R71 and other S Dor variables) contains in the visual spectrum also a few pure absorption lines; namely collisionally populated high excitation lines like Mg II, He I and Si II. The radial velocities of these lines are slightly variable ($\Delta v \approx$ 20 km $s^{-1}$) around the systemic velocity. From these lines Leitherer et al. (1986) inferred the existence of an extended pseudo-photosphere which appears to be the base of the stellar wind of the

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S Dor variables. The pseudo-photosphere where the continuum forms is in the case of S Dor of spectral type A and its extent is estimated to be about eight times larger during maximum than the stellar core. The radial velocity variations around the systemic velocity may indicate the presence of pulsation-like large-scale expanding and receding motions of the pseudo-photosphere. No theoretical explanations of how these pseudo-photospheres are formed during outburst have yet been provided. But an understanding of the pseudo-photosphere appears to be of fundamental importance for a realistic wind model of the eruptions of S Dor variables (cf. also Davidson, 1986). When the extended cool pseudo-photosphere is formed (i. e. hot stellar plasma is cooling down) the highly ionized metals are recombining to the second and first ionization state. From these ions the vast number of the before mentioned absorption lines in the UV originate which finally may produce a strong opacity driven wind as suggested by Lamers (1986) and Appenzeller (1986).

A consequence of the slow flow velocities of S Dor variables may be that dust can form in the winds of these intrinsically hot stars. In a recent paper Wolf and Zickgraf (1986) have shown that the LMC-S Dor variable R71 is an IRAS point source. The IRAS-measurements at 12, 25 and 60 microns are shown along with groundbased observations in the UBVRIJHKN bands, carried out during minimum phase, in Fig. 3. The very strong excess in the far infrared is ascribed to a very cool ($T_{Dust} \approx 140$ K) and very loosely bound dust shell ($R_{Dust} \approx 8000\ R_*$) around R71. The amount of dust condensed in this shell has been estimated to be of the order of $M_{Dust} \approx 3 \cdot 10^{-4}\ M_\odot$. Using the canonical value of the gas to dust ratio of 100 a total mass of the shell of $3.10^{-2}\ M_\odot$ is estimated. Assuming a mass-loss rate of $5.10^{-5}\ M_\odot yr^{-1}$ (Wolf et al., 1981) this amount of matter has been ejected within about 600 years. This agrees reasonably well with the kinematic age of 400 years derived from the radius $R_{Dust}$ and from the very low expansion velocity ($v_{exp} \approx 20$ km $s^{-1}$) at this distance as derived from the splitted [N II]-lines $\lambda\lambda$6548, 6583 (see Fig. 4).

To study the mass-loss history of S Dor variables and to get some observational basis for the estimate of the duration of the S Dor phase the spatial resolution of extended nebulosities is of crucial importance. Nebulosities have been detected around the galactic S Dor variables $\eta$ Car (Davidson et al. 1986 and literature quoted therein) and AG Car (Thackeray, 1977). Quite recently the nebulosity around the LMC-S Dor variable R127 has been resolved on long-slit high dispersion spectra in [N II] 6548, 6583, [S II] 6717, 6731, and also in $H_\alpha$. For contour plots see Appenzeller, Stahl and Wolf (1987, this volume). The nebula shows obviously deviations from total spherical symmetry.

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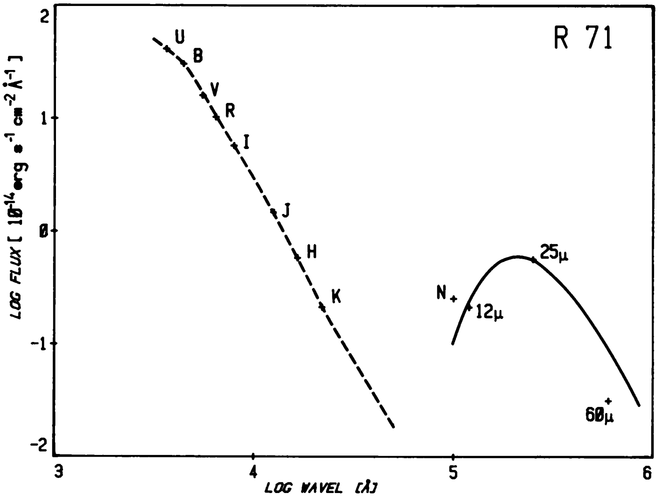


Figure 3. Broad-band fluxes of R71 during minimum phase from ground-based observations (UBVRIJHK and N) and IRAS-measurements at 12, 25 and 60 microns. Note the presence of a very strong excess in the far infrared which is ascribed to a very cool ($T_{Dust}$ = 140 K), losely bound ($R_{Dust}$ = 8000 $R_*$) dust shell around R71. The solid line is the black body curve for T = 140 K.

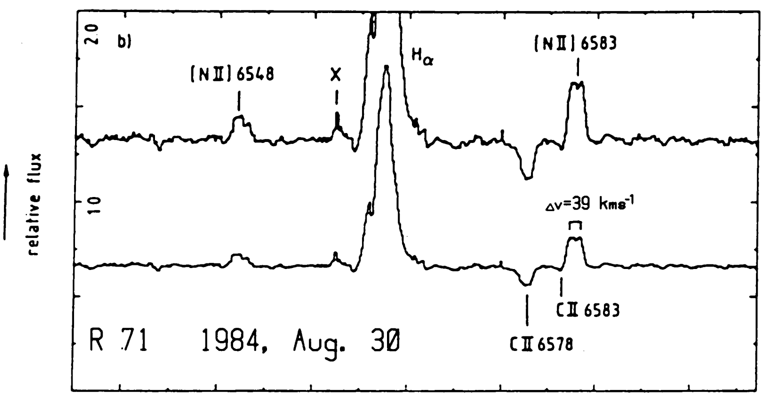


Figure 4. $H_\alpha$ and [N II] λλ6548, 6583 of R71. The [N II] lines are double peaked. An expansion velocity of the nebula of only 20 km $s^{-1}$ is derived from the separation. Note that [N II] λ6583 is disturbed by absorption of C II 6583.

Such deviations provide evidence for a non spherical wind during outburst and could e. g. cause the multi component substructure of the UV Fe II-lines shown in Fig. 5 and amply discussed by Stahl et al. (1983) and Stahl and Wolf (1986b). A kinematic age of $2.10^4$ yrs was derived for the

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nebula. This corresponds closely to the expected life time of the S Dor evolutionary phase.

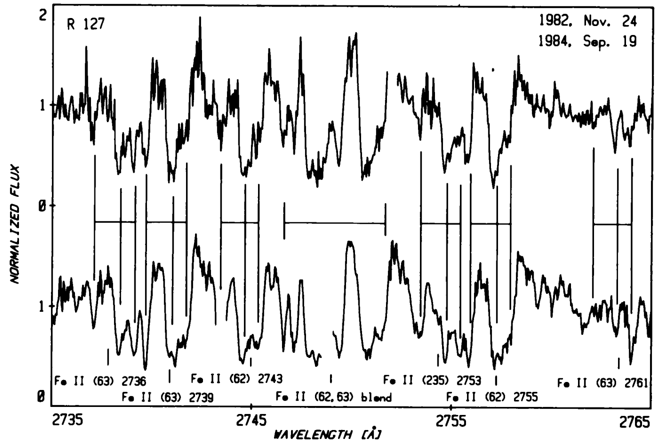


Figure 5. Fe II lines (mainly of multiplets Nos. 62 and 63) on IUE spectrograms taken in 1982 and 1984, respectively. Three components with heliocentric velocities 15, 157, and 232 km $s^{-1}$ are discernible. The radial velocities of the three components have not changed during the two years interval. Likewise no conspicuous variations of the relative intensities of the components have occurred.

The location of the S Dor variables (or Hubble-Sandage variables) of the LMC and of M31 and M33 in the HRD (Humphreys et al. 1984) is shown below (see Fig. 10). Earlier suggestions (Sterken and Wolf, 1978, Humphreys and Davidson, 1979, Wolf et al. 1980) according to which the S Dor variables represent a short-lived phase of massive stars ($M \gtrsim 50\ M_{\odot}$) as immediate progenitors of the massive WR stars got further support from Maeder's (1983) computation of evolutionary tracks of very massive stars including the S Dor phase and are now widely accepted. According to Maeder's computations CNO processed material should appear at the surface already during rather early phases of the evolution and should be detectable in the atmospheres or ejecta of S Dor variables. In fact Davidson et al. (1982) and Davidson et al. (1986) found e. g. in the S condensation of $\eta$ Car that most of the CNO is indeed nitrogen.

## 3. B[e]-SUPERGIANTS

Another particularly interesting subgroup of the luminous blue emission-line stars are the dusty B[e]-supergiants. These objects are located in the HRD in the same region as

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the S Dor variables (cf. Fig. 10) and have been recognized as a group particularly from studies of members of the MC's by Zickgraf et al. (1986).

B[e]-stars are characterized by the following typical properties:

a) strong Balmer emission lines, frequently with P Cygni profiles

b) permitted and forbidden emission lines of Fe II, [Fe II], [O I] etc.

c) strong infrared excess due to thermal radiation of circumstellar dust.

The determination of the spectral type of B[e]-stars is often very difficult due to the lack or scarcity of photospheric absorption lines. Hence only a few galactic B[e]-stars like MWC 349 (Hartmann et al. 1980), CPD -52°9243 (Swings, 1981), and MWC 300 (Wolf and Stahl, 1985) have been convincingly shown to be luminous supergiants.

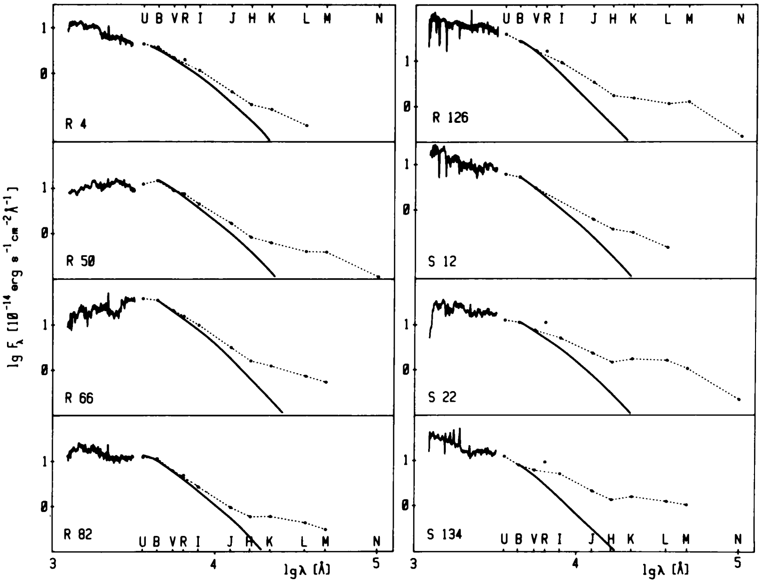


Figure 6. Continuum energy distributions of the MC's B[e]-supergiants from the satellite UV to the IR. The visual and IR-fluxes were deduced from broad-band photometry. An excess in KLM(N) with colour temperatures of 900 K to 1200 K is clearly discernible. In order to better judge the amount of free-free envelope emission and dust emission estimated visual and infrared fluxes for underlying Kurucz atmospheric models are also shown (full line). The conspicuous excess in the R-band of most objects is due to the very strong $H_\alpha$-emission.

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Eight B[e]-supergiants are known to be members of the MC's. Their spectral energy distribution has been well studied from the satellite UV to the infrared and are shown in Fig. 6. The dust component with typical dust temperature of 900 to 1200 K is clearly evident. By carefully looking for photospheric absorption lines it was found that apart from R66 (B8Ia) all stars are early B supergiants (B0-B3).

The spectral appearance of B[e]-supergiants in the optical range is very similar to the S Dor variables. Fig. 7 shows a section of the optical spectrum of the prototype R126. However, unlike the S Dor variables the B[e]-supergiants of the LMC e. g. have only shown (thus far?) little or no photometric variations. Their mass loss appears to be much more stationary and stable.

High dispersion IUE observations of the prototype R126 revealed an intriguing result. The LWP spectrum is dominated by narrow emission lines as expected from the spectral appearance of the optical range. However, the SWP range is dominated by broad UV-resonance lines of N V, C IV, Si IV etc. (see Fig. 8). These resonance absorption lines of high

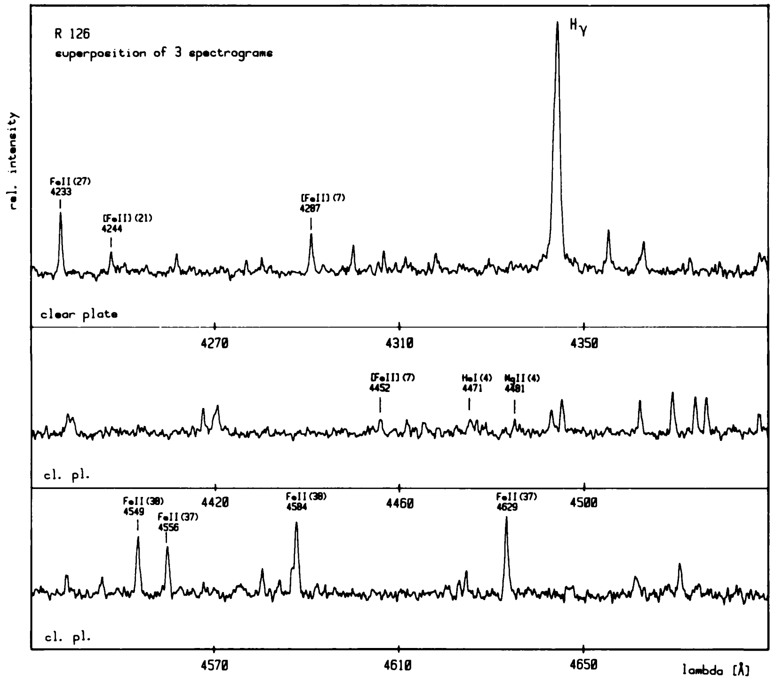


Figure 7. Section of the optical spectrum of the dusty B[e]-supergiant R126 around $H_\gamma$. Numerous Fe II- and [Fe II]-lines are conspicuous. The Doppler velocity derived from the width of the Fe II-lines is only 20 km $s^{-1}$. The [Fe II]-lines are not resolved.

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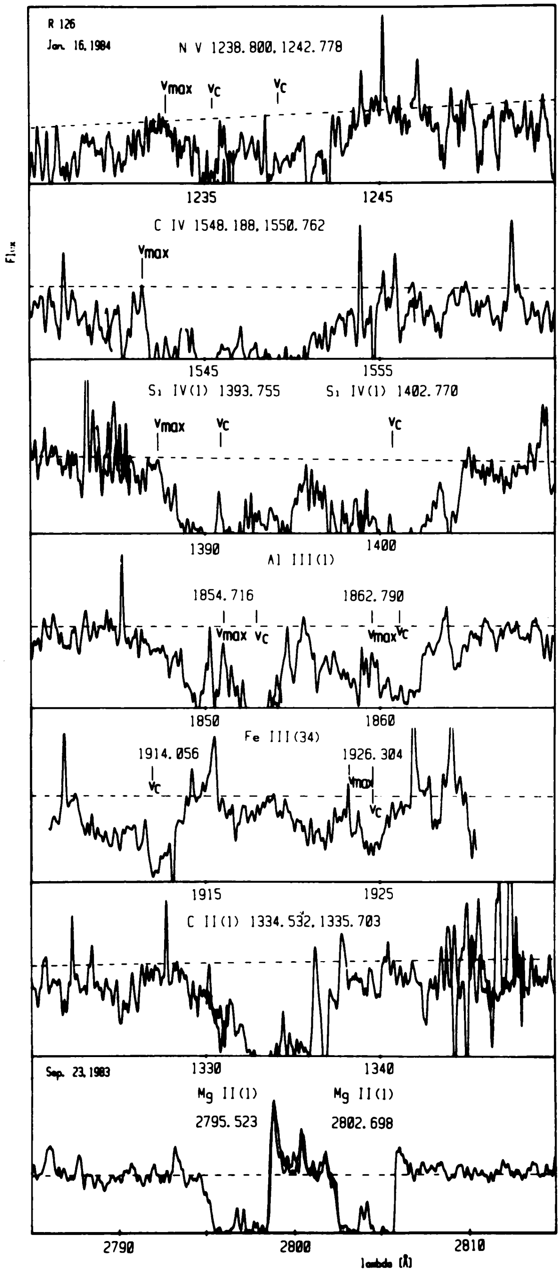


Figure 8. UV resonance absorption lines and Fe III(34)-lines of the dusty B[e]-supergiant R 126. Maximum expansion velocities $v_{max}$ are ranging from 750 km $s^{-1}$ (Fe III-lines) to 1760 km $s^{-1}$ (N V(1)).

expansion velocities ($v_{max}$ ~ 1800 km $s^{-1}$) are typical for a line-driven "normal" wind for hot stars (e. g. Castor et al., hereafter CAK). The hybrid character of the line spectrum, i. e. narrow emission lines (FWHM ≈ 20 - 50 km $s^{-1}$) in the optical spectrum and in the IUE-LWP range and broad absorp-

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tion resonance lines ($v_{max} \approx 1800$ km $s^{-1}$) can be interpreted by a two component wind model as depicted in Fig. 9 (Zickgraf et al. 1985).

According to this model the UV-resonance lines of highly ionized species (N V, C IV, Si IV etc.) originate in a high velocity line-driven CAK-type wind near the pole of the hypergiant star. The disk is supposed to be formed by a slow ($\approx$40 km $s^{-1}$), cool dense wind. The observed narrow emission lines of Fe II, [Fe II] and of other singly ionized metals in the IUE-LWP spectrum and in the optical wavelength range, as well as the thermal dust emission are produced in the disk. Stellar rotation at close to the break-up velocity is the driver of this two-component structure.

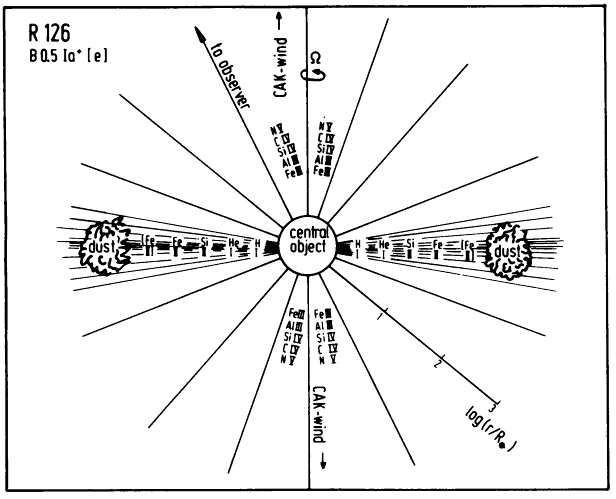


Figure 9. Proposed bipolar flow model for the prototype R126 of the B[e]-supergiants. The ions in the disk region are ordered corresponding to their line widths and in the polar region according to the expansion velocity. According to the model dust formation occurs in the slow dense wind in the equator region whereas a normal CAK wind is present in the polar region.

Zickgraf et al. (1986) extended this model which has many similarities to the model suggested for classical Be stars (Poeckert and Marlborough, 1978) to all eight known B[e]-supergiants of the MC's. Marked spectral differences observed between the individual B[e]- supergiants could be explained by assuming different inclination angles. (However, I should like to note the cautionary example R4 of the SMC which shows a very peculiar line spectrum being possibly formed in a binary system (Zickgraf and Wolf, 1987, this volume).)

A bipolar flow pattern of an angular extension of 0."5

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separated by a dark lane confirming the existence of a non-spherical mass loss (as e. g. suggested in the two-component wind model) was found by VLA observations of the luminous galactic B[e]-star MWC349 (White and Becker, 1985; see also Cohen, 1987, this volume). In addition Leinert (1986) resolved this star in the infrared, using speckle interferometry, and found a gaussian FWHM of 0".085 in the east west direction but only of 0".038 in the north south direction. This last result could also indicate the existence of a disk, in this case for a dust distribution. In the case of the LMC B[e]-supergiant Hen S22 evidence of deviations from spherical symmetry was also found from the study of Fe II emission and absorption lines and of the continuum energy distribution (Bensammar et al., 1983, Muratorio and Friedjung, 1986).

As noted above, stellar rotation is supposed to be the driver of the slow equatorial wind. At a first glance it appears unlikely that rotational effects can play an important role in supergiant stars as - for the case of local conservation of angular momentum - the ratio between centrifugal and gravitational acceleration at the surface decreases rapidly when the star evolves away from the main sequence. However, the B[e]-supergiants are in the same region in the HRD as the S Dor variables. Hence like in the S Dor variables and as outlined above the combined opaci-

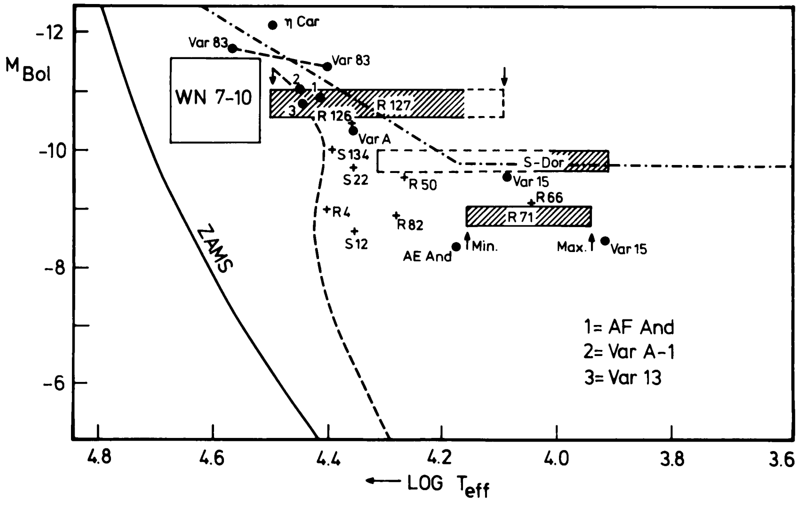


Figure 10. HRD showing the S Dor variables of the LMC (bars) and of M31 and M33(.). The position of the MC's-B[e]-supergiants are denoted by (+). Also given are the boundaries of the main-sequence band (ZAMS = solid line, TAMS = broken line according to Maeder, 1981). The dash-dotted line indicates the upper limit of stellar luminosities (cf. Humphreys and Davidson, 1979).

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ties of many merging lines exert an additional acceleration. In such a situation even a centrifugal acceleration which is smaller than the gravitational term can lead to a negative acceleration at the equator, which can be compensated only by an outward acceleration of matter, i. e. an enhanced mass loss. In addition, due to convective angular momentum transport from the contracting innermost layers and the loss of the outermost stellar layers in the main sequence phase the rotation of the surface layers of very massive supergiant stars may be higher than expected from the local angular momentum conservation hypothesis.

As mentioned above the B[e]-supergiants are located in the same region of the HRD as the S Dor variables (Fig. 10). As shown by the figure the B[e]-supergiants are located to the right of the main sequence band. From a comparison with evolutionary tracks it is clear that they represent evolutionary stages of massive ZAMS O stars. However, inspite of their similar luminosity B[e]-supergiants have not shown major outbursts. Possibly stellar rotation leading to an enhanced mass loss from the equatorial regions prevents them from becoming S Dor-type unstable.

## 4. CONCLUSIONS

The aim of the talk was to present "Some Observations Relevant to the Theory of Extended Envelopes" of luminous blue stars, the S Dor variables and the B[e]-supergiants. Considerable technical advances have been made during the past few years which allowed us to obtain of these objects e. g. spectrograms of high resolution and high S/N-ratio (e. g. wich CASPEC attached to the 3.6 m ESO telescope), to get spectra in the satellite UV with IUE and infrared data both from ground-based (JHKLMN) observations and from space observations with IRAS. A lot of interesting results have considerably improved our knowledge on S Dor variables and B[e]-supergiants. For a previously heterogenious group of blue luminous stars in the uppermost corner of the HRD a logical order is emerging in the form of an evolutionary sequence.

Yet very basic questions such as the nature of the wind mechanisms active in these objects, the nature of the pseudo-photospheres and the cause of the outburst of S Dor variables are essentially unanswered. However, we have learnt to put these questions and what we do need most urgently is "Some Theory Relevant to the Observations ...".

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