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# High-resolution spectroscopy of the SMC eclipsing binary HD 5980: the HeII $\lambda$4686 emission line*

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**Abstract.** During 25 nights distributed between September 1996 and September 1997, a programme of intensive spectroscopy of the SMC WR binary HD 5980 was conducted, providing a series of 116 high-resolution (R = 60 000) profiles of the HeII $\lambda$4686 emission line. These observations were complemented with 9 additional spectra obtained: 5 in October-November 1998 and 4 in January 1999, with a resolving power of R = 48 000. This observational material has allowed to investigate, as a function of the orbital phase, the variations of the line equivalent width, of the full line width at half-maximum, and of the line radial velocity, over many different orbits. The discovery, on one night, of a profile oscillation at the red side of the emission, on a timescale of $\sim$ 7 hours, is reported. Though revealing a rather complex phase-dependent behaviour of the HeII $\lambda$4686 line, the analysis of the present data still favours the hypothesis that in HD 5980 this highly variable emission feature does not characterize a genuine WR star, but arises instead in a wind-wind collision shock zone.

**Key words:** line profiles – techniques: spectroscopic – stars: binaries: eclipsing – stars: individual: HD 5980 – galaxies: Magellanic Clouds

## 1. Introduction

HD 5980 is associated with NGC 346, the largest HII region + OB star cluster in the Small Magellanic Cloud. The star was considered by Feast et al. (1960) to be spectroscopically similar to Wolf-Rayet (WR) stars but definitely peculiar, with strongly suspected spectral variations. Changes in the width and strength of the HeII $\lambda$4686 and $\lambda$4860 emission features were confirmed by Breysacher & Westerlund (1978) who pointed out that, because of the important variations observed, the star might not be a "classical" WN3 type. The eclipsing-binary nature of the star was discovered by Hoffmann et al. (1978) and Breysacher & Perrier (1980) found the correct orbital period, $P = 19.266$ days. A subsequent detailed light curve analysis of the system, which confirmed the strong eccentricity of the orbit, was carried out by Breysacher & Perrier (1991). Based on spectral morphology only, the early classifications of HD 5980 refer to a OB+WN or WN+OB type (cf. Breysacher et al. 1982, and references therein), but a detailed radial velocity study of the emission lines led Niemela (1988) to argue that the system contains a WN4.5+WN3 pair, plus a probable line-of-sight OB supergiant.

Between 1993 and 1995, HD 5980 exhibited sudden and major changes making it one of the most fascinating systems among massive binaries. Following a preliminary visual brightening of $\Delta m \sim 1$ in late 1993, HD 5980 underwent a luminous blue variable (LBV)-type eruptive event during June-October 1994 (Bateson & Jones 1994; Barbá et al. 1995; Koenigsberger et al. 1995). The magnitude of the eruption, with $\Delta m \sim 3$ in the visual domain, classifies it as a *giant* LBV outburst (cf. Humphreys & Davidson 1994), similar to the ones experienced by Eta Carinae but with a much faster return of HD 5980 to its pre-eruption brightness (cf. Breysacher 1997). A photometric monitoring campaign conducted in November-December 1995, $\sim$ 16 months after the LBV-like outburst (Sterken & Breysacher 1997), resulted in an improved orbital period and ephemeris of the system, and led to the discovery of a coherent 6.06 hour periodic oscillation in the light of the Strömgren *b* and *y* bands with amplitudes $\sim 0^m.025$.

The above described light changes were accompanied by unprecedented spectral variations. After having progressively evolved from an early-type WN3-4 to a late-type WN6, the WR spectrum of HD 5980 made a transition to WN8 in November 1993 (Barbá & Niemela 1995) before turning again to WN6 two months later. In September 1994, shortly after the maximum brightness of the LBV outburst, a W11-like spectrum was displayed (Heydari-Malayeri et al. 1997) and in November 1994, high-dispersion IUE spectra revealed similarities between the spectrum of HD 5980 and that of a B1.5 supergiant (Koenigsberger et al. 1996). Late 1995, the WR spectrum had reverted to the WN6 type. The optical spectral variations of HD 5980 before, during and after the outburst, have been described by Barbá et al. (1996, 1997). From a radial velocity analysis of the pre-outburst data, Niemela et al. (1999) confirmed that both components of the binary are massive stars with emission lines in their spectra.

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* Based on observations carried out at ESO, La Silla, Chile

A comprehensive study of HD 5980 requiring the understanding of the nature and evolution of the individual components of the system, it was of paramount importance to know which one has erupted. If controversial scenarios were proposed at the time of the LBV-type event, it is now unanimously agreed that the binary component "in front" at light-curve phase zero - formerly classified O7 I: by Breysacher et al. (1982) on the basis of the spectral morphology of the system, and denoted as *component A* by Barbá et al. (1996) - corresponds to the erupting star. Both photometric and spectroscopic evidences exist:

- the change in shape of the light curve primary minimum, now asymmetrical and much broader than before the outburst (Breysacher 1997),
- the H-rich spectrum exhibited during the outburst which contrasts with the very H-poor pre-eruption spectrum attributed to star B (Koenigsberger et al. 1998; Moffat et al. 1998),
- the fact that the NIII $\lambda$4634-40 emission feature, which appeared at the time of the brightening and cooling of the system, followed the orbital motion of component A (Niemela et al. 1997, 1999).

Complete and detailed reviews of previous investigations on HD 5980 can be found in Moffat et al. (1998) and Koenigsberger et al. (1998).

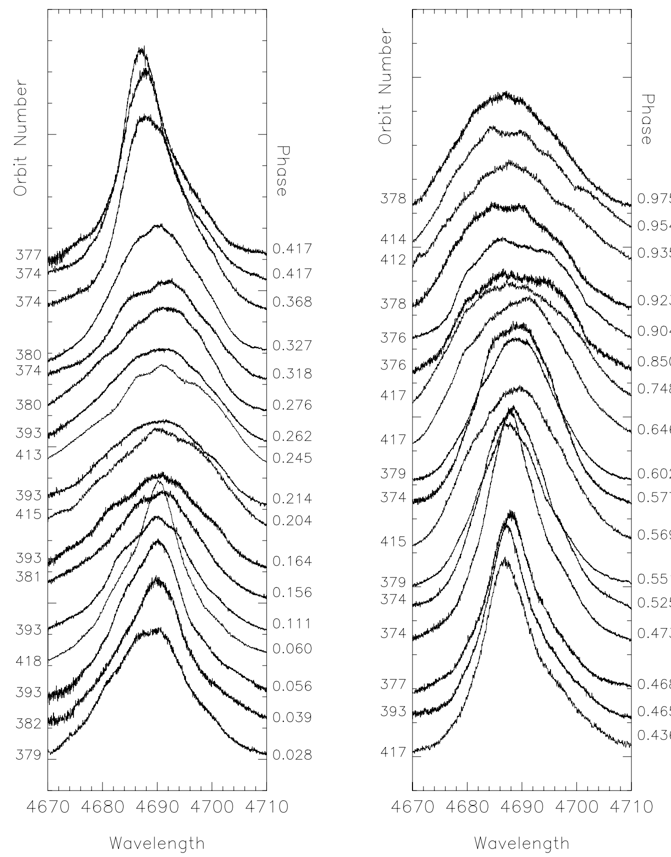


**Fig. 1.** Phase-dependent profile variations of the HeII $\lambda$4686 emission line in the HD 5980 spectrum

## 2. Spectroscopic data

In the period September 1996 - September 1997, HD 5980 was observed during 25 nights with the Long Camera of the Coudé Echelle Spectrometer (CES), at the ESO 1.4m CAT, La Silla, Chile. The CCD mounted on the CES Long Camera, ESO#38, was a LORAL/LESSER 2688 $\times$ 512 thinned, backside illuminated device (pixel size: 15 $\mu$m) with anti-reflection coating (cf. Pasquini & Kaper 1995). A total of 116 high-resolution spectra (R = 60 000, spectral window: $\sim$ 55 Å) were obtained, allowing a detailed study of the phase-dependent variations of the HeII $\lambda$4686 emission line over nine different orbits. For most of the nights the duration of the observations was commonly of 4–5 consecutive hours, but exceeded 6 hours on the night of September 24, 1997. The typical integration time was 30 minutes, however, a Th-Ar comparison spectrum being systematically recorded between the stellar exposures, the HD 5980 spectra were actually taken at a time resolution of about 35 minutes. On six nights, one spectrum per night only could be recorded.

On the night of September 26, 1996, simultaneously to the CES observations, a spectrum of HD 5980 in the range 4000–5200 Å was kindly secured for us by Dr. P. Molaro at the ESO 3.6m telescope with the CASPEC spectrograph, at a resolution of R $\sim$ 40 000.

Our series of CES observations has been complemented with five individual spectra obtained in October-November 1998 with the FEROS spectrograph (cf. Kaufer et al. 1999), during the commissioning of the instrument, at the ESO 1.52m telescope. The complete optical spectrum from 3700 to 8600 Å was recorded in one exposure of 30 minutes with a resolving power of R = 48 000. Four additional spectra, secured by the FEROS consortium in January 1999, during guaranteed time observations, were kindly made available to us by Prof. B. Wolf, Principal Investigator of the FEROS project.

Counting the cycles elapsed since the primary-eclipse ephemeris given by Breysacher & Perrier (1980), and revised by Sterken & Breysacher (1997), we have for convenience numbered the orbits. As a result, the CES observations relate to orbit nos. 374, 376 to 382, and 393; the FEROS observations to orbit nos. 412 to 415, 417 and 418.

The reduction of the data was done using MIDAS standard procedures. Fig. 1 shows the very clear phase-dependent profile variations of the HeII $\lambda$4686 line. In Fig. 2, the continuum-normalized CASPEC spectrum (a) is compared, in the 4200–5100 Å domain, to the continuum-normalized FEROS spectrum (b) obtained on November 28, 1998. Although some changes are noticeable over the 26 month interval separating these observations, the relative intensities of the typical WR emission lines indicate a WN6 spectral type for HD 5980 in that period. In the FEROS spectrum, the weak emission features visible at the bottom of the HeII $\lambda$4686 line and in the red part of the spectrum possibly correspond to forbidden lines of ionized iron. At, or very near, the observed wavelengths: $\lambda\lambda$ 4662, 4729, 4780 and 4897 Å, a number of [FeII] and [FeIII]

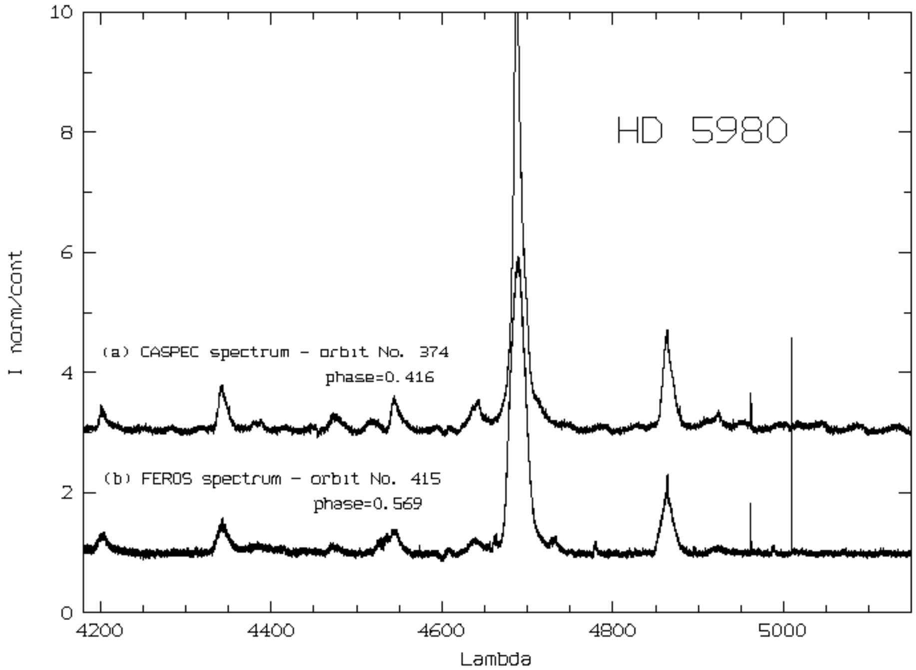


**Fig. 2.** Comparison of the continuum-normalized CASPEC and FEROS spectra respectively obtained on Sep. 26, 1996, and Nov. 28, 1998. The spectral window corresponding to the high-resolution CES observations covers 55 Å, from 4665 to 4720 Å

lines have indeed been identified in the spectrum of Eta Carinae by Damineli et al. (1998), a star which had giant eruptions and is "probably the most extreme well-studied LBV" (Morse, 1999).

The aim of this paper is, however, not to discuss the global spectral changes of HD 5980 but to concentrate on the HeII $\lambda$4686 line-profile variations as a function of the orbital phase.

## 3. Orbital phase-dependent variations

### *3.1. Line equivalent width (EW)*

For the CES spectra, a very accurate measurement of the HeII $\lambda$4686 EW was somewhat hampered by the narrowness of the available spectral window ($\sim$ 55 Å from 4665 to 4720 Å) in comparison to the width of the line, the extension of the wings preventing a proper estimation of the continuum level. To overcome this difficulty, taking advantage of the simultaneous CES and CASPEC observations on the night of September 26, 1996, we first derived the HeII $\lambda$4686 EW from the CASPEC spectrum and then determined on the corresponding CES spectrum the level of continuum intensity required to obtain the same EW value. In this calibration procedure the EW was measured between $\lambda_1 = 4670$ Å and $\lambda_2 = 4717$ Å on the CES spectrum, the continuum being reached only in the red wing of the line, at $\lambda_2$, in the available spectral domain. Assuming that the wavelength of this *wing-continuum merging point* was not significantly altered by the emission line-profile variability, all CES spectra were normalized using their respective continuum intensities at $\lambda_2$. One mean EW value per night was derived for the nights where the star was observed more than once. For the FEROS spectra, the measurement of the HeII $\lambda$4686 EW was performed in a straightforward manner.

Considering the inaccuracy inherent to the above described calibration procedure (estimated typical error $\sim$ 10 Å), no attempt was made to apply an EW correction to account for the small contribution of the weak HeI $\lambda$4713 emission line. As a consequence, all our EW values are possibly slightly overestimated.

In a first series of measurements, the orbital effects were deliberately ignored and the flux of the HeII $\lambda$4686 emission line was merely determined by integrating the observed line profile between $\lambda_1$ and $\lambda_2$ on the CES normalized spectra. Considering, however, that the EWs obtained at different orbital phases are in fact referred to a changeable continuum level, in a second series of measurements, a correction of the continuum intensity was performed using the light curve of Sterken & Breysacher (1997) in the Strömgren *y* filter. All CES spectra were re-normalized accordingly and new EWs derived for the various observed phases. The two sets of EW values thus obtained are plotted in Fig. 3a and Fig. 3b respectively. The CES data points corresponding to different orbits are identified with different symbols, no orbit differentiation is made for the FEROS data points.

In both series of measurements, the existence of a group of larger $-$EW values, at about 105 Å in the phase interval 0.35–0.75, is noticeable. These points correspond to the orbits Nos. 374 (CES data), 415 and 417 (FEROS data). In Fig. 3b, the continuum corrected values for orbit No. 374 show a remarkable progressive increase of the $-$EW from 60 Å to 110 Å over the six consecutive nights of observation. Most of the points in Figs. 3a and 3b are, however, distributed around the following mean EW values:

$EW = -79.6 \pm 7.0$ Å (without continuum correction)
$EW = -72.3 \pm 7.4$ Å (with continuum correction).

Surprisingly, the continuum corrected EW values present an unexpected slightly larger dispersion than the uncorrected ones. Together with the EW jump at about $-105$ Å observed for the

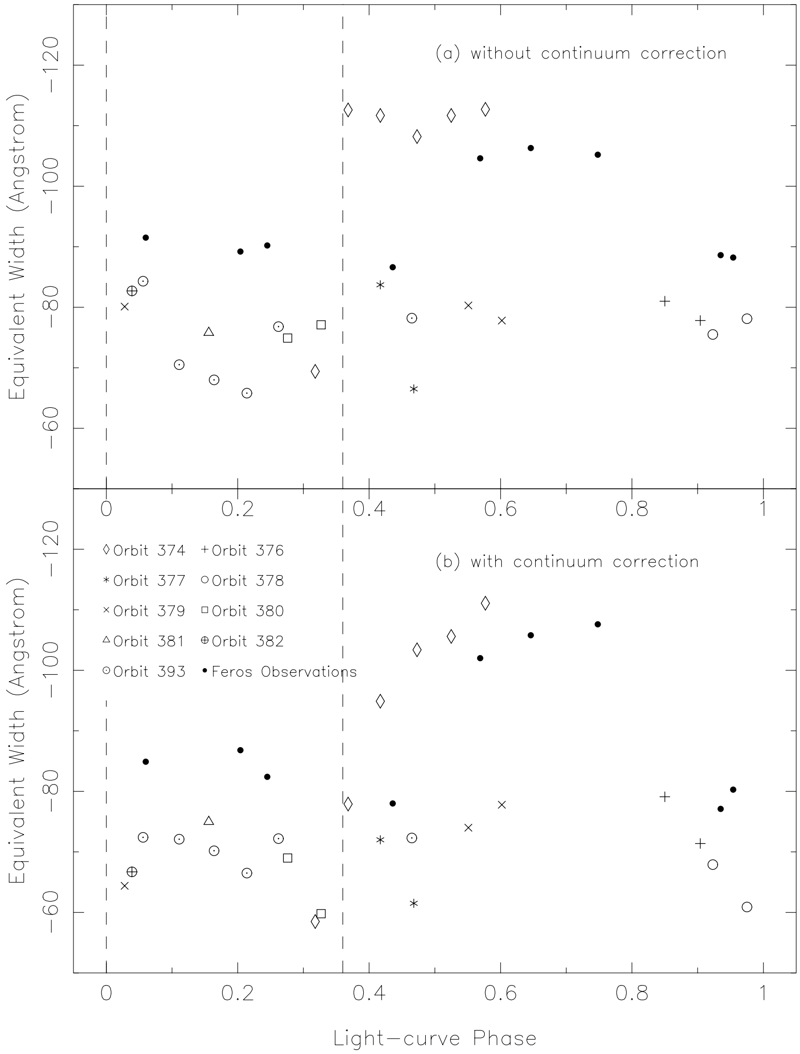


**Fig. 3a and b.** Equivalent width as a function of phase of the HeII $\lambda$4686 line integrated between 4670 Å and 4717 Å. The vertical lines indicate the primary ($\phi = 0.00$) and secondary ($\phi = 0.36$) eclipses

orbits 374, 415 and 417, this might be an indication that during the period September 1996 - January 1999, the flux in the HeII $\lambda$4686 emission line has almost permanently undergone small-scale variations with occasional *"mini-bursts"*. No correlation of the EW with the orbital motion can be inferred from the present data.

It is interesting to compare the above EW values with those determined at other epochs. The equivalent width behaviour of the HeII $\lambda$4686 line over the period September 1975 - January 1999 is summarized in Table 1.

According to Moffat et al. (1998), the pre-eruption spectra secured in October 1991 and October 1992 reveal that *"EW is constant with phase at each epoch after correction for the eclipse light curve of Breysacher & Perrier (1980)"*, the observed decrease in $-$EW of the HeII $\lambda$4686 emission line, from 1991 to 1992, being associated with a slight fading in brightness of HD 5980 during that period. However, in November-December 1993, when HD 5980 was in a state of minor eruption before the major one, the behaviour of the line changed completely and emerged a clear phase dependence in EW, with a $-$100 Å maximum near light-curve phase 0.7, i.e. close to apastron (cf. Fig. 7a of the paper by Moffat et al. 1998). In September 1994, i.e. shortly after the maximum visual brightness of the LBV-type eruptive event, very low $-$EW values showing a slight increase from 0.98 Å (September 10) to 1.52 Å (September 12) were reported by Heydari-Malayeri et al. (1997). In October 1994, the line was still weak with an $-$EW of 2.6 Å only (Barbá et al. 1995), but spectra secured during November-December 1994 revealed a remarkable change in the line strength with a $-$EW variation from a few Å to 80 Å over one orbital cycle (Barbá et al. 1997). From spectrophotometric data obtained on December 30, 1994, when the outburst was declining, Koenigsberger et al. (1998) derived a consistent $-$EW value of 81.0 Å. Our EW measurements for the period September 1996 - January 1999 do not reveal any subsequent big changes of the line equivalent width.

### 3.2. Full line width at half-maximum (FWHM)

The FWHM of the HeII $\lambda$4686 line, less sensitive to the choice of the continuum level than the EW, could be determined from the observed line profile with a fairly good accuracy for both

**Table 1.** Equivalent width variation of the HeII $\lambda$4686 emission line in HD 5980

| Date(s) | Phase[a] | $EW$(Å) | References |
|---|---|---|---|
| 1975 - September 29 | 0.390 | $-34.3$ | Breysacher & Westerlund 1978 |
| 1975 - November 10 | 0.627 | $-46.3$ | idem |
| 1976 - July 14 | 0.402 | $-26.5$ | idem |
| 1976 - November 1 | 0.109 | $-44.0$ | idem |
| 1976 - November 2 | 0.155 | $-44.5$ | idem |
| 1977 - February 20 | 0.913 | $-43.6$ | idem |
| 1989 - September 14 | 0.121 | $-66.9$ | Heydari-Malayeri et al. 1997 |
| 1991 - October | – | $\langle -95 \rangle$ | Moffat et al. 1998 |
| 1991 - December 27 | 0.401 | $-86.7$ | Heydari-Malayeri et al. 1997 |
| 1992 - October | – | $\langle -74 \rangle$ | Moffat et al. 1998 |
| 1993 - September 21–23 | 0.31–0.37 | $-77.6$ | Heydari-Malayeri et al. 1997 |
| 1993 - Nov./Dec. | – | $\langle -80 \rangle$ | Moffat et al. 1998 |
| 1994 - September 10–12 | 0.69–0.80 | $-1.36$ | Heydari-Malayeri et al. 1997 |
| 1994 - October 24–25 | 0.97–0.02 | $-2.6$ | Barbá et al. 1995 |
| 1994 - Nov./Dec. | – | $\Uparrow to - 80$ | Barbá et al. 1997 |
| 1994 - December 30 | 0.403 | $-81.0$ | Koenigsberger et al. 1998 |
| 1996 Sep. - 1999 Jan. | – | $\langle -72.3 \rangle$ | present work |

[a] *Column 2:* The phases have been computed using the Sterken & Breysacher (1997) revised ephemeris.

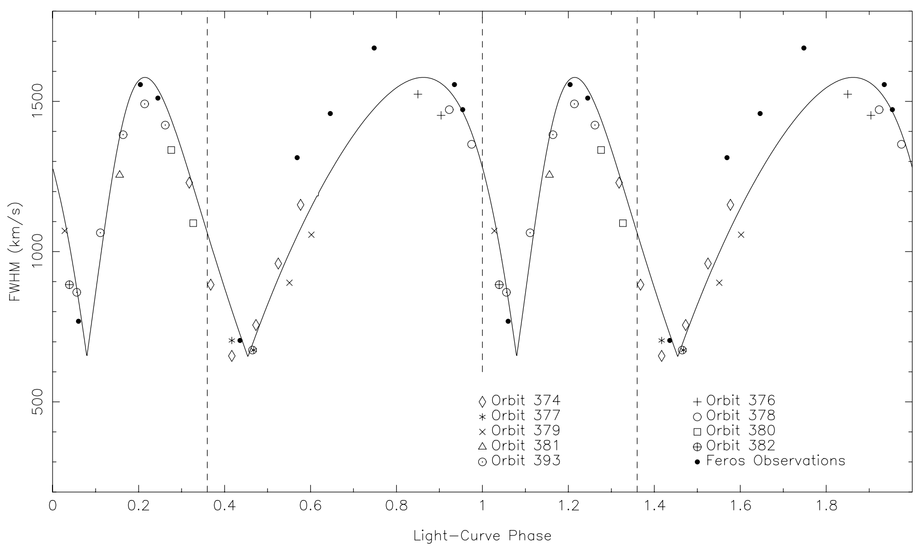


**Fig. 4.** Variation as a function of phase of the Full Width at Half-Maximum (FWHM) of the HeII $\lambda$4686 emission line. The curve represents the best fit of the data points as provided by the Lührs' model. The vertical lines indicate the primary ($\phi = 0.00$) and secondary ($\phi = 0.36$) eclipses

the CES and FEROS spectra. For the nights where the star was observed more than once, one mean FWHM value per night only was retained. Fig. 4 shows a plot of the FWHM data revealing a phase-dependent behaviour qualitatively similar to that found about two decades ago by Breysacher et al. (1982), and observed again by Moffat et al. (1998) in October 1991 and October 1992.

Quantitatively, differences however exist between the various epochs of observation, the most striking fact being the changeable amplitude of the FWHM variation. In Fig. 4 of the paper by Breysacher et al. (1982), the HeII $\lambda$4686 FWHM varies over the range 1000–2600 km s$^{-1}$, but in October 1991 and October 1992 (cf. Moffat et al. 1998, their Fig. 3) this is reduced to 800–1800 km s$^{-1}$. At the time of the minor eruption, in November-December 1993 (cf. Moffat et al. 1998, their Fig. 7a), still emerges a phase dependence in FWHM, but at a much lower amplitude: 900–1300 km s$^{-1}$. Our September 1996 - January 1999 post-eruption data (Fig. 4) reveal a new increased range of FWHM variation from 600 to 1600 km s$^{-1}$.

Also remarkable in Fig. 4 is the scatter of the points in the phase interval 0.45–0.95. While for the primary and secondary-descending-branch FWHM minima the data points corresponding to different orbits are pretty well fitted by the curve resulting from the model (see below), for the secondary-ascending-branch minimum and beyond, the fit is inaccurate due to the spread of the FWHM values. As shown in Fig. 5, in this critical zone the HeII $\lambda$4686 line profile can differ significantly from one orbit to the other, at an almost identical phase. This effect is possibly already present in the Breysacher et al. (1982) data (see their Fig. 3), but the dispersion of the points resulting from these early measurements prevents any conclusive statement. Due to the lack of observations in this phase interval during the months of October 1991/92, the Moffat et al. (1998) data

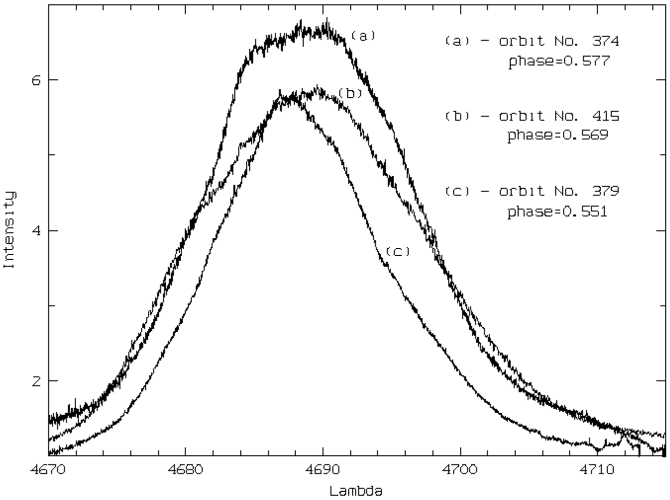


**Fig. 5.** Changes in the HeII $\lambda$4686 line profile for a similar phase of three different orbits

cannot be used. Therefore, the possible existence, before the LBV-type outburst, of a kind of HeII $\lambda$4686 width "instability" occurring after conjunction of the two stars at the secondary eclipse remains an unsettled issue.

Another important observational fact revealed by Fig. 4 is the phase shift of the FWHM minima with respect to the primary and secondary eclipses. While the conjunctions of the stars occur at phases $\phi$=0.00 and $\phi$=0.36 (Breysacher & Perrier 1980; Breysacher 1997), the corresponding line width minima are observed at $\phi \sim 0.07$ and $\phi \sim 0.43$ respectively. Not recognized by Breysacher et al. (1982), this phenomenon is taken into account by Moffat et al. (1998) in the analysis of their pre-eruption data set. Considering that a wind-wind collision between two stars with strong winds was the most plausible explanation for the phase-dependent behaviour of the HeII $\lambda$4686 FWHM, these authors applied the analytical colliding-wind model devised by Lührs (1995, 1997) to their October 1991/92 observations, to derive parameters for the A component (star in front at primary eclipse) of HD 5980.

The Lührs' model assumes that in a binary system with colliding winds, the excess emission line radiation expected from the cooling shocked material arises in an optically thin sheath on the shock cone that wraps around the stellar component having the weaker wind. The line-emitting material is supposed to flow at constant velocity $v_{strm}$ outward along this cone of opening half-angle $\theta$, which is tilted in the orbital plane by an angle $\delta\phi$ as a result of the Coriolis forces induced by the revolution of the companion. A sketch of the elementary basis for Lührs' model in a WR+O system can be found in Moffat et al. (1996).

According to the model (cf. Lührs 1997), the emission from the cone has a width

$$2v^* = 2v_{strm} sin\theta \sqrt{1 - sin^2 i cos^2(\phi - \delta\phi)}$$

where $\phi$ is the orbital phase and *i* is the orbital inclination. Assuming (cf. Moffat et al. 1998) that the width parameter $2v^*$ can be replaced by FWHM, with an added constant $\mathrm{FWHM}_0$ to account for the intrinsic broadening effects, one has

$$\mathrm{FWHM} = \mathrm{FWHM}_0 + 2v_{strm} sin\theta \sqrt{1 - sin^2 i cos^2(\phi - \delta\phi)}.$$

For elliptical orbits, the circular orbital phase $\phi$ has to be replaced by $u + \omega - \pi/2$ (and $\delta\phi$ by $\delta u$), where $u$ is the true anomaly and $\omega$ is the longitude of periastron. Applied to HD 5980 for which $86° \le i \le 88°$ (Breysacher & Perrier 1991; Moffat et al. 1998), and thus $sin i \sim 1$, the above equation takes the form

$$\mathrm{FWHM} = \mathrm{FWHM}_0 + 2v_{strm} sin\theta |cos(u + \omega - \delta u)|.$$

The true anomaly $u$ is obtained by solving the two equations

$$E - e sin E = 2\pi\phi$$
$$\tan\frac{E}{2} = \sqrt{\frac{(1-e)}{(1+e)}} \tan\frac{u}{2}$$

where $E$ is the eccentric anomaly and $e$ is the eccentricity of the orbit. The radial velocity of the WR star is given by the basic formula

$$\mathrm{V}_{WR} = \mathrm{V}_o + \mathrm{K}_{WR}[e cos\omega + cos(u + \omega)].$$

The best fit of the data points, as a curve in Fig. 4, is obtained for the following values of the parameters:

$$\begin{aligned} \mathrm{FWHM}_o\,(\mathrm{km\,s^{-1}}) &= 650 \pm 30 \\ 2v_{strm}\sin\theta\,(\mathrm{km\,s^{-1}}) &= 913 \pm 30 \\ e &= 0.30 \pm 0.02 \\ \omega(deg) &= 135 \pm 10 \\ \delta u(deg) &= 50 \pm 5. \end{aligned}$$

It is interesting to note that for $e$ and $\omega$ the above values are very similar to those determined independently from the light curve analysis: $e = 0.32, \omega = 133°$ (Breysacher & Perrier 1991), and from the polarization technique: $e = 0.27, \omega = 145°$ (Moffat et al. 1998). For the other parameters, the comparison with the pre-eruption results obtained by Moffat et al. (1998), also using the Lührs' model, reveals clear differences. The values derived by these authors are about 20% larger than ours for $\mathrm{FWHM}_o$ and $2v_{strm} sin\theta$, and approximately a factor 5 smaller for $\delta u$. As the effects of the Coriolis forces cannot be very important, the present fitting to FWHM as a function of phase obviously provides an unrealistic, much too large value, for the $\delta u$ angle. This might be an indication that the Lührs' model cannot fully account for the likely complex geometrical distribution of the emitting material in HD 5980 after the outburst.

Our attempt to fit Lührs' profiles directly to the HeII $\lambda$4686 line did not succeed at all in matching the broadness and shape of the emission. Interestingly, similar difficulties were also encountered occasionally by Bartzakos (1998) in using the Lührs' model for detailed profile fitting of carbon emission lines in some WC stars of the Galaxy and the Magellanic Clouds.

### *3.3. Radial velocities (RVs)*

It is a well-known fact that determining accurate RVs for WR stars is always a difficult task. In the present case, the dramatic

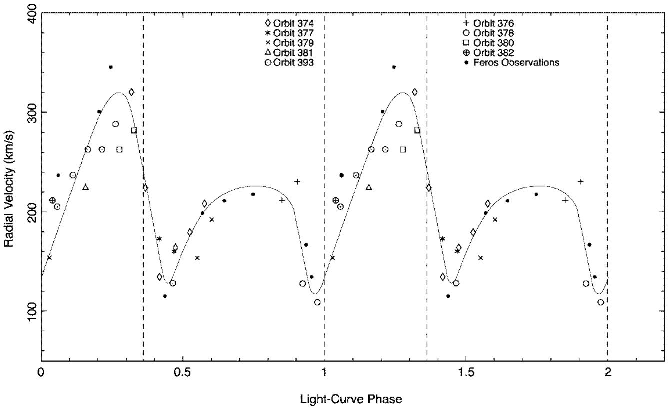


**Fig. 6.** Radial velocity as a function of phase determined from the FWHM central wavelength of the HeII $\lambda$4686 line. The curve corresponds to a hand-drawn fit of the data points. The vertical lines indicate the primary ($\phi = 0.00$) and secondary ($\phi = 0.36$) eclipses.
For the five profiles showing a double-peak structure the following set of RV values was obtained:

$\phi = 0.028$ (orbit 379) $+102 \Leftrightarrow +256\,\mathrm{km\,s^{-1}}$,
$\phi = 0.156$ (orbit 381) $+109 \Leftrightarrow +339\,\mathrm{km\,s^{-1}}$,
$\phi = 0.318$ (orbit 374) $+\ 90 \Leftrightarrow +378\,\mathrm{km\,s^{-1}}$,
$\phi = 0.923$ (orbit 378) $-\ 51 \Leftrightarrow +237\,\mathrm{km\,s^{-1}}$,
$\phi = 0.954$ (orbit 414) $-\ 77 \Leftrightarrow +250\,\mathrm{km\,s^{-1}}$

variations in shape exhibited by HeII $\lambda$4686 (cf. Fig. 1) prevented a gaussian-fit of most of the observed line profiles. Measuring the wavelength of the top of the line turned out to be not much easier due to the double-peak structure sometimes present. As a consequence, it was decided to derive the radial velocity from the FWHM central wavelength. The RV values thus obtained for the various orbits are folded in phase in Fig. 6.

The Lührs' model totally failed to provide an even rough fit of these observational data, the reason being that for a given line width, the RV variation required by the model is much larger than the one actually observed. Therefore, the curve in Fig. 6 results from a hand-drawn fit of the data points. Two dips not centered at the conjunctions are well visible, the first one at $\phi \sim$ 0.97, i.e. slightly before the primary eclipse, the second one at $\phi \sim$ 0.44 (almost the same value as for the second FWHM minimum). While the position of the second RV minimum appears fairly well established, the phase derived for the first one is much less secure and has to be taken with some caution. Similar dips occurring near the eclipses are also seen in the October 1991/92 RV data of Moffat et al. (1998); the displayed range of velocity variation: 100–350 $\mathrm{km\,s^{-1}}$ (cf. their Fig. 3) is very similar to the one in Fig. 6. According to these authors, the dips *"are primarily due to backscattering, mainly off the nearby moving plasma in the companion's wind"*.

The earlier velocity variations exhibited by the HeII $\lambda$4686 line (Breysacher et al. 1982) are hardly comparable with the RVs plotted in Fig. 6.

In a highly eccentric close binary system containing massive components with extended atmospheres like HD 5980, the existence of strong variable interaction effects, including wind-wind collision, is very likely at the origin of phase-dependent spectral variations difficult to interpret in terms of pure orbital motion. The peculiar RV behaviour of the HeII $\lambda$4686 emission line can presumably be attributed to such dominant non-orbital effects.

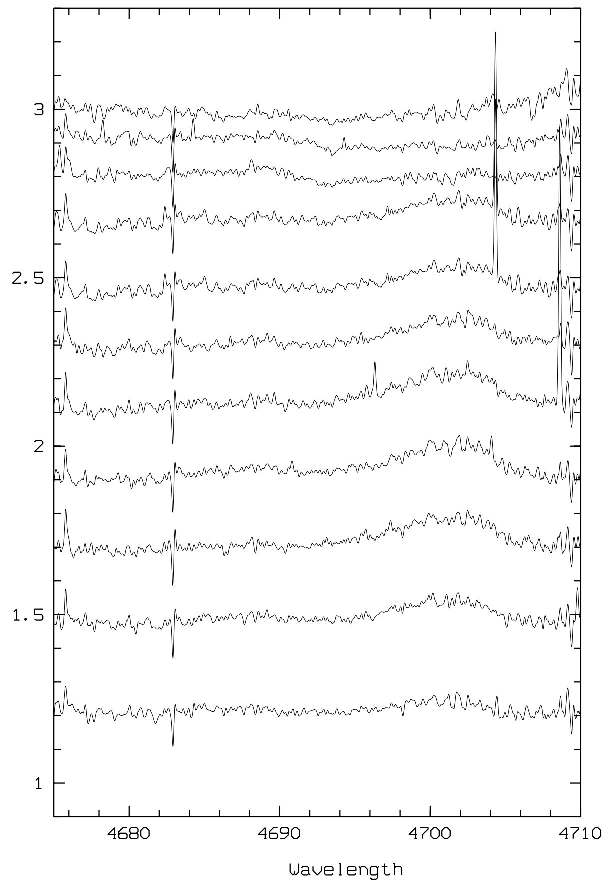


**Fig. 7.** Ratios of the spectra obtained during the night of Sep. 24, 1997, showing the existence of a "red bump". Each spectrum has been divided by the first one of the sequence taken as reference

## 4. Short time scale variability

In this section we report the discovery of short-term variations of the HeII $\lambda$4686 line profile. On the night of September 24, 1997, HD 5980 could be followed for more than six consecutive hours and a sequence of twelve spectra was obtained. Already suspected at the time of the observations, the variation with time of the red part of the emission line profile was confirmed by the analysis of the data. In order to quantify the phenomenon, each spectrum was divided by the first one of the sequence taken as reference, thus providing a series of new "spectra" showing a "red bump" (Fig. 7). For each such "spectrum" the strength of the bump was defined as the ratio between the maximum intensity and the mean value of the local "continuum" measured in the wavelength range $\Delta\lambda = 4683$–$4685$ Å.

In Fig. 8, the respective bump intensities obtained are plotted as a function of time. The sinusoidal fit of the points which minimizes $\chi^2$ reveals an oscillation of 7.25 hours duration. A period-

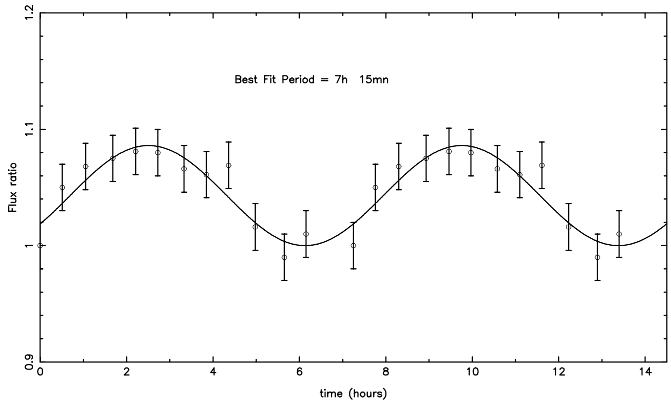


**Fig. 8.** Sinusoidal fit to the strength of the "red bump" as a function of time (see text)

icity is nevertheless difficult to ascertain as only one sequence of spectra, all secured on the same night, is available. If, neglecting this reservation, one assumes that the above described line profile variability is indeed periodic, it is then tempting to link this phenomenon to the photometric microvariations of period $\sim 6$ hours, discovered by Sterken & Breysacher (1997), for which one has no definite explanation yet. Whether this pulsation is due to the WR star or due to its companion, or to a third body, or even comes from the colliding winds, is still to be seen. The uncertainty on the "red bump" fitting appears, however, not to be large enough to account for the one hour discrepancy between the spectroscopic and photometric periods. Therefore, in the absence of simultaneous observations any conclusion about the existence of a possible correlation between the spectral and light changes observed in HD 5980 is premature.

Most of the WR stars that have been studied in detail are known to exhibit emission line profile variations on timescales ranging from a few hours to several days. These variations, not necessarily periodic, are indicative of time-dependent phenomena taking place in the line-emitting region. They may found their origin in the growth and propagation of shocks in the WR wind itself (Owocki 1991), they may be induced by the rotational modulation of large-scale wind structures (Vreux et al. 1992; Harries et al. 1999), or they may be due to the perturbations introduced by the presence of a binary companion (Koenigsberger & Auer 1992).

As shown by Hamann & Koesterke (1998), "clumping" is another effect which has consequences on the shape of the WR emissions, the presence of inhomogeneities in the WR winds reducing the relative contribution of the line wings. The HeII $\lambda$4686 emission is particularly well-suited for this type of study because the electron-scattering wings are more pronounced at the line red side. In the set of models computed by Hamann & Koesterke (1998), there is a clear relation between the adopted degree of clumping and the strength of the red wing of the HeII $\lambda$4686 line. The emission profile is enhanced at most in the homogeneous model, i.e. in the absence of clumps.

Our observations may possibly reveal a variation of the clump density in the HD 5980 colliding winds, on a timescale of $\sim 7$ hours, during the night of September 24, 1997. But the intervention of other mechanisms, such as pulsational instabilities, cannot be entirely excluded either. The available data are evidently too scarce to actually favor any interpretation of the phenomenon.

## 5. Concluding remarks

The spectroscopic monitoring of the HeII $\lambda$4686 emision line reported here has shown that in many aspects, the behaviour of this spectral feature two years after the LVB-like outburst of HD 5980 - and beyond - does not radically differ from what was observed in the pre-eruption period, at least during the months of October 1991 and October 1992. The line EW has reverted to an average value of about $-75$ Å, the phase-dependent variations of the FWHM are qualitatively similar, and the RV curve presents the same dips near the conjunctions of the two stellar components. Small-scale fluctuations of these quantities are nevertheless observed which prove that the system is far from being stable.

The profile oscillation detected on one night at the red side of the HeII $\lambda$4686 emission requires to be confirmed by a new spectroscopic monitoring spread over many nights, and encompassing all other suitable lines. If discovered to be either cyclical or periodic, this effect could then provide important clues regarding the physics and the structure of the line-emitting regions. Simultaneous photometric observations would badly be needed as well.

Moffat et al. (1998) have argued that, among the following conceivable explanations for the phase-dependent behaviour of the EW and FWHM of the He II emission lines in HD 5980:

- *two noninteracting emission-line (WR or Of-like) stars in mutual orbit,*
- *alteration of the line-formation zone caused by mutual wind deceleration between the two stars,*
- *mutual atmospheric eclipses as each star passes behind the other, causing selective line absorption along the line of sight,*
- *mutual tidal distorsions of the stars,*
- *wind-wind collision between two orbiting stars with strong winds,*

only the last one is the most plausible and therefore deserves consideration. The simple colliding wind model devised by Lührs, when used to fit the FWHM data, indeed provides for the orbital parameters $e$ and $\omega$, values that are in remarkable agreement with those derived independently by other techniques, thus giving some confidence in both the model and the hypothesis that the highly variable HeII $\lambda$4686 emission feature exhibited by HD 5980 does not characterize a genuine WR star, but arises instead in a wind-wind collision shock zone. Our attempt to apply the Lührs' model to observations obtained after the major eruption was nonetheless of limited success, leading us to conclude that this model is obviously oversimplified to fully account for the behaviour of the HeII $\lambda$4686 line in a complex erupting system like HD 5980. Despite these difficulties, our results still favour the wind-wind collision scenario as being the main contributor to the formation of this emission feature. We believe, however, that the somewhat “enigmatic” behaviour of the HeII $\lambda$4686 line does not entirely rule out the possibility of having a modest fraction of the emission produced outside the colliding-wind region, for instance in the winds themselves of the components, and which would vanish at the time of the mutual atmospheric eclipses. This remains actually highly speculative because, as was already pointed out, in massive and close binaries such as HD 5980, the situation is necessarily confused by the fact that very strong interaction effects are producing phase-dependent spectral variations which do not have a clear interpretation in terms of orbital motion.

HD 5980 is presently recognized as a key-object for the improvement of our knowledge of massive star evolution. If, as predicted by Koenigsberger et al. (1998), this star is likely to undergo a supernova explosion in the very near future, a further continuous and intensive observing campaign is an absolute requirement.

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## References

Barbá R.H., Morrell N.I., Niemela V.S., et al., 1996, Rev. Mex. Astron. Astrofis. Conf. Series 5, 85
Barbá R.H., Niemela V.S., 1995, In: van der Hucht K.A., Williams P.M. (eds.) Proc. IAU Symp. 163, Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution. Kluwer, Dordrecht, p. 254
Barbá R.H., Niemela V.S., Baume G., Vazquez R.A., 1995, ApJ 446, L23
Barbá R.H., Niemela V.S., Morrell N.I., 1997, In: Nota A., Lamers H.J.G.L.M. (eds.) Luminous Blue Variables: Massive Stars in Transition. ASP Conf. Series 120, p. 238
Bartzakos P., 1998, Ph.D. Thesis, University of Montréal
Bateson M.F., Jones A.F., 1994, Publ. Var. Star Section RAS New Zealand 19, 50
Breysacher J., 1997, In: Nota A., Lamers H.J.G.L.M. (eds.) Luminous Blue Variables: Massive Stars in Transition. ASP Conf. Series 120, p. 227
Breysacher J., Moffat A.F.J., Niemela V.S., 1982, ApJ 257, 116
Breysacher J., Perrier C., 1980, A&A 90, 207
Breysacher J., Perrier C., 1991, In: van der Hucht K.A., Hidayat B. (eds.) Proc. IAU Symp. 143, Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies. Kluwer, Dordrecht, p. 229
Breysacher J., Westerlund B.E., 1978, A&A 67, 261
Damineli A., Stahl O., Kaufer A., et al., 1998, A&AS 133, 299
Feast M.W., Thackeray A.D., Wesselink A.J., 1960, MNRAS 121, 337
Hamann W.-R., Koesterke L., 1998, A&A 335, 1003
Harries T.J., Howarth I.D., Schulte-Ladbeck R.E., Hillier D.J., 1999, MNRAS 302, 499
Heydari-Malayeri M., Rauw G., Esslinger O., Beuzit J.-L., 1997, A&A 322, 554
Hoffmann M., Stift M.J., Moffat A.F.J., 1978, PASP 90, 101
Humphreys R.M., Davidson K., 1994, PASP 106, 1025
Kaufer A., Stahl O., Tubbesing S., et al., 1999, ESO Messenger No. 95, 8
Koenigsberger G., Auer L.H., 1992, In: Drissen L., Leitherer C. & Nota A. (eds.) Nonisotropic and Variable Outflows from Stars. ASP Conf. Series 22, p. 239
Koenigsberger G., Guinan E., Auer L., Georgiev L., 1995, ApJ 452, L107
Koenigsberger G., Penã M., Schmutz W., Ayala S., 1998, ApJ 499, 889
Koenigsberger G., Shore S., Guinan E., Auer L., 1996, Rev. Mex. Astron. Astrofis. Conf. Series 5, 92
Lührs S., 1995, In: van der Hucht K.A., Williams P.M. (eds.) Proc. IAU Symp. 163, Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution. Kluwer, Dordrecht, p. 416
Lührs S., 1997, PASP 109, 504
Moffat A.F.J., Marchenko S.V., Bartzakos P., 1996, Rev. Mex. Astron. Astrofis. Conf. Series 5, 38
Moffat A.F.J., Marchenko S.V., Bartzakos P., et al., 1998, ApJ 497, 896
Morse J.A., 1999, In: Humphreys R.M., Damineli A. (eds.) Eta Carinae at the Millennium. ASP Conf. Series 179, p. 13
Niemela V.S., 1988, In: Blanco V.M., Phillips M.M. (eds.) Progress and Opportunities in Southern Hemisphere Optical Astronomy. ASP Conf. Series 1, p. 381
Niemela V.S., Barbá R.H., Morrell N.I., Corti M., 1997, In: Nota A., Lamers H.J.G.L.M. (eds.) Luminous Blue Variables: Massive Stars in Transition. ASP Conf. Series 120, p. 222
Niemela V.S., Barbá R.H., Morrell N.I., 1999, New Astron. Rev. 43, 475
Owocki S.P., 1991, In: van der Hucht K.A., Hidayat B. (eds.) Proc. IAU Symp. 143, Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies. Kluwer, Dordrecht, p. 155
Pasquini L., Kaper L., 1995, ESO Messenger No. 80, 9
Sterken C., Breysacher J., 1997, A&A 328, 269
Vreux J.-M., Gosset E., Bohannan B., Conti P.S., 1992, A&A 256, 148