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The puzzling Luminous Blue Variable-like object HD 5980 in the Small Magellanic Cloud*

M. Heydari-Malayeri[1], **G. Rauw** **[2], **O. Esslinger**[3], **and J.-L. Beuzit**[4]

[1] DEMIRM, Observatoire de Paris, 61 Avenue de l'Observatoire, F-75014 Paris, France
[2] Institut d'Astrophysique, Université de Liège, 5, Avenue de Cointe, B-4000 Liège, Belgium
[3] Department of Physics and Astronomy, University of Wales, College of Cardiff, CF2 3YB, Cardiff, UK
[4] Laboratoire d'Astrophysique, Observatoire de Grenoble, BP 53, F-38041 Grenoble cedex 9

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Abstract. We have observed the exceptional SMC star HD 5980 during several runs from 1989 to 1995 at ESO La Silla. CASPEC at the 3.6 m telescope and EMMI in echelle and long slit modes at NTT were used for spectroscopy. Subarcsecond images were obtained using SUSI at NTT and also an adaptive optics system at the 3.6 m telescope. In all our spectra taken before 1994 September HD 5980 shows a spectral type of WN 6. The 1994 September spectra were taken shortly after the maximum of the visual light-curve of the LBV-like phenomenon (Bateson & Jones 1994) and about one month before the observations of Barbá et al. (1995). Near maximum visual brightness, HD 5980 displays a WN 11-like spectrum with the He I lines and the Balmer lines Hδ and Hγ showing well-developed P Cyg profiles. The sub-arcsecond images ($0''.17$ FWHM), through the near infrared bands J, H, and K, obtained in 1993 and 1996, show no stellar components down to 6.7 mag fainter than HD 5980 in K at a separation of $1''.0$ and the 3σ level. For a separation of $0''.3$ this upper bound is 4.1 mag fainter than HD 5980. The observed behavior of this object raises serious problems for our comprehension of the LBV phenomenon in the conventional scenarios of massive star evolution. The present observations cover a crucial period in the evolution of HD 5980 and will therefore be helpful for better understanding this peculiar object especially during its outburst as well as the evolution of W-R stars in general.

Key words: stars: Wolf-Rayet – stars: individual: HD 5980 – binaries: eclipsing – stars: mass-loss – circumstellar matter – Magellanic Clouds

1. Introduction

HD 5980 = AB 5 (Azzopardi & Breysacher 1979) is an eclipsing binary (Hoffmann et al. 1978) with an orbital period of 19.266 days derived from its light-curve elements (Breysacher & Perrier 1980, 1991). It lies at the eastern border of the giant H II region NGC 346 or N 66 (Henize 1956), the most active site of star formation in the Small Magellanic Cloud (Niemela et al. 1986, Massey et al. 1989) containing a large number of massive O stars. The spectral classification of HD 5980 has changed according to authors or epochs of observation. The oldest mention of a spectral type goes back to Henize (1956) who noted a rough type of Oa (his star S 28). Later, Feast et al. (1960) including this star (R 14) in their list of the brightest stars of the Magellanic Clouds ($V = 11.61$), labelled it as Wp and noted spectral line variations. Smith (1968b) classified HD 5980 as OB + WN, Walborn (1977) proposed OB? + WN3, Breysacher & Westerlund (1978) confirmed the existence of spectral variations and assigned a spectral type WN3p + OB. Subsequently, Breysacher et al. (1982) classified the system as WN4 + O7I:. Spectroscopic observations by Niemela (1988), conducted during 1981–1983, showed that the emission lines arising from N V ions moved peculiarly in antiphase with those originating from N IV, whereas the absorption lines did not seem to participate in the 19.3 days orbit. This result led her to the conclusion that the system contains a WN4.5 + WN3 pair. Massey et al. (1989), based on point spread function fitting, detected a faint component lying at $\sim 1''$ from the main star at a position angle of $\sim 150°$. The presence of a third component contributing to the total light of the system was also supported by the solution of the visual light curve of HD 5980 (Breysacher & Perrier 1991).

Recently, drastic variations in the spectrum of HD 5980 were reported (Koenigsberger et al. 1994). Between 1978 and 1990 the spectrum of HD 5980 became cooler and evolved from an early type WN3–4 star to a late-type WN6. Furthermore, according to Barbá & Niemela (1995), HD 5980 showed an extraordinary spectral change in 1993 November, when the star brightened by about 1 mag and a WN8 type spectrum ap-

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Send offprint requests to: M. Heydari-Malayeri

* Based on observations obtained at the European Southern Observatory, La Silla, Chile.

** Aspirant au Fonds National de la Recherche Scientifique (Belgium) peared, but two months later, the Wolf-Rayet (hereafter W-R) spectrum turned again to WN 6. After this event, HD 5980 underwent an even more spectacular change evolving abruptly into a sort of Luminous Blue Variable (LBV) type (Barbá et al. 1995, Koenigsberger et al. 1995). This was accompanied by a visual brightening of HD 5980 by $\sim$ 3.5 mag in August 1994 (Bateson et al. 1994, Bateson & Jones 1994). High dispersion IUE spectra obtained shortly after the discovery of the eruption show characteristic lines of a B1.5Ia$^+$ type (Koenigsberger et al. 1996). These authors report also that about one year later HD 5980 returned to its WN6 spectrum. The latter finding is also confirmed from optical spectra by Barbá et al. (1996) and from infrared data by Eenens & Morris (1996) who notice a significant increase of the ionization of the wind of HD 5980 from their K-band spectra obtained in 1995 May and November.

All these facts underline the exceptional character of HD 5980 as to the evolutionary status of the W-R stars of the nitrogen sequence and the advent of LBV characteristics. We have observed this puzzling SMC object at ESO using high-resolution imaging and spectroscopy. Since HD 5980 is a binary and a third component has been suspected, it is of prime importance to know how many components are involved and which of the objects has undergone eruption. We used NTT+SUSI and the 3.6 m telescope equipped with an adaptive optics system to take sub-arcsecond images of HD 5980. On the other hand, to study the spectrum of the object, we used NTT+EMMI in echelle and slit spectroscopy modes. Our observing run of September 1994 was carried out nearly one month before the observations of Barbá et al. (1995). The present observations are unique in the sense that they cover a crucial period in the evolution of HD 5980. The data presented here will therefore be helpful for better understanding this peculiar object in particular and the evolution of W-R stars in general.

2. Observations and data reduction

2.1. Sub-arcsecond imaging

HD 5980 was observed on 1991 September 26 using the ESO New Technology Telescope (NTT) equipped with the SUperb Seeing Imager (SUSI) which functions with an active optics system (see ESO Web site for more information). The detector was a Tektronix CCD (#25) with 1024^2 pixels of 24 μm, each corresponding to $0''.13$ on the sky. The filters were R, V, and B, and the seeing was around $0''.7$ during the observations. Also, bias and flat-field frames necessary for image calibrations were secured during the run.

We observed HD 5980 also using the ESO VLT adaptive optics prototype installed at the Cassegrain focus of the 3.6 m telescope at La Silla (Rigaut et al. 1991, Hubin et al. 1993). On 1993 November 8 the COME-ON-PLUS system was used and on 1996 January 1st the more advanced system ADONIS. In both systems the incoming light from a reference source is analyzed by a wavefront sensor. Using this information, the surface of a deformable mirror is modified in real time by a servo-control to compensate the wavefront distortions induced by the atmospheric turbulence. This technique yields resolution close to the diffraction limit of the telescope, at least longward of 1 μm wavelength. The visible magnitude of HD 5980 (brighter than 12) being within the sensitivity range of the wavefront sensor detector, HD 5980 was used as its own reference for the wavefront measurement. The corrected images were recorded on a 256×256 infrared camera (Sharp II) with a $0''.05$ pixel scale on the sky. Images were obtained in standard photometric bands J (1.25 μm), H (1.68 μm), and K (2.25 μm) with an elementary integration time of 10 s. As a typical example, a total integration time of 200 s in J and 400 s in H and K were achieved on the source in the 1993 run. An internal chopping mirror allowed to move the source on two different areas of the detector and thus to simultaneously record both the source and the sky background for later subtraction. Exposures were also recorded in the same conditions on the reference stars SAO 248288, 255763, and 255729 for later deconvolution of the images.

We applied the standard infrared reduction procedure (sky subtraction, dead pixel removal, and flat fielding) using the IRAF/NOAO image reduction package. Some periodic features due to the detector electronics were minimized by a treatment in the Fourier plane. The different cleaned frames were eventually centered and averaged. In order to improve the resolution, we used two deconvolution methods in the IRAF/STSDAS package, the Lucy-Richardson and maximum entropy algorithms. The results were reconvolved by a gaussian to avoid an unrealistic resolution. The FWHM of the final images are $0''.28$ in J, $0''.24$ in H and $0''.17$ in K.

2.2. CASPEC observations

HD 5980 was observed with the CASPEC spectrograph attached to the 3.6 m telescope on 1989 September 14. The 31.6 lines mm^{-1} grating was used with a 300 lines mm^{-1} cross dispersion grating and an f/1.5 camera. The detector was CCD #8, a high resolution chip of type RCA SID 006 EX with 1024×640 pixels and a pixel size of 15 μm. The central wavelength was λ4250 Å and the useful wavelength range 3975 to 4820Å corresponding to orders 118 to 142 of the Thorium-Argon calibration arc. The resulting FWHM resolution as measured on the calibration lines is $\sim$ 0.2 Å.

2.3. EMMI echelle spectroscopy

The New Technology Telescope (NTT) coupled with the ESO Multi-Mode Instrument (EMMI) was used during two runs, 1993 September 21–23 and 1994 September 10–13 in order to get high dispersion spectra of HD 5980. The instrument mode was the red arm REMD. Grating # 9 defined the dispersion and grism #3 served as a cross-disperser. The resulting dispersion was 18.3 Å mm^{-1}, corresponding to a resolving power of 6900 for a $1'' \times 10''$ decker. The detector was a CCD chip (Loral # 34) with 2048^2 pixels of 15 μm corresponding to $0''.35$ on the sky. This covered (in 1994) orders 22 to 41 corresponding to $\lambda\lambda$3920–7610 Å.

The echelle spectra were reduced using the echelle context implemented in the MIDAS package. Flat-field exposures were used to define the order positions. The sky spectrum was extracted over 6 pixels aside of the object spectrum and the wavelength calibration was performed using exposures of a Thorium-Argon lamp. The resolution as measured from the calibration lines is ~ 0.8 Å at 5000 Å.

Due to the low level of the flat-field exposures in the blue region we had to use the stellar spectrum itself to define the positions of the highest orders. For the same reason we were not able to perform an appropriate background definition in the blue region of the flat-field and no flat-field correction was applied between λ4130 and λ5200 for the 1993 spectra and λ3920 and λ4750 for the 1994 data. The wavelength calibration was done separately for each of the blue orders leading to residuals of 0.01 Å. Individual orders were corrected for the blaze function using properly chosen continuum windows. The quality of the normalization was checked by comparing overlapping regions of adjacent orders.

2.4. EMMI slit spectroscopy

Several moderate long-slit spectra were taken of HD 5980 using NTT+EMMI with grating # 12 on 1991 December 27, 1993 September 21–23, and 1994 September 10–13. The CCD detector in 1991 was Tektronix #28, while in 1993 and 1994 we used Tektronix # 31. In both cases the format was 1024^2 pixels with a pixel size of 24 μm. The range was $\lambda\lambda$3810–4740 Å and the dispersion 38 Å mm^{-1}, giving FWHM resolutions of 2.70 ± 0.10 pixels or 2.48 ± 0.13 Å for a 1$''$.0 slit.

3. High-resolution images

There are several indications that massive stars form in groups (see, e.g. Lada et al. 1991, Larson 1992, Hodapp 1994). This is in line with recent high-resolution ground-based results, namely the decomposition of the so-called Magellanic supermassive stars into tight clusters of massive components (see Heydari-Malayeri 1996 for a review), as well as *HST* observations (e.g. Walborn et al. 1995). HD 5980 is a binary and a third component was suspected to lie at $\sim 1''$ from the main star (Massey et al. 1989). It is therefore necessary to see to what extent we can resolve this star and to check the presence of possible line-of-sight components that may contribute to the light of HD 5980.

A sub-arcsecond image of HD 5980 in the R band taken with SUSI at NTT is presented in Fig. 1. A resolution of 0$''$.65 FWHM makes it, to our knowledge, the best quality optical image ever published of the HD 5980 field. The closest star to HD 5980 visible on this image, lying at $\sim$ 4$''$.1 SE, has a V mag of $\sim$ 19.1. Also, the closest fainter star is a $V \sim 20.5$ mag situated at $\sim$ 4$''$.4 SE. We did not try to resolve HD 5980 on these SUSI observations because of the presence of saturated pixels. An attempt to resolve HD 5980 was made using our adaptive optics images which allow us to put constraints on the presence of stellar components and extended structure around HD 5980. There are no stellar components down to 6.7 mag fainter than

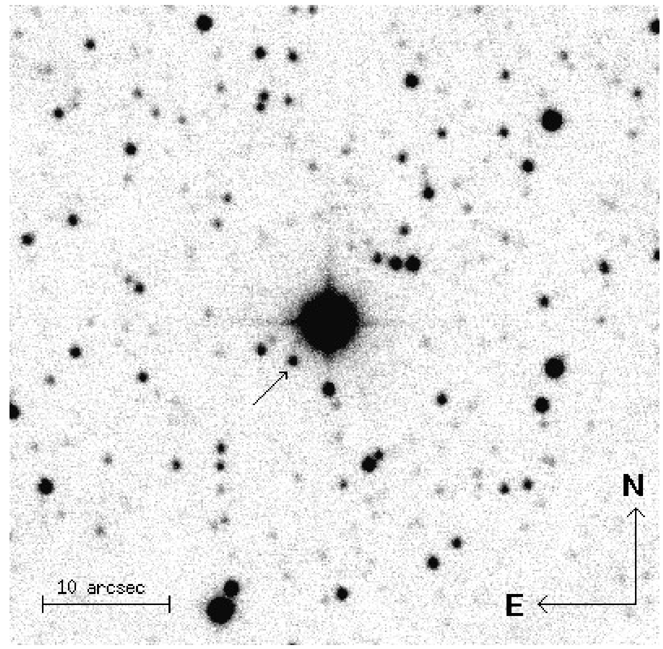

Fig. 1. An R image of HD 5980 obtained using NTT+SUSI. Resolution 0$''$.65 FWHM without applying any restoration technique. Field $\sim$ 50$''\times$ 50$''$. Exposure time 10 s. North is at the top and east to the left. The arrow indicates the closest star to HD 5980, visible on our images, at $\sim$ 4$''$.1 SE and $V \sim 19.1$ mag.

HD 5980 in K at a separation of 1$''$.0 and S/N = 3. For a separation of 0$''$.3 this upper bound is 4.1 mag fainter than HD 5980. These are in line with the results of *HST* observations reported by Koenigsberger et al. (1995). Furthermore, the observations of January 1996 would have detected a structure 3.9 mag arcsec^{-2} fainter than HD 5980 at 1$''$.0 and the 3σ level.

4. Spectral characteristics

4.1. HD 5980 before 1994

The spectra taken from 1989 to 1993 show similar main features, without any significant major changes. This is why we concentrate here on the description of the slit and echelle spectra obtained on 1993 September 21 and 22 ($\phi = 0.30$ and 0.36, according to the ephemeris of Breysacher & Perrier 1980). These spectra seem to show some time variations, but since this is not the main purpose of the present work, they were co-added to increase the S/N ratio. Fig. 2 presents the mean spectrum, while Table 1 gives the line measurement results for all the spectra from 1989 to 1994. The equivalent width (EW) accuracies are $\sim$ 5% for the brighter, non-blended lines and $\sim$ 10% for weaker, or blended, features. For heavily blended or very weak lines, we provide only upper or lower limits of the EW. The ions are identified in column 1, and the corresponding theoretical wavelengths listed in column 2. Column 3 indicates the emission (E) or absorption (A) nature of the lines and column 4 the corresponding EWs. Note that the sign "–" refers to emission features and that $>$ and $<$ refer to the absolute values of the EWs. Also, for the

Table 1. Lines detected in the spectrum of HD 5980

Ion	λ	1989 ($\phi = 0.11$)		1991 ($\phi = 0.39$)		1993 ($\phi = 0.30$–0.36)		1994 ($\phi = 0.68$–0.79)		
		Type	EW	Type	EW	Type	EW	Type	EW_a	EW_e
He II	3923					E	–1.0			
He I	3926							P Cyg	0.65	–0.17
Ca II	3934					A (ISM)		A (ISM)		
He I	3936							P Cyg		< -0.1
He I	3965							P Cyg		
Ca II	3968					A (ISM)		A (ISM)		
Hε (+He II)	3970			E	–1.6	E	–2.0	P Cyg		
N II	3995							P Cyg	0.17	–0.26
He I	4009					E	–0.1	P Cyg	0.73	–0.49
He II+ He I	4026			E	–1.5	E	–1.8			
He I	4026							P Cyg	0.87	–3.08
N II	4041							E		
N IV	4058	E	–2.6	E	–2.7	E	–2.9			
Hδ (+He II+N III)	4102	E	–5.6	E	–8.1	E	–8.7	P Cyg	0.20	–2.60
He I	4121							P Cyg	0.30	–1.16
He I	4144					E	–0.2	P Cyg	1.00	–0.66
He I	4169							P Cyg	0.16	–0.17
He II	4200	E	–3.3	E	–3.1	E	–3.5			
N II	4239							E		
Hγ (+He II)	4340	E	–7.5	E	> -6.8	E	> -7.8	P Cyg	0.05	–5.00
He I (+N III)	4388	E	> -1.0	E	> -0.5	E	> -1.0	P Cyg	0.90	–1.43
Fe III	4420							P Cyg	0.26	–0.17
Fe III	4431							P Cyg	≤ 0.05	≤ -0.03
He I	4438							P Cyg	0.16	–0.38
N II	4447							E		≤ -0.09
He I	4471			E	–2.0	E	–2.05	P Cyg	0.50	–6.05
N III	4511-24			E	> -1.0	E	> -1.2			
He II	4542	E	–5.7	E	–5.6	E	> -5.6			
Si III	4553							P Cyg	0.15	–0.15
Si III	4568							P Cyg	0.10	≤ -0.06
Si III	4575							P Cyg	≤ 0.04	≤ -0.03
N II	4601							P Cyg	0.08	–0.06
N V	4604			P Cyg	0.3 / –0.4	P Cyg	0.2 / –0.3			
N II	4607							P Cyg	0.07	≤ -0.04
N II	4614							P Cyg	0.05	–0.07
N V	4620					P Cyg				
N II	4621							P Cyg	0.05	–0.09
N II	4630							P Cyg	0.26	–0.27
N III	4640			E	> -2.3	E	> -4.0			
N II	4643							P Cyg	0.10	–0.13
He II	4686	E	–66.9	E	–86.7	E	–77.6	E		–1.36
He I	4713							P Cyg	0.18	–3.70
N II	4788							E		≤ -0.04
N II	4803							E		–0.08
Hβ (+He II)	4861					E	–11.8	E		–18.5
He I	4922							P Cyg	0.64	–4.41
N V	4944					E	–1.1			
He I	5016					E	–0.4	P Cyg	0.84	> -8.70
He I	5048							P Cyg	> 0.50	> -1.60
Fe III	5074							P Cyg	0.15	≤ -0.06
Fe III	5087							P Cyg	0.15	≤ -0.05
Fe III	5128							P Cyg	0.33	–0.30
Fe III	5156							P Cyg	0.42	–0.22
Fe III	5194							P Cyg	0.06	≤ -0.05

Table 1. (continued)

Ion	λ	1989 ($\phi = 0.11$)		1991 ($\phi = 0.39$)		1993 ($\phi = 0.30$–0.36)		1994 ($\phi = 0.68$–0.79)		
		Type	EW	Type	EW	Type	EW	Type	EW_a	EW_e
Fe III	5243							E		≥ -0.10
Fe III	5303							E		
He II	5412					E	–17.6			
N III	5500					E	–0.3			
N II	5667							P Cyg	0.26	
N II	5676							A		
N II	5680							P Cyg		
N II	5686							P Cyg		
C III	5696					E	–0.1			
Al III	5696							E		≥ -0.05
N II	5711							P Cyg	0.20	–0.06
Al III	5723							E		–0.07
Si III	5740							E	≤ 0.04	≤ -0.03
N II	5747							P Cyg	≤ 0.04	
C IV	5802					E	–7.5			
Fe III	5834							E		–0.15
He I	5876					E	–10.5	P Cyg	–37.50	
Na I	5890					A (ISM)		A (ISM)		
Na I	5896					A (ISM)		A (ISM)		
Fe III	5920							E		
Fe III	5930							E		
He II	5932					E	–0.4			
He II	5952					E	–0.5			
Fe III	5954							E		
Si II	5958							E		
He II	5977					E	–0.6			
Si II	5979							E		–0.43
Fe III	5999							E		–0.18
He II	6005					E	–0.5			
Fe III	6032							E		–0.29
He II	6037					E	–0.7			
He II	6074					E	–0.8			
He II	6118					E	–1.2			
He II	6170					E	–1.6			
N II	6170							E		–0.27
N IV	6212-20					E				
He II	6234					E	≥ -1.5			
N II	6243							E		–0.16
He II	6311					E	≥ -1.8			
Si II	6347							E		–1.26
Si II	6371							E		–0.35
N IV	6383					E	–0.4			
He II	6406					E	–2.7			
N II	6486							P Cyg		–0.30
Hα (+He II)	6563					E	–73.8	E		–70.00
N II	6611							E		–0.25
He I	6678							P Cyg	–23.55	
He II	6683					E	–12.8			
He I+ N IV	7065					E	–30.00			
He I	7065							E		–42.16
He II	7177					E				
He I	7281							E		
He I	7500							P Cyg		–0.26
He II	8237					E	–14.56			

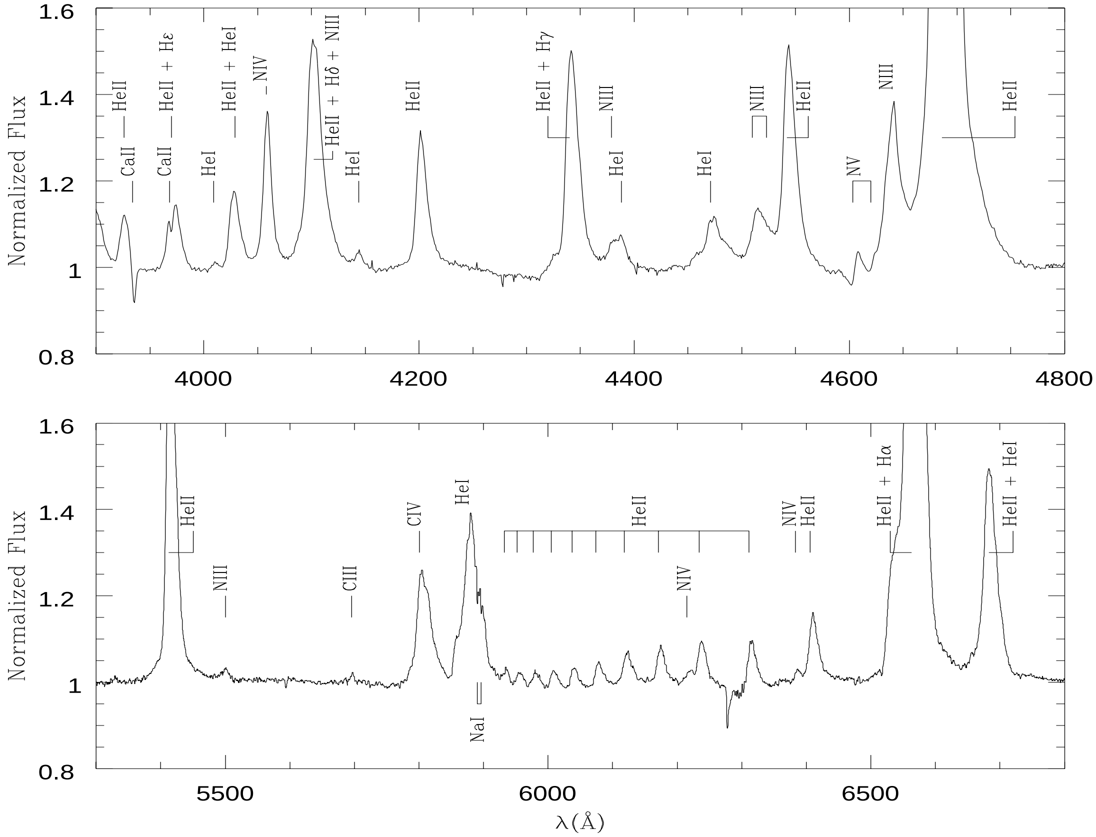

Fig. 2. Spectra of HD 5980 obtained in 1993 September using the ESO NTT+EMMI with grating #12 (top) and echelle mode (below). The normalized intensities of the strongest lines are 6.8 for He II λ4686, 2.1 for He II λ5412 and 4.0 for Hα.

He I $\lambda\lambda$5876, 6678 lines in 1994 the EW is relative to the total profile (emission + absorption).

In order to classify the spectra taken from 1989 to 1993, we use the criteria given in the W-R catalog of van der Hucht et al. (1981), which is based on the Smith (1968a) system. The classification essentially uses the relative strengths of nitrogen lines N III, N IV, and N V at $\lambda\lambda$4634–4640, 4057, and 4604–4620 respectively. We derive a spectral type of WN 6 since N III $\sim$ N IV, and N V is present. Assuming that SMC WN stars can be classified according to the criteria established for Galactic and LMC WN stars, we have also used the new 3-D spectral classification of Smith et al. (1996). In this new classification scheme, the primary indicator of ionization, i.e. the ratio between the line intensities of He II λ5411 and He I λ5876 (2.25), also indicates a WN 6 spectral type.

This means that HD 5980 had essentially the same spectral characteristics from 1989 to 1993 September including the 1990 observations by Koenigsberger et al. (1994). However, we note some differences between these spectra. While N IV and N V lines have comparable strengths in the 1990 and 1993 spectra, the N III lines appear stronger in 1993. In fact, according to Smith et al. (1996), the ratio of N V λ4604 and N III λ4640 on our 1993 spectra (0.09) is more typical of a WN 8 star. We also notice significantly stronger He I and He II lines with respect to the N IV and N V lines in the 1993 spectra. Particularly, the weaker He I lines at $\lambda\lambda$4009 and 4144 are practically absent in the 1990 spectrum, whereas the He I λ4144 line is weakly present in the 1991 spectrum and both lines are seen in weak emission in the 1993 observations. These differences might be related to the more substantial change in spectral type that occured only two months after our 1993 September observations when HD 5980 displayed a WN 8 spectral type (Barbá & Niemela 1995).

Smith et al. (1996) use the oscillations of the Pickering decrement to infer the presence of hydrogen in the atmospheres of WN stars. In the case of the 1993 September spectrum of HD 5980 the two criteria of Smith et al. comparing respectively the Hβ and Hγ lines to the surrounding unblended He II Pickering lines, lead to contradictory results: while the Hβ/He II line intensity ratio indicates no hydrogen (r_1 = 0.05 $\pm$ 0.09), the Hγ line appears stronger than expected from the He II $\lambda\lambda$4200 and 4541 lines (r_2 = 0.54 $\pm$ 0.13) and is therefore indicative of a small but significant amount of hydrogen. However, one has to bear in mind that in the case of a rather complex system, where at least two stars contribute to a composite spectrum, the reliability of such criteria might be questionable. Finally, one has to be careful since our spectra were obtained around the secondary minimum and the line strengths could be affected by the eclipse.

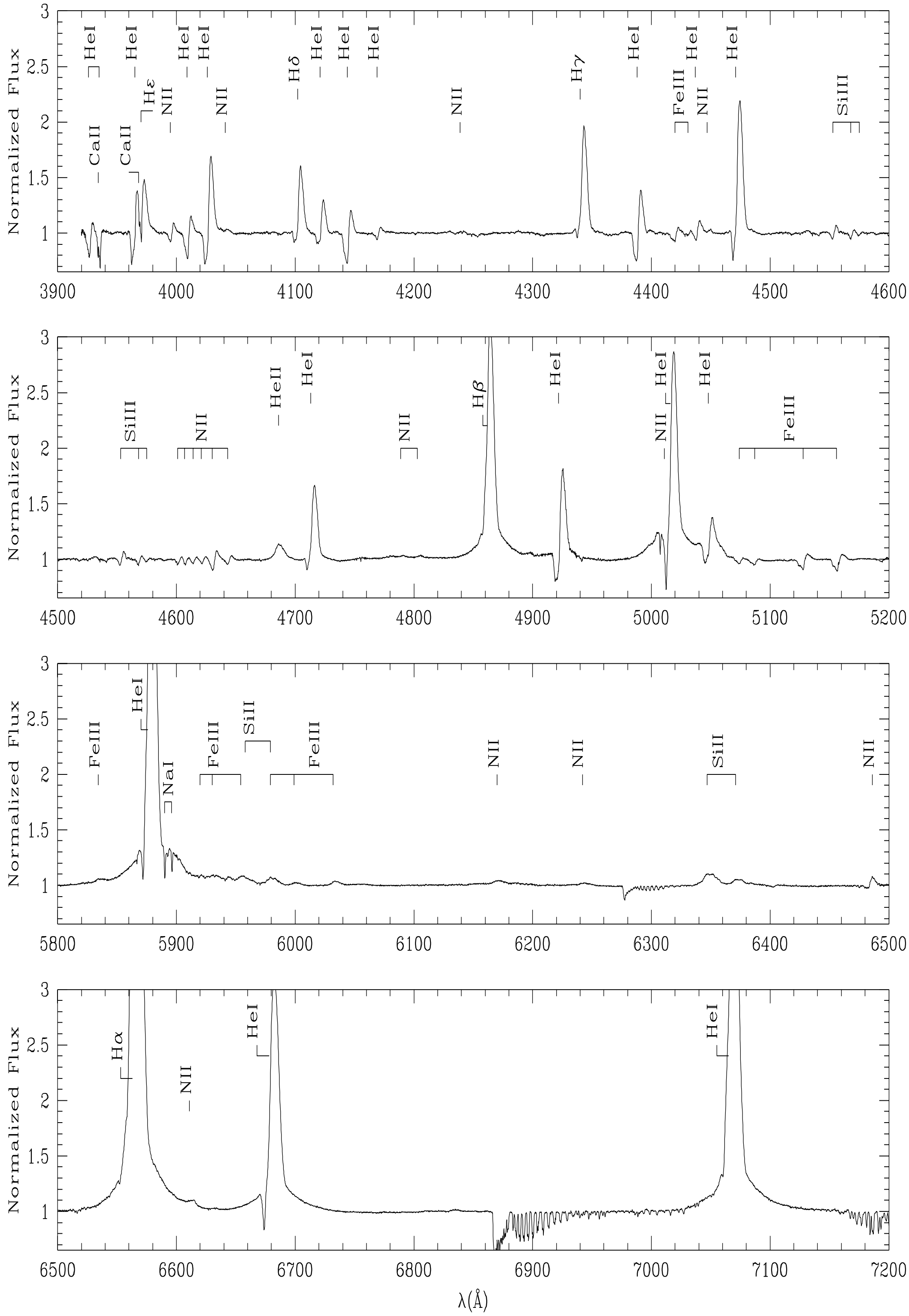

Fig. 3. Echelle spectra of HD 5980 obtained in 1994 September using the ESO NTT+EMMI. The normalized intensities of the strongest lines are listed in Table 2.

On what concerns the radial velocities of the N IV λ4058 line and the emission component of N V λ4604, we find a good agreement with the radial velocity curves of Niemela (1988) for the N V emission and Barbá & Niemela (1995) for the N IV line.

4.2. HD 5980 in September 1994

The spectroscopic observations conducted in 1994 September (Fig. 3) were obtained only a few weeks after the maximum of the visual light curve of the LBV-like outburst (Bateson & Jones 1994) and more than one month before the observations reported by Barbá et al. (1995). These observations are unique since they provide information about the spectrum of HD 5980 during the very early stages of the eruption. The spectrum is dominated by strong H I and He I lines. Weaker lines of N II, Fe III, Si II and Si III are also detected either as pure emission lines or P Cyg profiles. Some detailed information on the 1994 spectra are listed in Table 1. Columns 10 and 11 give the EWs of the absorption or emission components respectively in the P Cyg features. The radial velocities of the most important lines of hydrogen and He I are given in Table 2, where v_{abs} and v_{em} refer to the heliocentric velocity of the absorption minimum and emission peak respectively. Column 4 contains the relative intensities of the emission peaks of the P Cyg profiles.

The profiles of the lower Balmer lines from Hδ to Hα are shown in Fig. 4. Whereas Hε, Hδ and Hγ display shallow, complex P Cyg absorption components, Hβ and Hα are nearly pure emission lines with only a weak absorption dip remaining in the blue wing of the emission line. The relatively sharp emissions in the Balmer lines suggest that an important fraction of the stellar wind moves at velocities below $\sim 300\,\mathrm{km\,s^{-1}}$. Most of the He I lines have P Cyg profiles displaying some morphological differences between different transitions: the lines at λλ4120 and 4920 present a rather flat and shallow absorption component similar to the absorption of the Hδ line, whereas the lines at λλ4144 and 4388 have a very steep red absorption wing and a lower velocity of the absorption minimum. The red edges of the emission components are between 0.7 and 0.9 times less displaced with respect to the position of the emission peak than the blue edges of the absorptions. A similar situation was found for the Balmer lines in R 127 and was ascribed to a decelerated velocity field (Stahl et al. 1983).

A closer inspection shows that the absorption component of Hδ and of some of the He I lines is split into two subcomponents, the most blueshifted one being the strongest. We measure a velocity difference of $\sim 100\,\mathrm{km\,s^{-1}}$ for the two subcomponents of the Hδ line. From the complex profiles of Hα and He I λλ5876 and 7065, Barbá et al. (1996) deduce the presence of an expanding shell at $300\,\mathrm{km\,s^{-1}}$ surrounding the binary system. Such absorption features have been seen in some LBVs, and described first by Stahl et al. (1983) in the case of R 127. Other known cases are AG Car (Wolf & Stahl 1982, Leitherer et al. 1994), and HR Car (Hutsemékers & Van Drom 1991). The feature is generally explained as being due to the presence of shells with different velocities in the stellar atmosphere. A new explanation, put forward recently by Stahl (1996), ascribes it to the remnants of a higher velocity wind. In the case of a binary system, such as HD 5980, an alternative explanation for the shape of these absorption components could be some kind of interaction between the wind of the erupting component and its componion.

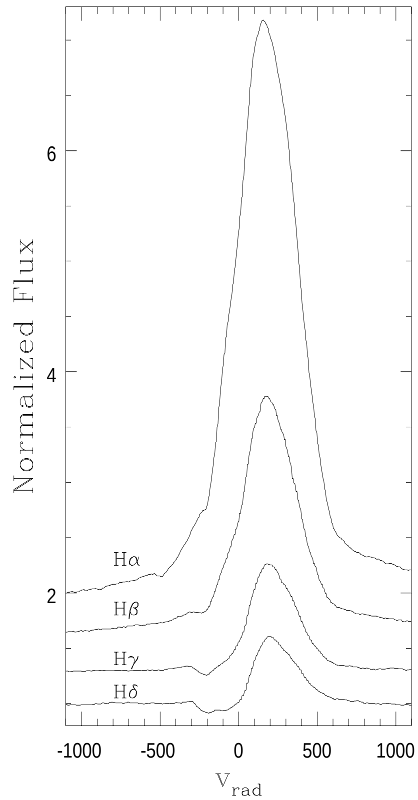

Fig. 4. The lower hydrogen Balmer line profiles in the spectrum of HD 5980 as observed in 1994 September.

The strongest lines of H I and He I display very extended wings superimposed on the narrow emissions. Although the exact extent of these wings critically depends on the normalization procedure, we can measure a full width of more than about $3000\,\mathrm{km\,s^{-1}}$ for the strongest lines (Hβ, Hα, He I λλ5016, 5876, 6678, 7065). Such broad features are often encountered in the spectra of LBVs and related stars (see e.g. Wolf & Stahl 1982, Stahl et al. 1983, Hutsemékers & Van Drom 1991). Different interpretations such as electron scattering or the existence of a high velocity motion in the atmosphere have been suggested. In the present case, the wings are slightly asymmetric, usually more extended to the red, as would be expected from electron scattering (Auer & Van Blerkom 1972).

The only outstanding variations in the spectrum of HD 5980 during the 1994 September observing run (ϕ = 0.68–0.79) concern the strength and to a certain extent the velocity of the He II λ4686 line. The EW of this line increases from –0.98 Å (Sept. 10) to –1.52 Å (Sept. 12) whereas its radial velocity as measured by gaussian-fitting varies from 66 to 129 $\mathrm{km\,s^{-1}}$.

Comparison of these spectra with those obtained by Barbá et al. (1995) one month later reveals some differences. In 1994

Table 2. Heliocentric radial velocities of the absorption minimum and emission peak and emission peak intensity of the most important P Cyg profiles seen on our September 1994 spectra. For the lines labelled with an asterisk there exists no clear absorption component and v_{abs} is the velocity of a weak residual absorption dip in the blue wing of the emission line.

Line	v_{abs}	v_{em}	I_{peak}
Hδ	–192	202	1.60
Hγ	–205	182	1.96
Hβ*	–237	170	3.18
Hα*	–208	166	6.26
He I λ4120		211	1.30
He I λ4144	10	227	1.20
He I λ4388	–43	216	1.38
He I λ4471	–188	200	2.20
He I λ4713	–211	196	1.66
He I λ4922	–186	204	1.80
He I λ5016	–203	179	2.86
He I λ5876*	–206	171	5.11
He I λ6678	–203	192	3.10
He I λ7065*	–219	163	4.29

September the He I lines show well-developed P Cyg profiles, while in October this feature is missing in most of the He I lines. Interestingly, the He I lines that have conserved a rather weak P Cyg profile in 1994 October (at λλ3926, 4009, 4144, 4169, 4388, 4438, 4922, 5048) are generally those with significantly less blue-shifted absorption components in our spectra. P Cyg profiles are lacking also for the Hδ and Hγ lines in the October spectrum. This is probably due to an enhancement of the emission components in October. In fact, we notice a substantial increase of the relative intensity of the emission lines between September and October. For example the Hα emission has a normalized intensity of 6.3 in our spectra whereas it reaches 10.1 one month later. The He II λ4686 line that has a mean EW of –1.31 Å on our spectra has increased its EW to –2.6 Å in 1994 October. Subsequent spectroscopic observations obtained during the declining phase of the outburst indicate a much faster increase in the EW of the He II λ4686 line between October and December 1994 (Barbá et al. 1996).

5. Discussions and concluding remarks

In order to get an insight into the behavior of HD 5980, we should first compare it with other LBVs and related objects. Nota et al. (1996) study a sample of eight Ofpe/WN9 objects in the LMC. Comparison with these objects indicates that HD 5980 has an eruption spectrum quite similar to BE 294 (HDE 269582), mainly on what concerns the P Cyg profiles of hydrogen and He I lines. Moreover, the EWs of He II λ4686 are comparable in both cases given the accuracies (–1.31 and –1.5 Å for HD 5980 in September 1994, and BE 294 respectively). There are however some slight differences. For instance, the emission and absorption components of the He I P Cyg profiles (i.e. He I λλ4713, 5876, 7065) in BE 294 are generally stronger than the corresponding components in HD 5980.

More remarkable differences concern the absence of some higher ionization spectral features in HD 5980 as following. The He II λ5412 line which is in weak absorption in BE 294, does not show up in HD 5980. Regarding other ions, the lines N III λλ4634-41, C IV λ4658 and Si IV λλ4089, 4101, and 6702 do not appear in HD 5980. C II λλ7231–36 is visible in HD 5980 but due to the strong telluric absorptions, it is difficult to compare the strength of the line with that in BE 294. Nota et al. (1996) report a relatively strong C III λ5696 emission blended with Al III λλ5697, 5723 and Si III λ5740 in the spectrum of BE 294. In the case of HD 5980 we have attributed the blend between λλ5650 and 5750 to the same Al III and Si III ions but to N II rather than to C III. The weak emission at λ4507, visible in BE 294, which is possibly due to the "unidentified" λ4504 feature (Crowther & Bohannan 1996) is not detected in the spectrum of HD 5980.

Barbá et al. (1995) compare the eruption spectrum of HD 5980 in the visible to the spectrum of the Galactic peculiar object He 3–519 discussed by Davidson et al. (1993). The latter authors suggest that He 3–519 could be a post-LBV object and notice the similarity of its spectrum with that of BE 294 as observed by Bohannan & Walborn (1989). However, using high dispersion spectra, Smith et al. (1994) notice important differences between He 3–519 and the Ofpe/WN9 stars. These differences mainly concern the absence of the same N III and Si IV Of spectral features as discussed above for HD 5980. These authors therefore introduce the WN 11 spectral-type as an extension of the WN classification towards lower ionization. They suggest to classify He 3–519 and AG Car at minimum as WN 11 stars. Given the similarity between HD 5980 and He 3–519 (Smith et al. 1994), HD 5980 could also be classified as WN 11 with some of the Balmer lines displaying P Cyg profiles instead of pure emission lines. These morphological similarities with WN 11 and/or quiescent LBV stars are also noticed in the infrared (Eenens & Morris 1996).

A comparison between the eruption spectrum of HD 5980 and blue spectra of He 3–519 and AG Car at minimum, kindly provided by D. Hutsemékers, shows that He II λ4686 has nearly the same EW in all the spectra, whereas the most important lines (Hβ, He I, N II, Si III) are generally stronger in AG Car and He 3–519. We also note that neither HD 5980 nor He 3–519 display the [Fe II] emissions seen in the spectrum of AG Car at minimum.

Assuming a relative velocity of the SMC with respect to the Galaxy of $\sim 150\,\mathrm{km\,s^{-1}}$, we find a mean corrected velocity of $\sim 350\,\mathrm{km\,s^{-1}}$ for those lines that display a high velocity absorption component (Table 2). This value is again very similar to the value of $v_\infty = 365\,\mathrm{km\,s^{-1}}$ found by Smith et al. (1994) in the case of He 3–519, but slightly higher than the terminal velocities of the LMC WN 11 stars investigated by Crowther & Smith (1996).

It is also interesting to compare the 1994 spectrum of HD 5980 with that of the star P Cygni (Stahl et al. 1993). Almost all the lines characterizing HD 5980 are present in

P Cygni (B1Ia); the most important exception being of course He II λ4686 which does not show up in P Cygni. Also, some ions present in P Cygni are missing or perhaps very weak in HD 5980 (i.e. O II, [Fe II], Mg II, Ni II). This may be due to the fact that our spectral resolution is half that used by Stahl et al. (1993). Another remarkable difference is that while in star P Cygni all the hydrogen Balmer and He I lines show P Cyg profiles, in HD 5980 some of them (i.e. Hβ, Hα, He I λ7065) are almost pure emission lines. On the other hand, the Fe III lines in the spectrum of HD 5980 indicate the same dichotomy as reported by Stahl et al. (1993) for the star P Cygni: transitions with low multiplet numbers display P Cyg profiles, while those with high multiplet numbers show pure emission lines. The resemblance between HD 5980 and the star P Cygni is somewhat expected since Koenigsberger et al. (1996) assign a spectral type B1.5Ia$^+$ to the ultraviolet spectrum of HD 5980 during the eruption.

HD 5980 is not the only LBV candidate in the SMC. In fact, the first LBV-like event in the SMC was reported for R 40 (Szeifert et al. 1993). A noteworthy difference between HD 5980 and R 40 is that contrarily to HD 5980 and other well-studied LBVs, R 40 has no P Cyg-type profiles of singly ionized metallic lines. In reality, the spectrum of R 40 strikingly resembles the spectra of normal hypergiants. An expanding envelope and strong wind in R 40 are only inferred from extended blue wings of the metallic lines and the P Cyg profile of Hα.

While some LBVs at visual minimum resemble Ofpe/WN9 stars (see Bohannan & Walborn 1989; Humphreys & Davidson 1994 and references therein), or WN 11 stars (Smith et al. 1994), HD 5980 is unique in the sense that it displays an WN 11-like spectrum near maximum visual brightness! Since mass loss, which is a key parameter of the LBV phenomenon, is now believed to be metallicity dependent (Abbott 1982, Leitherer et al. 1992 and references therein), it is necessary to compare LBVs in environments with different metallicities. The difference between HD 5980 and R 40 on the one side and the similarity between spectral features of HD 5980, BE 294, and He 3–519 which lie in three galaxies with significantly different metallicities on the other side may hint that other physical factors play a role as important as metallicity.

Several Galactic shell nebulae are known to be ejected mainly by W-R stars (see Esteban et al. 1992, Chu 1991 and references therein). Also, circumstellar nebulae are found to be associated with Galactic LBVs and related objects, in particular He 3–519 (Nota et al. 1995 and references therein). These nebulae have abnormal chemical abundances, in the sense that helium and nitrogen are enhanced and oxygen is depleted with respect to the Solar values, in agreement with predictions of stellar evolutionary models (Maeder 1990). As to the Magellanic Clouds, low-excitation nebular lines have been detected towards a number of LMC transition stars of category Ofpe/WN9 (Nota et al. 1995). The first case of abundance enhancements in a high-excitation nebula in the Magellanic Clouds was reported by Heydari-Malayeri et al. (1990) for the LMC N 82, a very compact H II region of radius $1''.3$. The central star that has undergone a violent mass loss is probably a unique transition star that has no known counterpart (Heydari-Malayeri & Melnick 1992).

On what concerns HD 5980, in view of the tight similarity to He 3–519, we may expect the presence of a surrounding nebular envelope. However, our high-resolution imaging attempts have failed to reveal such structure. This is not astonishing should the envelope be due to the 1994 eruption. In fact, some 700 years are necessary before a detectable shell shows up at a $0''.1$ separation from the star, corresponding to a linear distance of ~ 0.03 pc, if we assume a mean velocity of 40 km s^{-1} for the ejecta, comparable to that found for He 3–519 (Davidson et al. 1993). However, if future observations bring out an associated circumstellar ejecta, this means that HD 5980 has undergone at least another major mass loss in the past. If the 1994 event was not the only eruption of HD 5980, the detection of a nebula around the system and its detailed study should provide valuable information on the mass-loss history of HD 5980 and help to better understand the models of mass ejection during the evolution of massive stars. It is noteworthy to underline that HD 5980 has now returned to its pre-eruption state (Koenigsberger et al. 1996, Barbá et al 1996), showing a WN 6 type spectrum, as if nothing has happened.

The true nature of HD 5980 is far from being understood. Barbá et al. (1996) suggest that the main component of the eclipsing binary, a WN3 type, has undergone the outburst. They argue that there is no obvious indication of an O type component in the system, since the absorption lines, present in the pre-outburst spectrum, did not follow the orbital motion of the system. These lines may have been due to a line-of-sight O star (a resolution of $0''.1$ at the SMC corresponds to a linear separation of some 6200 AU, enough room to contain other components). If the WN3 component is indeed confirmed to be the one that has undergone the eruption, this raises serious problems for the conventional scenarios of the evolution of massive stars. For instance, the LBV phenomenon is commonly admitted to be a transitional step in the evolution of O type stars into W-R stars and the evolution of WN stars is usually believed to proceed from late spectral types (WNL) to early types (WNE). In the case of HD 5980 we are dealing with a system of W-R stars that has changed its spectral type from WNE to WNL in less than twenty years!

On the other hand, Moffat et al. (1996) suggest that HD 5980 likely consisted of two hot, luminous Of or hybrid Of/WNE stars in which the primary went into eruption. They ascribe the emission lines and the important spectral variability observed before the event to the action of two nearly equal colliding winds according to Usov's (1995) model. However, it is not clear how this scheme can explain the observed behavior of the emission spectrum and in particular the motionlessness of the absorption lines.

Further studies, observational as well as theoretical, are necessary in order to better understand this peculiar object. HD 5980 may represent the prototype of a new class of LBV phenomena occuring in close massive binaries in metal-poor environments.

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