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THE Ofpe/WN9 CLASS IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

The remarkable Ofpe/WN9 spectroscopic category in the LMC now contains ten members, including two newly identified here. Both photographic and digital spectrograms are presented, to establish the characteristics of the class in terms of the latter data, as a reference for future work. Two of these objects have shown large spectrum variations which transiently remove them from the class; one is currently undergoing a giant outburst which establishes it as a Luminous Blue Variable and suggests the possibility that the others may also be quiescent LBVs. Some significant correlations with the recent infrared spectral phenomenology of McGregor *et al.* (1988) are also pointed out.

Key words: Of-type stars–Luminous Blue Variables–spectrum variables–Large Magellanic Cloud

1. Introduction

Four peculiar supergiants in the Large Magellanic Cloud (LMC) whose spectra combine the Of characteristics with extensive lower-ionization emission features constituted the charter membership of a category now designated as Ofpe/WN9 (Walborn 1977). Further members were discovered and discussed by Bohannan (1979), Azzopardi and Breysacher (1979), Walborn (1982, 1986), and Stahl (1986). As their designation suggests, these objects might be interpreted as an extension to later types of the WN sequence. Several of them have been found to possess nonspherical, nitrogen-rich circumstellar nebulae (Walborn 1988 and references therein). Two new members of this interesting class have now been identified in the course of follow-up to an extensive survey for luminous emission-line stars in the LMC (Bohannan and Epps 1974, hereafter BE; Bohannan 1986).

One of the original members of the class, HDE 269858 = Radcliffe 127, entered a state of outburst in or about 1980 (Stahl *et al.* 1983; Walborn 1984) and recently became the visually brightest star in the LMC after SN 1987A, establishing itself as a Luminous Blue Variable (LBV). The Of features disappeared, the spectrum evolved through an intermediate B-type stage, and, most remarkably, it is now of peculiar supergiant A-type virtually identical to S Doradus, the prototype LBV in the LMC (Stahl and Wolf 1986; Wolf *et al.* 1988). Conversely, Of-type emission has recently been discovered during a light minimum of the galactic LBV AG Carinae (Stahl 1986), which at other times has displayed spectra very similar to P Cygni (B-type, Hutsemékers and Kohoutek 1988) and S Dor (A-type, Wolf and Stahl 1982). These observations provide strong indications of previously unsuspected close relationships among these apparently disparate objects, which may well lead to an improved understanding of their evolution.

An unprecedented survey of the 2-micron spectra of emission-line supergiants in the LMC has recently been presented by McGregor, Hillier, and Hyland (1988). They have found a number of well-defined morphological categories, including one in which the neutral helium line in this region is stronger than hydrogen Br γ. A near identity between the latter category and the Ofpe/WN9 class will be shown to exist.

Basic data for the ten currently known members of the Ofpe/WN9 class in the LMC are listed in Table 1, together with the references originally describing them as such, and including the two new members presented here, HDE 269687 and Sanduleak (1970, Sk) −69°297. Attention was also recently drawn to the former by Conti,

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TABLE 1

Ofpe/WN9 Stars in the LMC

BE	HDE	Sk	Radcliffe, Henize	V	$B-V$	Source	M_V	Reference
153	—	−67°266	S61	12.01	−0.13	1	−7.1	1
261	269445	−68°73	R99,S30	11.45	+0.27	2	−8.9	1
294	269582	−69°142*a*	—	11.88v	−0.04	3	−7.5v	2
335	269687	−69°175	S119	11.90	−0.07	2	−7.4	3
381	—	—	—	13.26:	+0.04	4	−6.4:	4,5
397	269858	−69°220	R127,S128	var	var	—	var	1
470	—	−69°297	S142	12.73	+0.11	2	−7.1	3
543	269227	−69°79	R84,S91	11.70	+0.20	1	—	1
—	269927C	−69°249C	—	12.48:	−0.11:	4,5	−6.7:	5,6
—	—	−66°40	S9	12.89	+0.03	6	−6.7	7

Photometry sources: (1) Ardeberg *et al.* (1972), (2) Isserstedt (1975), (3) Stahl (1986), (4) Feitzinger and Isserstedt (1983), (5) Westerlund quoted in Azzopardi and Breysacher (1979), (6) Isserstedt (1979).

Classification references: (1) Walborn (1977), (2) Stahl (1986), (3) this paper, (4) Bohannan (1979), (5) Walborn (1982), (6) Azzopardi and Breysacher (1979), (7) Walborn (1986).

Garmany, and Massey (1986). Other references providing fundamental information about several of these objects are Henize (1956), Smith (1957), Feast, Thackeray, and Wesselink (1960), Shore and Sanduleak (1984), and Stahl *et al.* (1985).

2. Observations

Digital spectroscopy has come of age from the viewpoint of spectral classification, since current instruments provide the required quality, and their enhanced capabilities with respect to photography will supersede the latter for most future applications. However, the establishment of a well-defined standard reference frame is equally essential for systematically reliable results with the new data. Both photographic and digital spectrograms will be presented here, to establish the transition between the two kinds of data for the Ofpe/WN9 class. An analogous transitional study for the entire OB classification reference frame is being undertaken by N.R.W. and E. L. Fitzpatrick.

The present material consists of three kinds of data, all from CTIO, which are listed in Table 2 and further described below.

TABLE 2

Observation Dates (UT)

HDE/Sk/BE	Image Tube	Shectman	Vidicon
−67°266	1984 Oct 31	1986 Dec 4	1984 Dec 31
269445	1983 Nov 3	1986 Dec 5	—
269582	1983 Nov 3	1986 Dec 5	—
269687	1984 Nov 2	1986 Dec 4	—
381	—	1986 Dec 3	—
269858	1983 Nov 3	1986 Dec 4	1984 Dec 31
−69°297	1984 Oct 31	1986 Dec 4	—
269227	1984 Nov 1	1986 Dec 4	1984 Dec 31
−66°40	—	—	1984 Dec 31

2.1 *1-Meter Photographic Image Tube*

The photographic spectrograms were obtained by B.B. with the Cassegrain image-tube spectrograph at the CTIO-Yale 1-meter reflector. The original dispersion is 43 Å mm^{-1} and the widening 0.9 mm. Baked IIIa-J emulsion was used, and the resolution is about 1 Å.

2.2 *1-Meter Shectman System*

Digital spectroscopy was also carried out by B.B. at the CTIO-Yale 1-meter telescope with the Cassegrain spectrograph and the two-dimensional, photon-counting detector system originally developed by S. A. Shectman. The original resolution was about 3 pixels over the central 60% of the detector and the spectral coverage 3800 Å–5100 Å over 3040 pixels. Rectification was performed with IRAF software routines. The final spectrograms were smoothed over 3 pixels, resulting in a typical measured $S/N = 40$ and a measured resolution of 2.4 Å in the outer 30% of the spectrograms.

2.3 *4-Meter SIT Vidicon*

Several objects were observed by N.R.W. at the CTIO 4-meter telescope with the Cassegrain spectrograph and the SIT Vidicon detector. The resolution is 1.5 Å and the spectral coverage 4025 Å–4700 Å. Two separate observations were averaged for each object, providing a S/N of about 30 for optimum exposures. These data have not been smoothed, and they have been rectified with assistance by Jonathan Wheatley using software written by Keith Horne.

3. Description of the Spectra

As previously discussed by Walborn (1977, 1982, 1986), when considered in detail the Ofpe/WN9 spectra subdivide into three subclasses, particularly in terms of the morphology near Hδ. The prototypes are HDE 269858 (before outburst)/Sk −67°266, with exceptionally narrow Si IV λ4089 and N III λ4097 absorptions; HDE 269227, with a striking array of partially overlapping P Cyg profiles there; and HDE 269445, so far unique with no absorption features except for a possible diffuse N III λ4097. Furthermore, two members of the class are known to exhibit large spectrum variations: HDE 269582, which evidently oscillates between high- and low-ionization states (Shore and Sanduleak 1984; Stahl 1986), and HDE 269858, currently in outburst as discussed in the Introduction. The variable objects raise the possibility that some other peculiar LMC objects which lack the Of features but otherwise resemble the Ofpe/WN9 class may actually be members of that class in temporary low-ionization states, as will be further discussed below.

Figure 1 (see page 561) displays the image-tube spectrograms of the two new Ofpe/WN9 objects together with HDE 269227 and Sk −67°266 for comparison. It is immediately evident that the two new members belong to the HDE 269858/Sk −67°266 subclass, with their defining, narrow Si IV λ4089 and N III λ4097 absorption features below Hδ. Both the high- and low-ionization emission features are quite weak but definite in HDE 269687. Sk −69°297 is very nearly identical to Sk −67°266 in all respects. Figure 2 (see page 561) shows the image-tube spectrograms of the two variable objects in non-Of states, HDE 269582 in November 1983 and HDE 269858 during outburst development also in November 1983. As mentioned by Stahl (1986), a CTIO 1.5-meter SIT Vidicon observation of HDE 269582 obtained by N.R.W. in December 1982 is essentially similar to this spectrogram, with no Of features, and the November 1975 spectrogram described by Shore and Sanduleak (1984) is also similar.

Figure 3 presents the Shectman data for HDE 269227 and its subclass comember BE 381; the new objects HDE 269687 and Sk −69°297 together with their prototype Sk −67°266; and HDE 269582 in December 1986, now with a fully developed Ofpe/WN9 spectrum. The reappearance of the latter is delimited by the spectrogram of Figure 2 and the observation of Stahl (1986) to sometime between November 1983 and December 1984. Clearly this object should be monitored as frequently as possible. Its Ofpe/WN9 subclass is also that defined by HDE 269858/Sk −67°266, although with rather stronger emission lines. (Note that HDE 269858 also had stronger lines than Sk −67°266—Walborn 1977.) The digital spectrograms of the new objects HDE 269687 and Sk −69°297 appear to be very faithful counterparts of their image-tube spectrograms in Figure 1. Figure 4 illustrates the Shectman data for the unique object HDE 269445 and for HDE 269858 in December 1986.

Finally, Figure 5 presents the SIT Vidicon observations of HDE 269227 and Sk −67°266, together with HDE 269858 in December 1984 and Sk −66°40, a relatively recent addition to the HDE 269858/Sk −67°266 subclass (these are the same data shown unrectified by Walborn 1986). Sk −66°40 is remarkably similar to HDE 269582 in Figure 3, with quite strong emission lines. These two objects show that the difference between the HDE 269858/Sk −67°266 and the HDE 269227 subclasses is not merely one of emission-line strength, since the lines in Sk −66°40 and HDE 269582 are as strong as—and in some cases stronger than—those in HDE 269227 and BE 381. Rather, there is some indication of an ionization difference in that the He II/He I as well as N III/N II ratios are greater in the HDE 269227 subclass. It could well be that the strikingly different morphologies of the Hδ spectral regions between the two subclasses are due to the relatively greater strengths of the Si IV and N III emission features there in the HDE 269227 subclass. The indistinctness of the N III λλ4634–4640–4642 emission in Sk −67°266 (December 1984) in Figure 5 is rather discrepant with Figure 3 (December 1986), as well as with the December 1982 CTIO 1.5-meter SIT Vidicon observation shown by Walborn (1984), possibly indicating some moderate spectrum variability in this object.

To summarize the Ofpe/WN9 subclassifications, the HDE 269858/Sk −67°266 subclass includes, in addi-

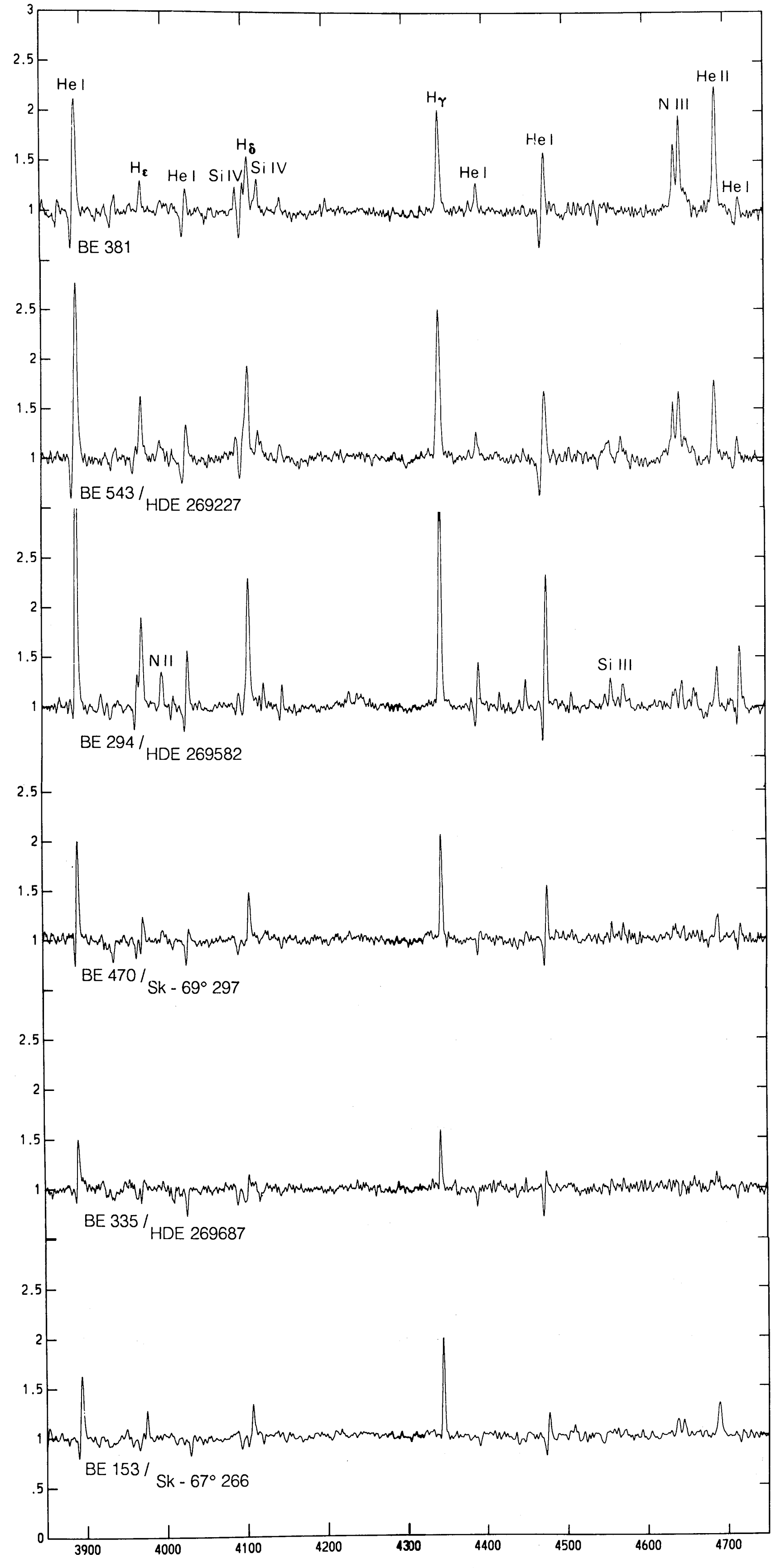

FIG. 3–Shectman data for several Ofpe/WN9 objects, including the two new ones HDE 269687 and Sk −69°297. In this and subsequent figures, normalized relative intensities are plotted versus wavelength in Å. Note the strong similarity of BE 381 to HDE 269227, and contrast this spectrogram of HDE 269582 from December 1986 with that in Figure 2. The features identified in the spectrum of BE 381 are, from left to right, He I λ3888, Hϵ λ3970, He I λ4026, Si IV λ4089, Hδ λ4101, Si IV λ4116, Hγ λ4340, He I λ4387, He I λ4471, N III λλ4634-4640-4642, He II λ4686, and He I λ4713. In addition, N II λ3995 and Si III λλ4552-4568-4575 are identified in the spectrum of HDE 269582.

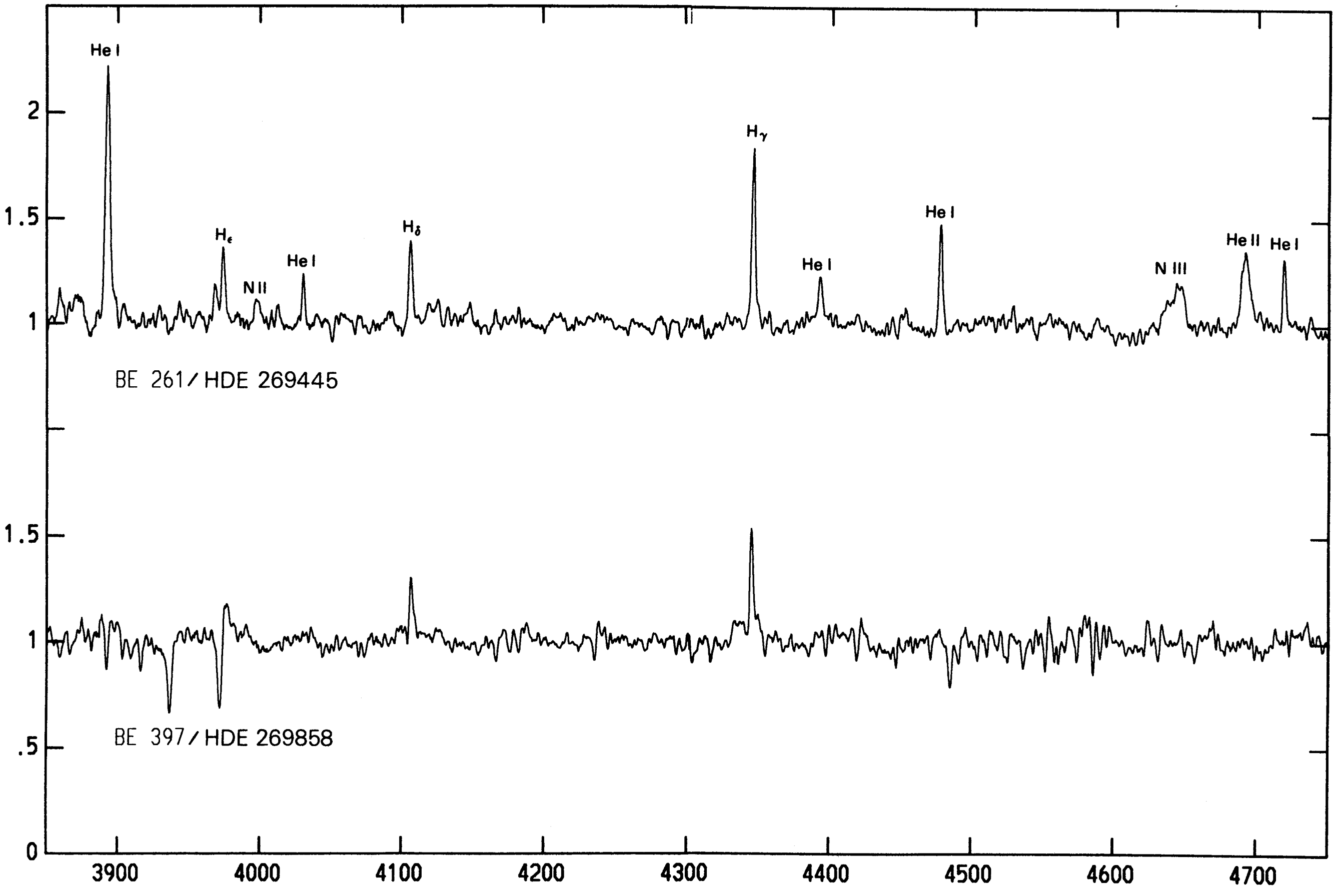

FIG. 4–Shectman spectrograms of the unique object HDE 269445 and of HDE 269858 in December 1986. The spectral lines identified are, from left to right, He I λ3888, Hε λ3970, N II λ3995, He I λ4026, Hδ λ4101, Hγ λ4340, He I λ4387, He I λ4471, N III λλ4634-4640-4642, He II λ4686, and He I λ4713.

tion, HDE 269582, HDE 269687, Sk −66°40, and Sk −69°297; the HDE 269227 subclass includes HDE 269927C and BE 381; while HDE 269445 stands alone.

4. Discussion

4.1 *Luminous Blue Variable Relationships*

The LBVs, a category including the Hubble-Sandage (HS), S Dor, and P Cyg variables (Conti 1984), lie near the Humphreys-Davidson (1979) limit in the H-R diagram, which evidently corresponds to an instability leading to episodic shell ejection and curtailing further redward evolution of the most massive stars. During outburst, the LBVs develop false photospheres with later spectral types while maintaining constant bolometric luminosities. A connection between the Ofpe/WN9 and LBV categories has been established by the current behavior of HDE 269858 (R127), as described in the Introduction. The fact that the minimum-state spectrum of HDE 269858 was actually a prototype for one of the Ofpe/WN9 subgroups (Walborn 1977, 1982) suggests the hypothesis that other Ofpe/WN9 stars may also be quiescent LBVs. Moreover, the identity between the A-type outburst spectrum of HDE 269858 and S Dor (Wolf *et al.* 1988) suggests that the converse may also be true, i.e., that many or perhaps all LBVs are Ofpe/WN9 objects at true minimum light. Further arguments in favor of that possibility are provided by the recent discovery of Ofpe/WN9 spectral features in AG Car during a deep minimum (Stahl 1986), together with the spectroscopic identity of its intermediate B-type phase (Hutsemékers and Kohoutek 1988) to P Cyg and to the HS variables AF Andromedae and M 33 Variable B (Kenyon and Gallagher 1985), as well as of its A-type maximum spectrum again to S Dor (Wolf and Stahl 1982). A corollary of this hypothesis would be that the true minimum spectra of P Cyg and S Dor have not yet been observed and that these objects are currently in extended intermediate or maximum states.

Another kind of relationship is suggested by the spectrum variations of HDE 269582; as discussed above and shown in Figure 2, its Of features can disappear, leaving a rather nondescript array of H and He I emission lines which might be classified simply as Bpe. (The relation of these spectral changes to the light variations of this star

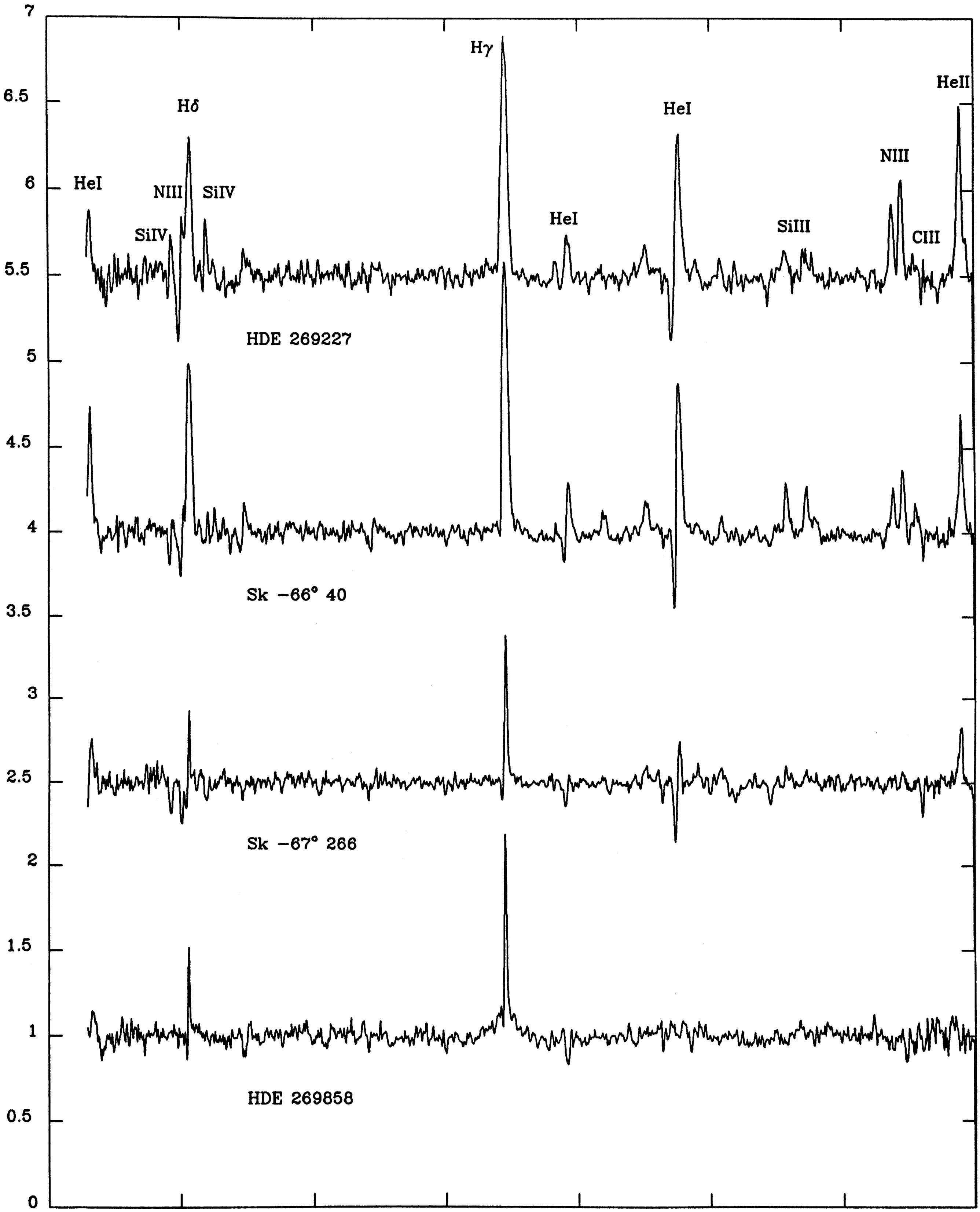

FIG. 5–SIT Vidicon data for four Ofpe/WN9 objects, including HDE 269858 in December 1984. The spectral features identified are, from left to right, He I λ4026, Si IV λ4089, N III λ4097, Hδ λ4101, Si IV λ4116, Hγ λ4340, He I λ4387, He I λ4471, Si III λλ4552-4568-4575, N III λλ4634-4640-4642, C III λλ4647-4650-4651, and He II λ4686.

has not yet been established.) But there are a number of other peculiar LMC supergiants with very similar Bpe spectra, which raises the interesting question whether they, too, might be Ofpe/WN9 objects in temporary low-ionization disguise. Two such objects, for which Shectman data are available, are HD 37836 (BE 601) and HDE 268840 (BE 182); in addition to the H and He I, their optical spectra show only weak Fe II emission lines. However, HD 37836 has been shown by Stahl and Wolf (1987) to have ultraviolet stellar-wind line profiles appropriate for a late-O supergiant; they also suggested that it is physically related to HDE 269445 (Table 1) and Sk $-69°240$ (Henize S131, Be 415), although these latter two spectra do show He II λ4686 emission. Further evidence for a relationship among all of these objects and the Ofpe/WN9 class is discussed in the next subsection.

4.2 *Infrared Relationships*

The ground-breaking 2-μm spectroscopic survey of peculiar LMC emission-line supergiants by McGregor *et al.* (1988) has identified a striking category in which He I 2.058 μm is stronger than H Br γ, which they have suggested to indicate an evolutionary abundance anomaly. Of the eight stars showing this characteristic, five are members of the Ofpe/WN9 class (HDE 269445, HDE 269582, HDE 269687; Sk $-66°40$ = Henize S9, Sk $-67°266$ = S61), while the other three are HD 37836, HDE 268840, and Sk $-69°240$ = Henize S131 which were just discussed above.

They also observed two Ofpe/WN9 objects which did not show He > H, for which plausible explanations can be suggested in the context of the present discussion. One is HDE 269858 observed in outburst, which shows only Br γ and a 2-μm spectrum identical to that of S Dor—hardly surprising in view of their currently identical optical spectra! It is likely that the He I line is not seen because the low, A-type photospheric ionization of HDE 269858 and S Dor at the time of the IR observations is insufficient to excite it. Furthermore, it is predicted that if they can be observed at 2 μm in Ofpe/WN9 minimum-light states, they will show He > H. The other Ofpe/WN9 object without He I 2-μm emission is HDE 269227, which has a red supergiant companion that dominates this spectral region. Moreover, as discussed in Section 3 above, this object shows *higher* ionization in the optical than the others, which suggests that the He I may be suppressed for that reason. This suggestion can be tested by IR observations of the other two members of its subgroup, HDE 269927C and BE 381. It is noteworthy in this regard that Schmutz *et al.* (1989) have very recently derived a substantial helium overabundance in HDE 269227 (R84) from a quantitative analysis of its optical spectrum. Hence, the current observational situation is consistent with enhanced helium in all members of the Ofpe/WN9 class.

The evidence for enhanced nitrogen abundances in the atmospheres and circumstellar nebulae of Ofpe/WN9 stars and LBVs was recently reviewed by Walborn (1988). The new results concerning helium discussed above contribute further evidence that these are very highly evolved objects which have CNO-cycle products at their surfaces and are ejecting this processed material into their circumstellar environments.

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