"NORMAL" LBV ERUPTIONS A LA S DORADUS

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ABSTRACT. The main characteristics of the LBVs with "normal" S Dor-type outbursts are reviewed. At quiescence they are luminous ($M_{Bol} \approx$ -9 to -10) OB supergiants (14 000 K $\lesssim T_{eff} \lesssim$ 30 000 K) occupying an inclined instability strip in the HRD. The most luminous S Dor variables are the hottest ones. During outburst dense envelopes are expelled of equivalent spectral type middle A to early F. S Dor variables occupy at maximum a vertical strip in the HRD at T≈8000 K. The observed amplitudes in the visual range increase from 1 mag (e.g. R71; T_{eff} = 14500 K at quiescence) to 2.5 mag (e.g. R127; T_{eff} = 33000 K at quiescence). The existence of an amplitude-luminosity relation is suggested which can be used to derive extragalactic distances.

1 Introduction

Among the LBVs the S Dor type variables are particularly distinguished. S Dor type varibles or Hubble-Sandage variables are (apart from supernovae) during outburst the visually brightest stars in the Universe. Due to their characteristic line spectra and their irregular variability of typically one to two magnitudes in the visual in timescales of years to decades they can be easily recognised in extragalactic systems. For these reasons they belong potentially to the most powerful extragalactic distance indicators (cf. Wolf,1988).

During the past few years S Dor variables became particularly important in connection with current theories of the evolution of very massive (M $\gtrsim$ 50 $M_\odot$)stars. S Dor type variables are supposed to represent a short-lived ($\sim 10^4$ yrs) unstable phase before presumably becoming Wolf-Rayet stars (cf. Wolf et al. 1981a, Maeder, 1982, 1983).

During the past few years from detailed studies of some selected S Dor type variables (particularly of the LMC) our knowledge of their nature and outburst properties has considerably improved (for recent reviews see Wolf, 1986, Lamers, 1986). An important result of such investigation was the finding that although the visual brightness during outburst increases typically by more than one magnitude the bolometric luminosity remains essentially unchanged.This refers, however, to the more modest type of eruptions with amplitudes $\Delta V \lesssim 3$ mag only, but not to the most extreme cases like η Car, which seem to erupt with some extra brightening. For these "plinian" type of LBV eruptions see Davidson (1988; this volume). We call the type of outbursts occurring under the condition M_{Bol} = const "normal" LBV eruptions à la S Dor. The main properties of these objects are discussed here.

K. Davidson et al. (eds.), Physics of Luminous Blue Variables, 91–99.

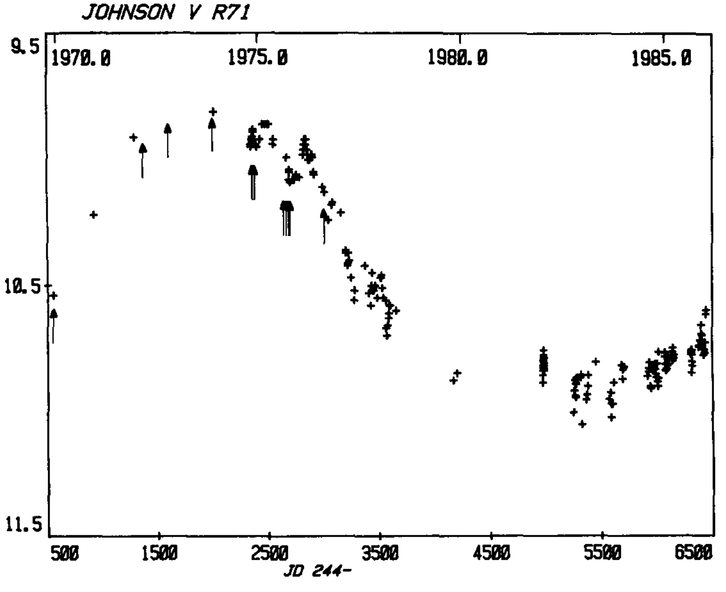

Figure 1: Light curve of the LMC-S Dor variable R71. The observations prior to 1978 were taken from van Genderen (1978) and the sources quoted by van Genderen. Observations after 1982 are from the "Long-term photometry of variables" group, initiated by C.Sterken. Arrows denote epochs at which coudé spectrograms were taken

2 General characteristics of S Dor variables

S Dor type variables are as bright as $M_v \approx -9$ to - 11. Members of this class have been identified in the Galaxy, in irregular and spiral galaxies of the local group and due to their extreme brightness in the galaxies M81, NGC 2403 and M101 outside the local group (cf. e.g. Wolf, 1988). They show irregular photometric variations in the visual of 1 to 2.5 mag in timescales of years or longer. From surrounding material from previous episodes of mass ejection a kinematic age of the order of several 10^4 years has been estimated (cf. Stahl, 1988, this volume) showing that S Dor variables represent indeed a very short-lived evolutionary phase of very massive stars.

Historically, R 71 of the LMC was the first case of a normal S Dor variable which has been observed both during minimum and maximum by means of high dispersion spectroscopy and is in the following regarded as a paradigmatic case for sketching the main properties of this group of LBVs. R 71 is now the best investigated S Dor variable. Apart from forbidden lines (mainly [FeII]) R 71 looks at quiescence like a rather normal B-type supergiant (Wolf et al. 1981) with a temperature of 14500 K. From a recent model atmosphere analysis (Kudritzki, 1988, this volume) the mass of this very luminous star ($M_{Bol} \approx -9$) was found to be surprisingly low ($M \approx 15 M_\odot$) and its He-abundance to be high (at least 20 %). Both findings are in agreement with the widely accepted scenario, that S Dor type variables represent a very late evolutionary phase prior to becoming WR-stars. R 71 is being continuously monitored by van Genderen's (1988) group and by Sterken's (1988, this volume) LTPV group. Fig. 1 shows the light curve of R 71 from the beginning of the maximum which R 71 had in the seventies to the present minimum state.

Apart from the large amplitude of the eruption of more that 1 mag between maximum and

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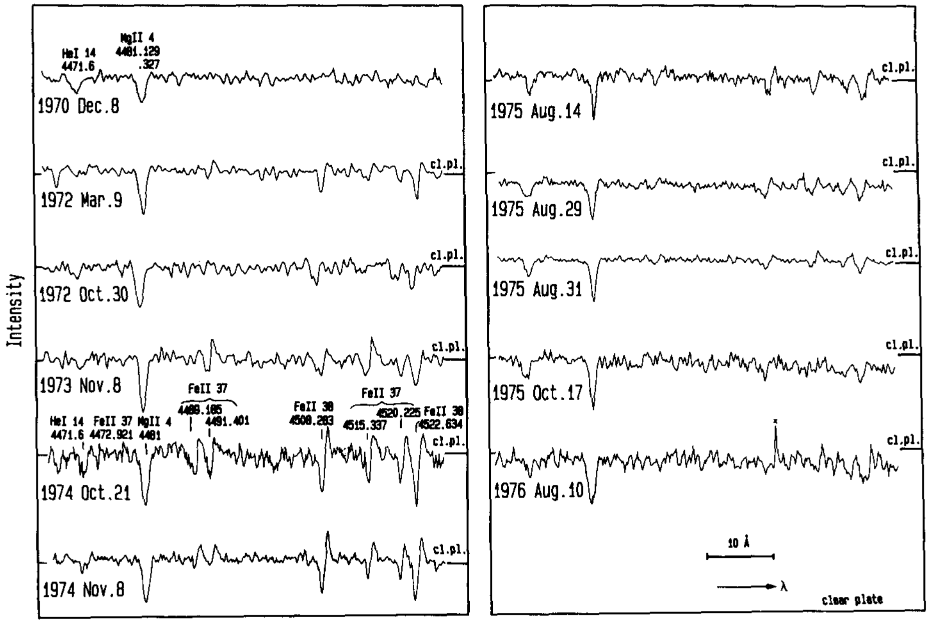

Figure 2: Intensity tracings of a section of some spectrograms taken between 1970 and 1976. For details see text

minimum there are superimposed microvariations occurring with timescales of the order of 23.5 days (1983 - 1985) and 14.3 days (1986 - 1987)(van Genderen et al., 1988). R 71's outburst in the seventies was monitored by Maart de Groot and the author with the ESO coudé spectrograph. Sections of this sequence of photographic spectrograms of high resolution are shown in Fig.2. The early spectrum (1970, Dec.8) clearly shows the minimum characteristics (e.g.HeI 4471), the spectra observed about maximum (e.g. 1974, Oct.21) shows typical cool A-type envelope spectrum (dominated by P Cygni type lines of singly ionized metals) of S Dor variables at outburst. From Fig. 2 it can be easily seen that even small photometric variations are paralleled by significant spectroscopic variations in the sense that the spectrum becomes later when the star becomes visually brighter. From Fig. 2 also the slow expansion velocity of the envelopes is evident which is typically about 100 to 200 $\mathrm{km\,s^{-1}}$ for S Dor variables. It is this low velocity and the high density (typically $N \approx 10^{11}$ $\mathrm{cm^{-3}}$ for S Dor variables at maximum) of the envelope which even allows dust formation around this early B-type star (Wolf and Zickgraf, 1986). The mass loss rate of R 71 during maximum phase was estimated to $\dot{M} = 5 \cdot 10^{-5}$ $M_{\odot}$ and a factor 10 to 100 lower during minimum phase (Wolf et al. 1981a). These are again typical values for S Dor variables. It is the variable mass loss which causes by a variable flux redistribution the brightness variations in the visual whilst the bolometric luminosity remains practically unchanged. This earlier hypothesis (Wolf et al. 1981, Appenzeller and Wolf, 1982) has been confirmed in the case of AG Car by direct flux integration (IUE and ground-based) during various phases of its light curve (Viotti et al. 1984).

The variability is suggested to be a consequence of a strong line driven wind which can become dynamically unstable (Appenzeller 1986, Lamers 1986 and Appenzeller 1988, this volume).

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3 S Dor Variables at Minimum - Instability Strip

Another example of a well investigated(both during minimum and maximum) S Dor Variable is R 127 of the LMC. This star has been detected as an S Dor variable by Stahl et al.(1983). During its present outburst it was for a short time the visually brightest star of the LMC before it was surpassed by SN1987A. Its outburst characteristics have been described in several papers (Stahl et al. 1983, Stahl and Wolf, 1986, Appenzeller et al. 1987, Wolf et al. 1988). R 127 has at minimum been classified by Walborn (1977, 1982, 1988, this volume) as a transition Ofpe/WN9 star. Hence this very luminous ($M_{Bol} \approx$ -10.3) star is at minimum much hotter (T≈ 33000 K) than R 71. Ofpe/ WN9 spectra are characterised by the simultaneous presence of HeII-and NIII - emission and HI-, HeI- and NII-lines. Two objects (S 61 and R 84 of the LMC) of this class which are anticipated to represent also the main properties of R 127 during minimum have been studied by means of high dispersion spectroscopy(IUE and CASPEC) by Wolf et al. (1987). Although quite normal mass loss rates were derived for these peculiar O-stars (for R 84 see also Schmutz et al. 1988, this volume),particularly the analysis of the UV spectra revealed the surprising result, that all UV-absorption lines (i.e. the lines originating from excited levels) are violet-shifted by about 200 $km\,s^{-1}$ indicating high column-densities due to an unusually slowly accelerated stellar wind in the deeper layers. In this respect the transition type Of/WN stars resemble the peculiar B-supergiant P Cygni (Lamers, 1986). It was therefore suggested (cf. Stahl et al. 1985, Wolf et al. 1987) that the Of/WN transition type stars are the hotter counterparts of the early B-type P Cygni stars.

Quite recently a detailed multi-frequency study has been carried out of Var C of M33 by Humphreys et al(1988). It was convincingly shown by these authors that Var C resembles in many details S Dor of the LMC. Var C showed at quiescence a spectrum not unlike P Cygni (Humphreys, 1975) and T = 22000 - 25000 K and $M_{Bol} \approx$ - 9.8 were estimated by Humphreys et al..

The location of R 71, R 127 and Var C at quiescence in the HRD are shown in Fig. 5. These objects occupy an inclined strip (hatched in Fig. 5). S Dor and AG Car (with its new distance of Humphreys, 1988) and P Cygni are also located in this strip which is called S Dor-instability strip (Wolf, 1988). It means that the temperature of S Dor type variables at quiescence increases with the absolute luminosity of the star.

Also located in this strip is R81 of the LMC which was previously shown to resemble P Cyg in many respects (Wolf et al. 1981b) and was recently established as an eclipsing binary (Stahl et al. 1987). From the lightcurve a mass of $\approx 25 M_{\odot}$ was estimated by these authors for this luminous star. 22 $M_{\odot}$ were derived for P Cyg and 15 $M_{\odot}$ have been estimated for R71 (Kudritzki, 1988, this volume) from model atmosphere analyses. Although these masses are low they are expected from evolutionary models (Maeder and Meynet, 1987) with mass loss for very evolved initially massive stars. Since there are other "normal" blue supergiants in the S Dor instability strip it is suggestive that only the very evolved low mass stars in the strip become S Dor- type unstable.

4 S Dor types at outburst - Opaque-wind limit

Whereas normal S Dor variables at quiescence occupy a wide temperature range (14000 to 35000 K) the outburst spectra are very much alike for all S Dor variables. This is well demonstrated in Fig. 3 which shows recent high resolution and high S/N ratio spectra (taken with CASPEC) of S Dor and R 127. From such observations it has been shown that during maximum S Dor variables are surrounded by cool (Te ≈ 8000 K), dense ($N_e = 10^{11}$ cm^{-3}), slowly expanding ($V_{exp} \approx$ 100 - 200 $km\,s^{-1}$) envelopes. As shown in Fig. 5 the S Dor variables are at maximum located in the shaded vertical area at T ≈ 8000 K in the HRD. This observationally well established vertical limit has recently got its theoretical interpretation. On the basis of his opaque wind model Davidson (1987) found that the temperature of the envelope of LBVs cannot fall far below 7500 K even if the mass-loss rate is enormous. A major role in this model plays the low speed ($v \lesssim 10\,km\,s^{-1}$) pseudo photosphere which is observed in maximum spectra of normal S Dor variables. The main characteristics of this false photosphere which is much more extended than the hot core visible during minimum have been described in the

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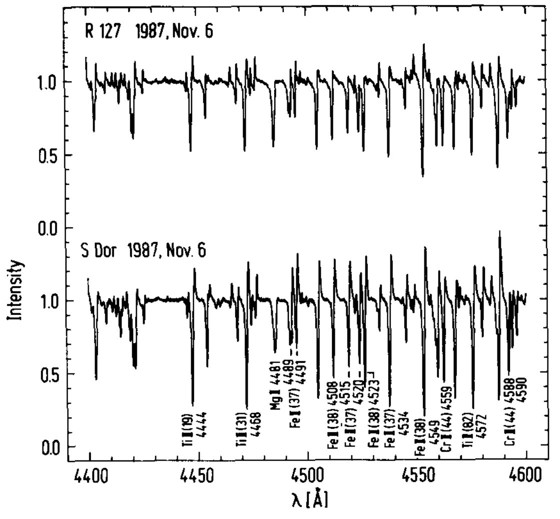

Figure 3: Section of the spectra of S Dor and of R127 of the LMC. Both stars are presently in the maximum state. The striking similarity of the spectra proves the very similar physical conditions in the maximum state envelopes

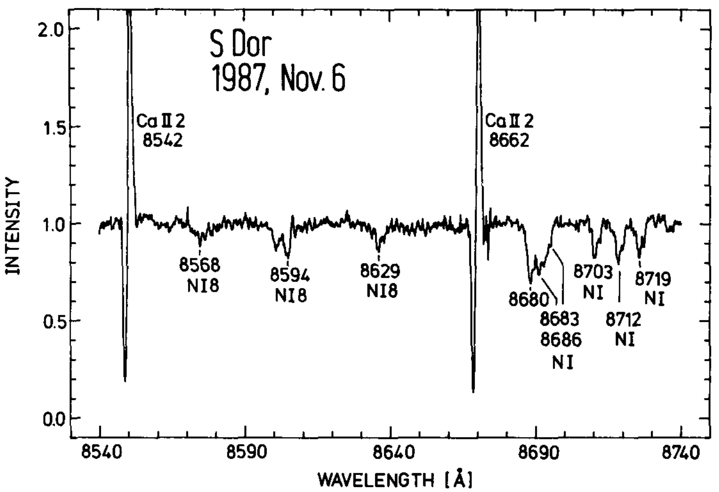

Figure 4: Section of a near infrared CASPEC spectrum of S Dor. Apart from the P Cygni-type profiles of the CaII triplet numerous absorption lines of NI and OI are conspicuous. These lines are unshifted with respect to the system velocity and are formed in the pseudo-photosphere of S Dor

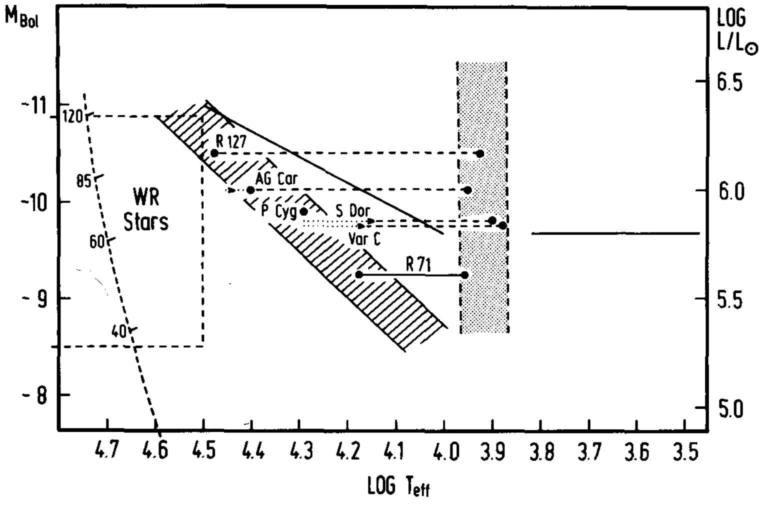

Figure 5: HRD showing the position of well studied S Dor variables and their range of variations. P Cyg is also included. At quiescence the S Dor variables are located in the inclined hatched area called S Dor instability strip. At maximum state they occupy the vertical shaded area called opaque wind limit. also included is the ZAMS (broken line). The solid line indicates the upper limit of stellar luminosities (see Humphreys and Davidson, 1979)

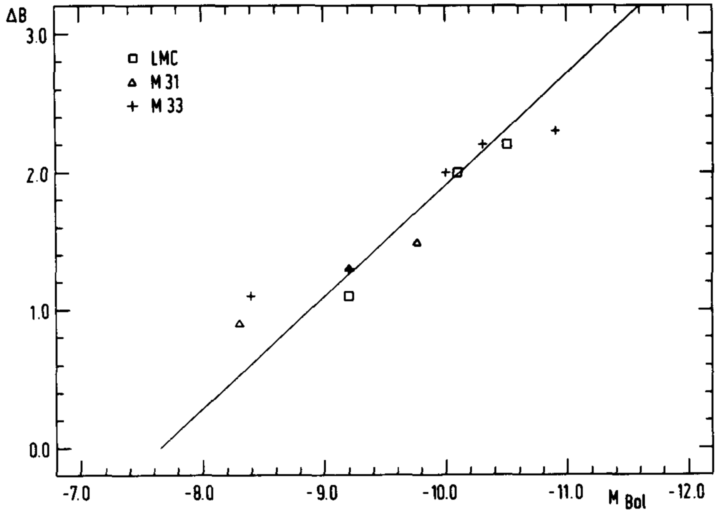

Figure 6: Composite amplitude-luminosity relation for S Dor variables derived from the sources indicated at the upper left (Wolf, 1988)

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case of S Dor by Leitherer et al.(1985). It is evidenced by high excitation lines like MgII 4481, HeI lines and SiII lines, which are essentially unshifted (with respect to the systemic velocity) except for small radial velocity variations with amplitudes of the order of 10 km s^{-1}. In addition to the few well known lines in the photographic wavelength range quite recently a considerable number of pseudo photospheric lines particularly of NI and OI have been identified in the near infrared range (cf. Fig. 4). On the basis of this large number of lines now available it should be possible in the future to derive a detailed physical model of the pseudo-photosphere which obviously plays a crucial role in the understanding of S Dor type outbursts.The finding that S Dor variables at quiescence are located in an inclined instability strip (hatched in Fig. 5) combined with the observationally well established existence of the vertical opaque wind limit(shaded in Fig. 5) for S Dor type variables at outburst has an interesting consequence. Since normal LBV eruptions à la S Dor occur under the condition $M_{bol} \approx$ const, this implies that the variation of the bolometric correction or likewise the photometric amplitude in the visual and blue range from minimum to maximum increases with the absolute luminosity of the star. The existence of an amplitude- luminosity relation is indicated. In fact such a relation has recently been derived by Wolf(1988) by combining published photometric data of the S Dor variables of the LMC and of the Hubble-Sandage variables of M31 and M33 (see Fig. 6). This relation provides a more physical basis for the determination of absolute luminosities of S Dor variables and hence can considerably improve the usefulness of S Dor variables for the extragalactic distance scale.

5 Conclusions

Since a previous review of S Dor variables by Sharov (1975) considerable technical advances allowed us to extend the observations of S Dor variables particularly of the LMC to the much wider wavelength range from the satellite UV to the infrared. On the basis of these new data our knowledge of the nature of S Dor variables and their outburst mechanisms has been considerably improved.Yet, many basic problems are still unanswered. Although it seems now well established that radiation pressure causes the S Dor type eruptions there is no quantitative theory predicting the photometric amplitudes of the eruptions or the amplitude-luminosity relation indicated by the observations. What role plays the pseudo-photosphere for the outburst mechanism? What is the duration of the S Dor phase and how do the characteristics depend on abundances? However, as the example of Var C of M33 has shown, with the advanced technical facilities rather detailed studies can be carried out for more distant objects. On the basis of such a more extended set of data further progress in understanding the nature of LBV eruptions à la S Dorados can be expected.

References

Appenzeller, I.: 1986, *IAU Symposium* **116**, p. 139
Appenzeller, I.: 1988, this volume
Appenzeller, I., Wolf, B.: 1982 *ESO Workshop* "The Most Massive Stars", p. 131
Appenzeller, I., Wolf, B., Stahl, O.: 1987, "Instabilities in Luminous Early Type Stars", p. 241
Davidson, K.: 1987, *Astrophys. J.* **317**, 760
Davidson, K.: 1988, this volume
Humphreys, R.M.: 1975, *Astrophys. J.* **200**, 426
Humphreys, R.M.: 1988, this volume
Humphreys, R.M., Davidson, K.: 1979, *Astrophys. J.* **232**, 409
Humphreys, R.M., Leitherer, C., Stahl, O., Wolf, B.: 1988a, *Astron. Astrophys.* **203**, 306
Humphreys, R.M., Stahl, O., Davidson, K., Wolf, B., Zickgraf, F.-J.: 1988, this volume Kudritzki, R.: 1988, this volume
Lamers, H.J.C.L.M.: 1986, "Instabilities in Luminous Early-Type Stars", p. 99
Leitherer, C., Appenzeller, I., Klare, G., Lamers, H.J.C.L.M., Stahl, O., Waters, L.B.F.M., Wolf, B.: 1985, *Astron. Astrophys.* **153**, 168

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Maeder, A.: 1982, *Astron. Astrophys.* **105**, 149
Maeder, A.: 1983, *Astron. Astrophys.* **120**, 113
Maeder, A., Meynet, G.: 1987, *Astron. Astrophys.* **182**, 243
Schmutz, W., Leitherer, C., Torres-Dodgen, A.V., Vogel, M., Conti, P.S., Hamann, W.-R., Wessolowski, U.: 1988, this volume
Sharov, A.S.: 1975, *IAU Symposium* **67**, p. 275
Stahl, O.: 1986, *Astron. Astrophys.* **164**, 321
Stahl, O.: 1988, this volume
Stahl, O., Wolf, B.: 1982, *Astron. Astrophys.* **110**, 272
Stahl, O., Wolf, B.: 1986, *Astron. Astrophys.* **158**, 371
Stahl, O., Wolf, B., de Groot, M., Leitherer, C.: 1985, *Astron. Astrophys. Suppl. Ser.* **61**, 237
Stahl, O., Wolf, B., Klare, G., Cassatella, A., Krautter, J., Persi, P., Ferrari-Toniolo, M.: 1983, *Astron. Astrophys.* **127**, 49
Stahl, O., Wolf, B., de Groot, M., Leitherer, C.: 1985, *Astron. Astrophys. Suppl. Ser.* **61**, 237
Stahl, O., Wolf, B., Zickgraf, F.-J.: 1987, *Astron. Astrophys.* **184**, 193
Sterken, C., 1988, this volume
van Genderen, A.M., Thé, P.S., Augusteijn, Th., Engelsmann, E.C., van der Grift, E.W., Prein, J.J., Remijn, R.L., Steeman, F.W.M., van Weeren, N.: 1988, *Astron.Astrophys. Suppl. Ser.* **74**, 453
Viotti, R., Altamore, A., Barylak, M., Cassatella, A., Gilmozzi, R., Rossi, C.: 1984, *NASA* Conf. Publ. 2349, p. 231
Walborn, N.R.: 1977, *Astrophys. J.* **215**, 53
Walborn, N.R.: 1982, *Astrophys. J.* **256**, 452
Walborn, N.R.: 1988, this volume
Wolf, B.: 1986, *IAU Symp.* **122**, p. 409
Wolf, B.: 1988, *Astron. Astrophys.* submitted
Wolf, B., Appenzeller, I., Cassatella, A.: 1980, *Astron. Astrophys.* **88**, 15
Wolf, B., Appenzeller, I., Stahl, O.: 1981a, *Astron. Astrophys.* **103**, 94
Wolf, B., Stahl, O., de Groot, M.J.H., Sterken, C.: 1981b, *Astron. Astrophys.* **99**, 351
Wolf, B., Stahl, O., Seifert, W.: 1987, *Astron. Astrophys.* **186**, 182
Wolf, B., Stahl, O., Smolinski, J., Cassatella, A.: 1988, *Astron. Astrophys. Suppl. Ser.* **74**, 239
Wolf, B., Zickgraf, F.-J.: 1986, *Astron. Astrophys.* **164**, 435

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DISCUSSION

Bohannan: From measurement of terminal velocities for many of the Of/WN stars in the LMC with low-resolution IUE spectra, I would not want to conclude that all of the Of/WN stars have low-velocity winds compared with normal O-type supergiants.

Wolf: I agree with you. I referred to those transition types originally introduced in 1977 and 1982 by Walborn, which are very closely related to R 127 at minimum. In fact R 127 is a member of the group discussed in that paper.

Leitherer: I think you can derive only an upper limit to the expansion velocity of the photosphere of R84 from radial velocities of absorption lines. An absorption line is by definition formed outside the photosphere. The question is, how far outside? This is immediately related to the shape of v(r), which should be derived from self-consistent, extended model atmospheres applied to the star -- not from plane-parallel hydrostatic models.

Wolf: I agree.

Sreenivasan: I find the suggestion of an instability strip for S-Dor stars interesting. These are thought to be non-radial pulsators. Where do the β Cephei stars lie with respect to the S Dor instability strip, if you extend it downward? (They are thought by those who study them to lie in a strip also.)

Wolf: It is widely believed that radiation pressure plays the important role as a physical mechanism for 'normal' S Dor eruptions. I do not know if the β Cep non-radial pulsation mechanism is important in connection with S Dor stars.

Walborn: I think the possibility remains that the true minimum states of P Cyg and S Dor have not yet been observed spectroscopically, and that they are actually Ofpe/WN9 objects like R 127 and AG Car. The light curve of P Cyg shows that it has been in an intermediate state throughout modern times, and its spectrum is identical to the intermediate-B-type spectrum of AG Car, while the spectrum of S Dor is identical to the maximum spectrum of R 127. Also, the detailed definition of an inclined instability strip for these stars may be an artifact. I do have a minimum-state echellogram of R 127 which can be subjected to further quantitative analysis.

Wolf: The S Dor instability strip suggested here is a conjecture to define the range in the H-R diagram where known LBV's are located. We do not know whether S Dor is an Ofpe/WN9 star. The spectrum taken by Thackeray during S Dor's deep minimum in the 1960's is certainly different from Ofpe/WN9; but it might well be that the star was not in an absolute minimum then, as you surmise. I would at least expect that R 71 has a later spectral type during minimum.

De Groot: I still see a lot of virtue in the S Dor instability strip. Its location in the H-R diagram seems to coincide with the ridge of luminous stars shown by Garmany earlier this morning. I do not know what this means, but I think we should not lose sight of this interesting coincidence.

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