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INFRARED SPECTRA OF MASSIVE STARS IN TRANSITION: WNL, Of, Of/WN, Be, B[e], AND LUMINOUS BLUE VARIABLE STARS

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ABSTRACT

We present an overview of the spectroscopic properties of several luminous stars belonging to Of supergiant, Ofpe/WN9, late-type nitrogen sequence Wolf-Rayet (WNL), B[e], Be supergiant, and luminous blue variable (LBV) classes at 2 μm and 1.6 μm, using recently published and new spectra of moderate to high resolution (500–1600). These objects are "transitional" in their optical classification and may be related in their evolution.

The 2 μm spectrum of the LBV AG Car has changed from its 1984–1985 appearance as an Of/WN star, now appearing as a Be or B[e] star by comparison to new spectra of HD 72754 (B2Iape) and GG Car (B[e], whose spectrum has varied since 1984–1985). Further support for a link between B[e] stars and LBVs is seen in the case of the SMC B[e] star S18, which has changed its 1987–1989 spectrum from one of Brγ emission only to one in which emission lines of Fe II, Mg II, Na I, ^{12}CO overtone, He I 2.112–3 μm, and He I 2.058 μm (strong) are present. As the earlier observations were not of a high signal-to-noise ratio, we confirm only the He I and ^{12}CO as new emission, where the latter was previously expected on the basis of TiO emission but was undetected. The overall morphology of the atomic spectrum of S18, including the He I 2.112–3 μm emission, are shared by only one other B star, namely, the quiescent LBV P Cyg (B1 Ia$^+$), but is shared also by the LBV and Ofpe/WN9 star HDE 269582. Only AG Car is observed to have also varied in the 2.112–3 μm line. We thus consider S18 a strong candidate LBV.

Our new high-resolution 2 μm spectra also include HD 5980, a WN binary recently observed to undergo an LBV-like outburst in short-term brightness and spectroscopic variations. We provide a detailed *K*-band line identification of the probable LBV He 3-591 (WRA 751), which is rich in lines of permitted and forbidden iron (mainly Fe II) and includes new identification of [Ni II] at 2.308 μm and 2.369 μm.

A significant degree of overlap in spectral morphology exists between the groups, where at least one example from each group may be classified as a member of another from its 2 μm spectrum. This has serious consequences for observations of hot, luminous objects in visually obscured regions. The overlapping infrared spectral morphology reinforces the notion that the objects in this study are interrelated in their evolution. We propose that "transitional" massive stars with hydrogen present at their surfaces (including the least extreme WN types) may not yet be in the stage of core-helium burning but rather are in a previous phase in which the stellar atmosphere/wind is sometimes dynamically unstable.

Subject headings: infrared: stars — stars: early-type — stars: emission-line, Be — stars: Wolf-Rayet — supergiants

1. INTRODUCTION

A small population of luminous stars with strong emission lines makes up the Wolf-Rayet (W-R) class, numbering so far ~300 objects known between the Galaxy and Magellanic Clouds (van der Hucht 1995). These objects are in the latter stages of massive star evolution (see, e.g., Lamers et al. 1991) and are readily identified by the strong optical emission lines that are the signature of a substantial stellar wind, $\dot{M} \sim 10^{-5}$ to 10^{-4} $M_\odot$ yr^{-1} (see, e.g., Hamann, Koesterke,

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& Wessolowski 1995). The surface compositions of W-R stars are striking in their deficiency *or total absence* of hydrogen, which also suggests a highly evolved nature. The paucity of W-R stars is understood mainly in terms of their relatively short lifetimes, as they spend only a few 10^5 yr in a post–main-sequence phase, following from a massive O-type state before a possible death as a supernova. Chiosi & Maeder (1986), Maeder (1991), and Maeder & Meynet (1994) have provided reviews of the evolutionary models; see also reviews of the content and evolution of massive stars in galaxies by Conti (1994) and Maeder & Conti (1994).

Although the overall scenario for massive star evolution is reasonably well understood, details of the genetic relationship between main-sequence O stars, possible "intermediate" stages, and the final W-R state are complex and remain controversial. Some confusion is added by the fact that *both* dwarf and supergiant O stars may be burning hydrogen in their cores, and thus the usual correspondence between "supergiant" and "post–main-sequence" is not assumed for the most massive stars. In any event, it is generally believed that single O stars with solar composition and initial masses larger than $\sim 35\ M_\odot$ will at some point evolve blueward across the H-R diagram toward the W-R stage. The reversal of normal redward motion is caused by hydrogen depletion at the stellar surface. This depletion is a consequence of mass loss of hydrogen-rich material, mixing of helium-rich material from the stellar core ("overshooting"), or some combination of these processes or others (e.g., in close binaries, Roche lobe overflow might remove substantial matter; the initial mass in these cases *might* be lower than $\sim 35\ M_\odot$). For single stars, the "intermediate" stages between main-sequence (core-hydrogen burning) O stars and W-R types *may* be identified in the following spectral classes: Of supergiants (high mass loss from relatively strong, steady, stellar winds; see Conti 1976; Lamers & Leitherer 1993); the luminous blue variable (LBV) stage (variable winds and episodic ejection events, leading to rapid loss of the outer envelope at rates of $\sim 10^{-4}$ to $10^{-3}\ M_\odot\ \mathrm{yr}^{-1}$ (Lamers 1989; Humphreys & Davidson 1994); and a red supergiant (RSG) phase. This latter phase probably occurs only for lower masses, as there is an observed upper luminosity limit for RSGs of log $(L/L_\odot) \gtrsim 5.8$, corresponding to $M_{\mathrm{initial}}/M_\odot \gtrsim 60$ according to Humphreys & Davidson (1994).

At the same time that these possible evolutionary links are consistent (in a general way) with the known spectral morphology, the navigation of evolutionary predictions through spectral classes and *subtypes* is hampered by the effects of massive star winds on spectrum formation. The two-dimensional classification scheme developed by Conti (1971) and Walborn (1971) for OB stars was improved upon by Walborn (1982) to take into account effects on optical spectral lines by the strong stellar winds in the OB supergiants. Classification of W-R stars has essentially remained one-dimensional, based primarily on the excitation states of nitrogen (the WN sequence) and carbon and oxygen (both defining WC and WO subtypes). But spectral line and continuum formation occurs over layers that extend well into the wind (see, e.g., Hillier 1987), and the one-dimensional scheme introduced by Hiltner & Schild (1966) and further developed by Smith (1968) does not fully reflect the conditions over the entire spectrum-forming region, resulting in heterogeneous physical properties for each subtype (see, e.g., Hamann et al. 1995). Schmutz, Hamann, & Wessolowski (1989) have taken measures of the wind density into account, and Smith, Shara, & Moffat (1996) have proposed including hydrogen abundance as a third parameter. These improved OB and W-R classification schemes are still limited mainly to the *optical* region (for obvious historical reasons). Remembering also that the production of reliable synthetic spectra from detailed model atmospheres requires well-determined temperature, density, and ionization distributions *throughout* the accelerating region of the wind, spectral types may not always associate (longer wavelength) spectral appearance with a unique set of physical properties.

The fundamental problem in fully understanding massive star evolution in the framework of mass-loss processes and "overshooting" is that we are able to *observe* the stellar surface conditions and abundances, from which we must *infer* the interior composition by using models. The evolutionary state of the star is defined by the physics of the stellar core, which in turn determines the atmospheric conditions (Schaerer & Schmutz 1994; Schaerer 1995). Note also that for massive stars, luminosity classifications reflect only small differences in absolute magnitudes and, more important, they have *no* implication concerning the evolutionary state; in other words, *all* "classical" O-type stars are understood to be core-hydrogen burning ("main-sequence") objects. Similarly, "classical" W-R stars have been assumed to be core-helium burning objects, although the presence of hydrogen in some WN objects has suggested that these might be core or shell hydrogen burning (Conti 1976; Conti et al. 1995). Further evidence that not all W-R stars are in a state of core-He burning may be found in the remarkable results of Rauw et al. (1996), who followed spectral and photometric variations of the eclipsing WN7 + O binary WR 22 over several years to find from radial velocity measurements that the *minimum* current mass of the primary WN7 star is 72 $M_\odot$. Since the WN7 star also exhibits a high hydrogen mass fraction, the attributes are that of a massive core-H burning O star with a wind instability (in the sense of exceeding the "single-scattering limit" applied to mass loss by radiative pressure in the spectral lines) and producing the WN star spectrum. The primary is considered to have evolved chiefly by mass loss in the wind rather than Roche lobe overflow. If true, the conclusions drawn for this case may well extend to other objects with similar spectral morphology and physical properties, such as the other two well-known WN7 + abs stars in Carina, WR 24, and WR 25.

Two different scenarios receiving the widest attention have been recently proposed to account for the occurrence and order of the stages between O star and W-R star, distinguished principally by where the LBV stage might occur. Crowther et al. (1995c) have suggested that a late-type WN (WNL) stage directly follows the Of stage for stars with the highest initial masses ($M_{\mathrm{init}} \gtrsim 60\ M_\odot$), of which WR 22 may be an example, but is interrupted by an excursion through an LBV or RSG phase at lower masses. The WNL stars would then evolve to early-type WN and finally WC objects. Langer et al. (1994) and Meynet et al. (1994) have proposed from evolutionary calculations that the LBV phase is possible (at least under certain conditions) *between* hydrogen-rich and hydrogen-poor WNL stars.

A close observational connection between LBVs and W-R stars is found in the stars classified as Ofpe/WN9, the so-called slash stars. These were initially defined by

Walborn (1982) to account for optical spectra intermediate in their properties between the most extreme O stars and the least extreme WN stars, where "extreme" refers to a combination of strength and degree of ionization of the emission lines in particular. There is substantial evidence that these stars link LBVs to W-R stars: Stahl et al. (1983) found that the Ofpe/WN9 star R127 in the Large Magellanic Cloud (LMC) had entered a period of pronounced variability in only a few years. Furthermore, the spectral properties of Ofpe/WN9 stars are reproduced in the well-known LBV AG Carinae when observed at visual minimum (Stahl 1986). Walborn (1989) has suggested that perhaps *all* Ofpe/WN9 stars can be identified with the high-temperature ($T_{\rm eff} = 20{,}000$–$30{,}000$ K), visual minimum phase of LBVs. The notion that LBVs (He 3-519 and AG Car, in particular) are directly tied to the latest type WN stars has recently been explored by Smith, Crowther, & Prinja (1994), reassociating the visual minimum state of AG Car with WN 11 rather than Ofpe/WN9 from a subtle distinction in the optical classification lines and otherwise similar physical properties.

Different mass-loss rates in preceding stages can result in significantly different evolutionary paths (Maeder 1991; Maeder & Meynet 1994). Nota et al. (1996) have compared and analyzed optical-to-infrared photometry and ultraviolet-to-optical spectra of several Ofpe/WN9 stars and (possibly) related objects. Their conclusions not only support the likelihood that Of, Ofpe/WN9, and LBV objects represent closely related evolutionary stages but also support the suggestion by Schulte-Ladbeck et al. (1993) that B[e] stars (emission-line B-type supergiants with forbidden lines in their optical spectra) with similar spectral properties may be more intertwined with this transition group (with LBVs, in particular) than previously thought.

In this paper we examine the *near-infrared* spectral morphology of "transition" early-type supergiants to expand our empirical understanding of the evolutionary status of these objects. We compare basic spectral properties of several Of, Be, B[e], and late-type WN stars in the *K* (2.02–2.35 μm) window, and Ofpe/WN9 and LBV stars in the *H* (1.45–1.80 μm) and *K* bands, demonstrating consistencies and differences in spectral appearances that might not be expected on the basis of optical classification. We will devote special attention to the plausibility of a connection between B[e] stars and LBVs, showing a 2 μm analogy to the earlier spectroscopic links found between LBVs and Ofpe/WN9 stars. For the sake of clarity, we will not perform analyses here, keeping the presentation of the numerous spectra and overview of properties as concise as possible. Line identifications and measurements (equivalent widths) will be provided, laying the groundwork for spectral analyses to be presented in a following paper. The *K* band will be emphasized here, because it is in this range that luminous stars visually obscured by dust are most easily observed and that our data are most complete. Hanson, Conti, & Rieke (1996, hereafter HCR) have published moderate-resolution *K*-band spectra of several Galactic OB stars that cover a range of luminosity classes; comprehensive *J*-, *H*-, and *K*-band spectral atlases of WN and WC stars are currently in preparation by P. R. J. E. and P. W. M.

Our observational data set is described in § 2. In § 3 we present our comparisons, provide line identifications, and discuss spectral morphology. Since the Of and WNL stars have, historically, been closely associated in their spectral morphology and evolutionary status, we treat them as reference points for subsequent examination of the Ofpe/WN9, LBV, and B[e] stars as possible intermediate stages. Further discussion is contained in § 4, and a summary and outline for continued work is given in § 5. Comments on individual spectral features in the various stellar subsets are given in the Appendix.

2. THE OBSERVATIONS

All but two of the spectra shown here were obtained over the period 1993–1995 from observing runs at Cerro Tololo InterAmerican Observatory (CTIO) and Kitt Peak National Observatory (KPNO); the spectra of WR 108 and WR 123 were graciously provided to us by Marten van Kerkwijk from his observing run on the United Kingdom InfraRed Telescope in 1990. See Table 1 for a summary.

The Ofpe/WN9 stars and the LBV star S Doradus were observed by Darren Depoy in 1993 September at the CTIO 4 m telescope using the Ohio State Infrared Imager/Spectrometer (OSIRIS; Depoy et al. 1990), which employs a 256 × 256 Rockwell HgCdTe (NICMOS III) array with a plate scale of 0″.45 pixel^{-1}. The spectrometer was arranged in a cross-dispersed mode, which allows for simultaneous coverage of the *J* (1.20–1.45 μm), *H* (1.45–1.84 μm), and *K* (1.93–2.40 μm) bands at low resolution, $R \simeq 570$. A detailed description of the observation and reduction procedures is given in Blum, DePoy, & Sellgren (1995a), who utilized the *H* and *K* spectra as comparison standards for their observations of helium emission-line sources in various Galactic center locations.

M. M. H. used OSIRIS at the CTIO 4 m telescope to observe the O8 supergiants HD 151804 and HD 152408 at high resolution, $R \simeq 1300$, in the *K* band (2.02–2.23 μm). The rectified spectra of these stars, obtained in 1993 August, are taken from the preliminary atlas of OB stars by Hanson & Conti (1994), in which the observations and reductions are discussed.

Low-resolution spectra of WR 22 and all LBVs, excluding S Doradus, were obtained by P. W. M. (CTIO 4 m telescope; 1993 November) and P. J. R. E. (CTIO 1.5 m telescope; 1994 April), who used OSIRIS in its cross-dispersed configuration. The low-resolution LBV spectra were observed on the night of 1994 April 29. Extraction of these data was performed by P. W. M. by using IRAF software available from the National Optical Astronomy Observatories. Basically, each frame was flat-fielded by using dome flats taken at the beginning of each night and then corrected for OH sky and thermal emission by differencing "offset" frames. These were created at the telescope by stepping the star in the slit, which was oriented in the east-west direction, to positions separated by ~2″. Averaging spectra extracted from the offset positions reduces the effects of variations in scattered light and detector response. At low resolution, and with a fairly short slit (20″ × 1″.3), neither fringing nor anamorphic demagnification is present. Wavelength solutions in the three bands were derived for *each* star from telluric OH airglow. This procedure involved a low-order polynomial fit to the background sky of each frame, which was then subtracted from the original (source + sky) frame in order to separate stellar and sky spectra. An exceptionally clean sky frame is obtained this way.

TABLE 1

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Star[a]	Type	References[b]	Observation Date	Facility	$\Delta\lambda$[c]	$\lambda/\delta\lambda$	S/N
HD 16691	O4.5 If+	1	1994 Sep	KPNO 1.3 m CRSP	K_1	800	100
HD 190429	O4.5 If+	1	1994 Sep	KPNO 1.3 m CRSP	K_1	800	100
HD 108	O6 f?pe	2	1994 Sep	KPNO 1.3 m CRSP	K_1	800	100
HD 151804	O8 Iaf	2	1993 Aug	CTIO 4 m OSIRIS	K_2	1300	70
HD 152408	O8: Iafpe	2	1994 Aug	CTIO 4 m OSIRIS	K_2	1300	70
BD +36 4063	ON9.7 Ia	3	1994 Sep	KPNO 1.3 m CRSP	K_1	800	100
GG Car	B[e]	4	1995 May	CTIO 1.5 m IRS	K_2	1600	90
			1995 Nov	CTIO 4 m IRS	K_2	1600	90
HD 72754	B2 Iape	5	1995 Nov	CTIO 4 m IRS	K_1	1600	75
S18	B[e]	6	1995 Nov	CTIO 4 m IRS	K_1	1600	~20
HDE 268840	Ofpe/WN9?	...	1993 Sep	CTIO 4 m OSIRIS	*HK*	570	60
HDE 269445	Ofpe/WN9	7	1993 Sep	CTIO 4 m OSIRIS	*HK*	570	60
HDE 269582	Ofpe/WN9[d]	7	1993 Sep	CTIO 4 m OSIRIS	*HK*	570	60
WR 122	? Ofpe/WN9 or B[e]	8	1993 Sep	CTIO 4 m OSIRIS	*HK*	570	60
WR 85a	? Ofpe/WN9 or B[e]	8	1993 Sep	CTIO 4 m OSIRIS	*HK*	570	60
WR 22	WN7+abs[e]	9	1993 Nov	CTIO 4 m OSIRIS	*K*	570	50
WR 158	WN7	9	1993 Sep	KPNO 1.3 m CRSP	K_1	700	100
WR 123	WN8	9	1990	UKIRT CGS	*K*	600	55
WR 156	WN8	9	1993 Sep	KPNO 1.3 m CRSP	K_1	700	100
WR 108	WN9+abs[e,f]	9, 10	1990	UKIRT CGS	*K*	600	55
HD 5980	WN4+O7	11	1995 May	CTIO 1.5 m IRS	K_2	1600	90
S Dor	LBV	12	1993 Sep	CTIO 4 m OSIRIS	*HK*	570	60
He 3-519	LBV[g]	13, 14	1994 Apr	CTIO 1.5 m OSIRIS	*HK*	570	50
			1995 May	CTIO 1.5 m IRS	K_1	1600	90
WRA 751	LBV	15	1994 Apr	CTIO 1.5 m OSIRIS	*HK*	570	50
			1995 May	CTIO 1.5 m IRS	K_1	1600	90
HD 160529	LBV	16	1994 Apr	CTIO 1.5 m OSIRIS	*HK*	570	50
AG Car	LBV[h]	17	1994 Apr	CTIO 1.5 m OSIRIS	*HK*	570	50
			1995 May	CTIO 1.5 m IRS	K_1	1600	90
			1995 Nov	CTIO 4 m IRS	K_1	1600	90
HR Car	LBV	18	1994 Apr	CTIO 1.5 m OSIRIS	*HK*	570	50

[a] WR numbers are taken from the catalog of van der Hucht et al. 1988. WRA 751 = He 3-591.

[b] CLASSIFICATION REFERENCES.—(1) Walborn 1973; (2) Walborn 1972; (3) Mathys 1989; (4) Carlson & Henize 1979; (5) Thackeray et al. 1973; (6) Shore et al. 1987; (7) Bohannan & Walborn 1989; (8) K. A. van der Hucht, private communication; (9) van der Hucht et al. 1988; (10) Crowther et al. 1995a; (11) Breysacher et al. 1982; (12) Wolf et al. 1988; (13) Davidson et al. 1993; (14) Smith et al. 1994; (15) Hu et al. 1990; (16) Sterken et al. 1991; (17) Wolf & Stahl 1982; (18) Humphreys & Davidson 1994.

[c] H = 1.48–1.84 μm; K = 1.93–2.40 μm; K_1 = 2.02–2.42 μm; K_2 = 2.02–2.23 μm.

[d] Also a confirmed LBV (Humpreys & Davidson 1994).

[e] Spectral types appended with " +abs" denote the presence of higher (generally $n \geq 5$) hydrogen Balmer lines in absorption believed to be intrinsic to the W-R star spectrum.

[f] WR 108 has been classified, and still often referred to, as O7:Iafpe (Hutchings 1979; Walborn 1982), but weak emission of He II 2.189 μm is more consistent with a WN classification. Crowther et al. (1995b) have performed a detailed spectral analysis of WR 108, confirming the WN9 classification.

[g] LBV candidate; WN11 star at visual minimum (Smith et al. 1994).

[h] Ofpe/WN9 at visual minimum (Stahl 1986), or WN11 at visual minimum (Smith et al. 1994).

Removal of telluric absorption features was done by division with late-type G, early-type F, and early-type A dwarf stars matched in air mass with the program sources as closely as possible. The A stars are the most ideal correction sources because, outside of the H I lines, their spectra are featureless. Metal absorption lines in the G and F stars (e.g., Si I and Ti I) are weak—no stronger than ~2 Å in equivalent width; this is near our detection threshold. The most difficult telluric corrections are for strong absorption by the CO_2 vibrational band heads centered at 2.00 and 2.06 μm and for H_2O absorption during times of poor seeing (ranging from 1.″5 to greater than 2″) caused by variable atmospheric cirrus in the November and April evening observations. Solar-type absorption lines (namely, the H I Paschen β line at 1.28 μm and Brackett series in the H and K windows) were removed from each standard star by either (1) using a solar spectrum already corrected for telluric absorption (provided by the National Solar Observatory; see Livingston & Wallace 1991) or (2) "bridging" out the absorption when the spectral type of the standard is earlier than late-type G. The disadvantage of the second method is that it is difficult to prevent removal of overlapping telluric features, but these are generally quite weak (as judged from the telluric spectrum separated from the solar spectrum), resulting in as much as a few percent increase in the flux of the spectral lines that are coincident with the H I transitions in the program stars.

BD +36 4063, HD 16691, HD 190429, HD 108, WR 156, and WR 158 were observed at $R \simeq 800$ by M. M. H. with the Cryogenic Infrared Spectrometer (CRSP; Fowler & Heynssens 1993), a 256 × 256 SBRC InSb array, on the 1.3 m telescope at KPNO in 1994 September. Spectral coverage of these objects is limited to the K band (2.02–2.42 μm). The spectra of the O4.5 If$^+$ stars were recently shown by Conti et al. (1995); they will be included along with BD +36 4063 in the OB atlas of HCR, in which details of the reduction procedures can be found.

High-resolution observations were obtained with the CTIO IRS spectrometer by M. M. H. on 1995 May 11 on the 1.5 m telescope (HD 5980, He 3-519, WRA 751, AG Car,

TABLE 2

OF STARS: LINE IDENTIFICATIONS AND EQUIVALENT WIDTHS (Å)[a]

λ (μm)	Transition	BD +36 4063 (ON9.7 Ia)	HD 108 (O6f?pe)	HD 152408 (O8:Iafpe)	HD 151804 (O8Iaf)	HD 190429 (O4.5 If$^+$)	HD 16691 (O4.5 If$^+$)
2.038	He II 15–8	...	...	0.3 abs	0.3 abs	1.1	$\lesssim$0.9
2.058	He I $2s^1S$–$2p^1P^o$	...	...	6.8 abs	3.0 abs	0.3 abs	...
		5.0	4.6	2.3	0.8	$\lesssim$0.3	0.4[b]
2.078[c]	C IV $3d^2D$–$3p^2P^o$	...	1.0	0.8	0.5	0.3	0.5
2.100	N V 11–10 ?	...	...	2.3	0.7	0.7	0.4
2.116[d]	N III/C III 8–7	$\simeq$1[e] abs	4.5	9.3	3.8	4.6	4.5
2.165[f]	H I 7–4	28.2	...	23.5	7.6	7.2	8.8
2.189	He II 10–7	...	$\lesssim$0.3 abs?	1.0 abs	0.9 abs	5.0	1.4
2.346	He II 13–8	...	...	n/a	n/a	3.1	1.6

[a] Equivalent widths (in units of Å) refer to emission lines except where denoted by "abs" for absorption lines; "n/a" denotes insufficient spectral coverage.

[b] Uncertain identification of the 2.058 μm feature in HD 16691; possibly distorted by insufficient correction for telluric absorption.

[c] The C IV $3d^2D$–$3p^2P^o$ configuration produces triplet transitions at 2.069, 2.078, and 2.082 μm, where the 2.078 μm line is the strongest.

[d] Blended with He I 2.112 μm ($3p^3P^o$–$4s^3S$) and He I 2.113 μm ($3p^1P^o$–$4s^1S$). He I is in absorption in HD 151804; EW $\geq$ 1.1 Å. Weaker absorption is probably present in HD 152408.

[e] Absorption due to He I 2.112–3; N III detection uncertain.

[f] Blended with He I 2.161 μm ($7f^3F^o$–$4d^3D$) and He I 2.162 μm ($7f^1F^o$–$4d^1D$). Probably also blended with He II 2.166 μm (14–8) absorption in HD 152408 and HD 151804 and emission in HD 16691 and HD 190429 (see text).

and GG Car) and by P. W. M. and P. R. J. E. on 1995 November 9–12 on the 4 m telescope (HD 72754, AG Car, GG Car, and S18). The IRS (described by Depoy et al. 1990) has recently been upgraded to use a 256 × 256 InSb array and is operated in a manner similar to that of the KPNO CRSP instrument. The 75 line mm^{-1} grating was used in second order, giving a resolution of 1600 and a spectral coverage from 2.03 to 2.38 μm. Typical signal-to-noise ratio (S/N) for most sources was rather high (S/N > 80) for the high resolution obtained. A S/N ratio of ~20 resulted from the high air mass of 2.1 at which S18 was observed in the K window. Further details on observational procedures using IRS and reduction of the data may be found in Hanson (1996) and HCR.

3. LINE IDENTIFICATION AND SPECTRAL MORPHOLOGY

In this section, we show montages of K- and (where available) H-band spectra, identify the primary features, and provide equivalent width measurements. For clarity, notes on individual features are given in the Appendix. These notes will pertain mainly to identification, blending, and profile shape. The Of and WNL stars are presented first as the earliest recognized descendents of massive main-sequence O stars. Objects representing possible intermediate stages (Ofpe/WN9, LBV, Be/B[e]) follow. Along the way, we illustrate as clearly as possible a number of similarities in the K-band appearance of different classes of objects (differing in their optical classification or by identification as an LBV), which unavoidably complicate the task of classification from infrared spectra alone.

Identifications of H I and He II lines are taken from the tables of Wiese, Smith, & Glennon (1966) and Garcia & Mack (1965), respectively. Higher hydrogenic transitions, including those of H I ($n_j > 20$), He II ($n_j > 15$), N III–V, and C III–IV and are calculated using $\lambda = 0.0911138Z^{-2}[(n_i^2 n_j^2)/(n_j^2 - n_i^2)]$.

Wavelengths for He I transitions are calculated from the 1*sns* and 1*snp* energy levels published by Martin (1987). Allowed and forbidden transitions of N II–V and C III–IV are determined from the energy levels provided by Bashkin & Stoner (1975, 1978). Each possible identification is narrowed down on the basis of transition probability and ability to locate connecting lines with similar spectroscopic terms. We also refer to previous spectroscopic studies of luminous sources where possible, including Hillier, Jones, & Hyland (1983); Allen, Jones, & Hyland (1985); McGregor, Hillier, & Hyland (1988a); McGregor, Hyland, & Hillier (1988b); Eenens, Williams, & Wade (1991); and Hamann et al. (1994). The spectroscopic studies of the LBV η Carinae by Allen et al. (1985) and Hamann et al. (1994) are particularly useful for identifying iron transitions. We have also used preliminary infrared line lists by van der Hucht & Koornneef (1994) and P. van Hoof (private communication) for use with the Short Wavelength Spectrograph on the *Infrared Space Observatory.*

3.1. *The Of and WNL Stars*

The appearance of the 2 μm spectra of OB stars spanning all luminosity classes has been given by Hanson & Conti (1994) and Hanson et al. (1996). Figure 1 is a montage of Of supergiant, WN8, and WN9 stars, representing a close morphological correspondence in two different cases where the O star He II 2.189 μm line is in (*a*) absorption and (*b*) weak emission. All Of stars are extreme in the sense that they exhibit both N III 4634, 4640 Å and He II 4686 Å in emission; hence, the "f" in the Of classification (Walborn 1971). Line identifications are given in Figure 1, and equivalent width measurements for the O supergiants (including HD 108 and BD +36 4063, which are discussed later) are given in Table 2. Line identifications and measures of the B supergiant spectra of this study are provided in Table 3; the spectra are presented later, alongside that of AG Car (§ 3.5). The WN star line measures will be published in a forthcoming atlas.

In Figure 1*a*, He II 2.189 μm is in absorption in the O8 If stars, which were observed at high resolution (see Table 1). This transition is in very weak emission in WR 108 and (probably) in WR 156. Other than this subtle variation from weak absorption to weak emission, the K-band appearance of the WNL and O8 If spectra would be *indistinguishable* at

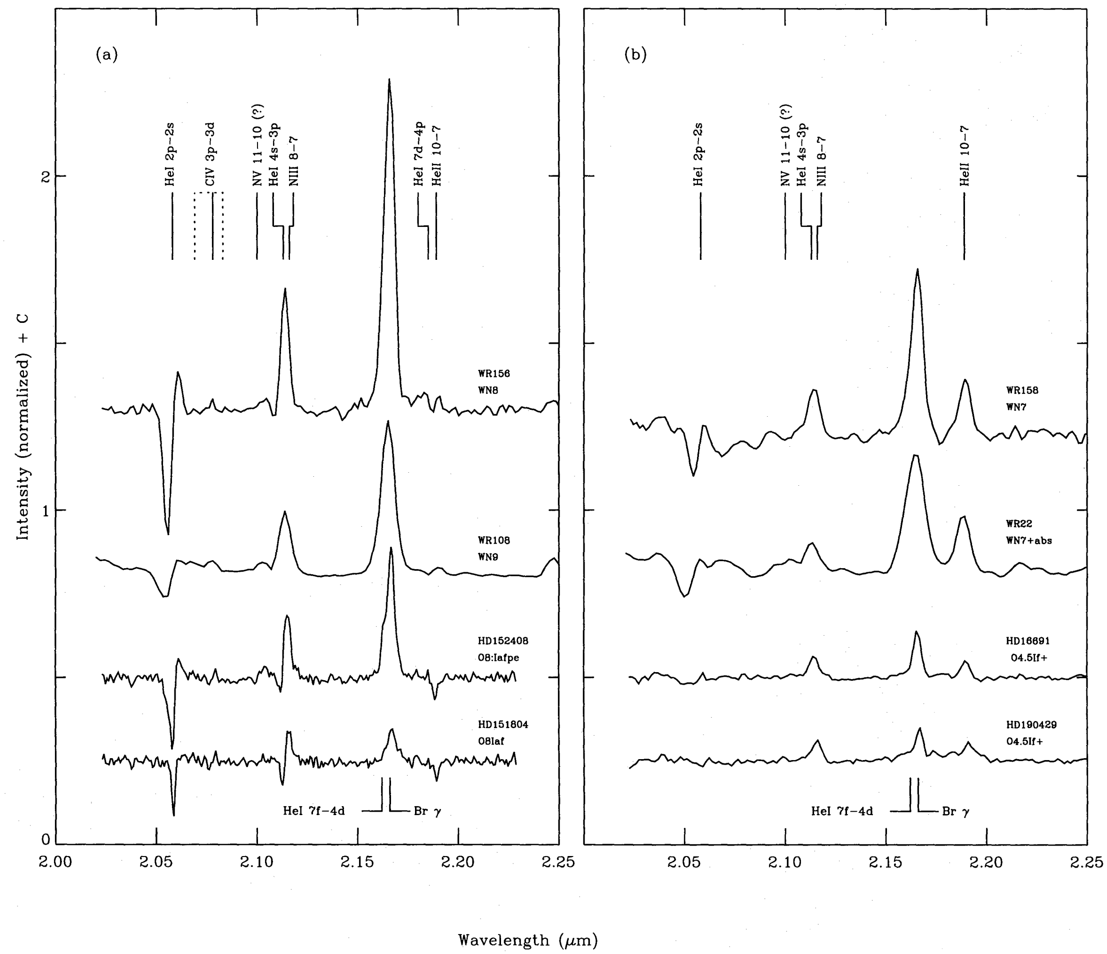

FIG. 1.—Of and WNL stars in the K band, with O-star He II 2.189 μm in (a) absorption and (b) emission. The O8 If stars data are of resolution $R \simeq 1300$; other objects have been observed at $R \simeq 570$–800.

lower signal-to-noise ratios, which are typical of many Galactic center observations for which long integrations are required. This similarity not only includes the dominant features of He I + Brγ 2.165 μm, He I + N III 2.112–2.116 μm, and He I 2.058 μm but also extends to the presence of weak 2.078 μm emission in each, arising from the strongest line of the C IV $3d^2D$–$3p^2P^o$ triplet and emission at 2.105 μm (see Appendix) in all but HD 151804. We note that a

TABLE 3

B SUPERGIANTS: LINE IDENTIFICATIONS AND EQUIVALENT WIDTHS (Å)[a]

λ (μm)	Transition[b]	HD 72754 (B2 Iape)	GG Car (B[e])	S18 (B[e])
2.058	He I $2s^1S$–$2p^1P^o$	≲0.6 abs	≲0.8 abs	≲2.5 abs
		13.6	3.3	11.3
2.089	Fe II $z^4F^o_{3/2}$–$c^4F_{3/2}$	2.1	1.3	1.5
2.112	He I $3p^3P^o$–$4s^3S$	0.4 abs	...	3.6
	+He I $3p^1P^o$–$4s^1S$ 2.113	bl	bl	bl
2.138	Mg II $5s^2S_{1/2}$ – $5p^2P^o{}_{3/2}$	2.0	1.5	1.1
2.144	Mg II $5s^2S_{1/2}$–$5p^2P^o_{1/2}$	1.3	1.0:	0.8:
2.165[c]......	H I 7–4	32.9	13.9	42.5
2.206	Na I $4p^2P^o_{3/2}$–$4s^2S_{1/2}$	3.3	p?	5.0:
	+Na I $4p^2P^o_{1/2}$–$4s^2S_{1/2}$ 2.209	bl	p?	bl
2.294	^{12}CO (2, 0) band head	...	4.7	7.1
2.323	^{12}CO (3, 1) band head	...	4.0	6.6
2.352	^{12}CO (4, 2) band head	...	3.1	2.0:

[a] Equivalent widths (in units of Å) refer to emission lines except where denoted by "abs" for absorption lines.

[b] First entries for each feature in this column are judged to be the dominant transition in each feature according to measured central wavelengths and line transition probability. Weaker transitions are measured where resolvable, and are otherwise denoted as blended, "bl," and measured with the dominant transition as a conglomerate.

[c] Blended with He I 2.161 μm ($7f\,^3F^o$–$4d\,^3D$) and He I 2.162 μm ($7f\,^1F^o$–$4d\,^1D$).

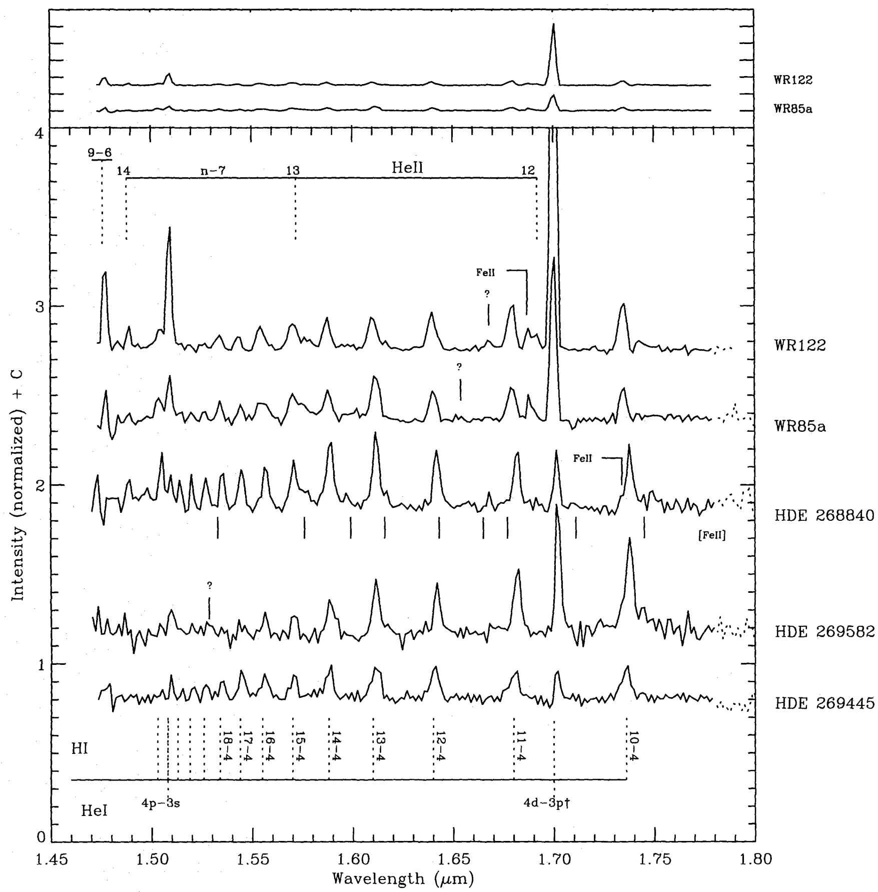

FIG. 2.—Ofpe/WN9 stars at low resolution ($R \simeq 550$) in the K window. Symbols: double dagger, doublet; dagger, triplet. WR 122 and WR 85a are considered uncertain as Ofpe/WN9 (see text).

K-band spectrum of WR 105, recently published by Crowther & Smith (1996) and reclassified from WN8 to WN9 by Smith et al. (1996), is similar to that of WR 108 and WR 156 except for a noticeably stronger He I 2.058 μm emission. Each of these WN stars is relatively abundant in hydrogen (Crowther, Hillier, & Smith 1995b; Crowther et al. 1995c; Hamann et al. 1995).

Similar scaling of spectral features is also seen among the stars of Figure 1*b*, which all show He II 2.189 μm in emission. As pointed out by Conti et al. (1995), the O4.5 If$^+$ stars HD 190429 and HD 16691 are exceptional cases: these are the *only* two OB-type stars known to exhibit subordinate He II transitions in emission. An explanation for this will be proposed in future analyses, but for now it is sufficient to reemphasize how "extreme" these two stars are in terms of the proximity of their spectroscopic properties to those of WNL stars. This point raises interesting questions about the core-burning status of the Of and "least extreme" WNL stars that are discussed below.

At low resolution or signal-to-noise ratios, and without the benefit of optical classifications, all four O stars in Figure 1 could easily have been classified as WNL. Note, however, that absorption of both He I and He II is apparent in the cooler Of stars, distinguishing them from the WNL stars at this resolution. A related criterion that *may* prove useful for distinguishing some Of stars from WNL stars is the feature at 2.112–6 μm, which should not be mistaken as a P Cygni line in, e.g., HD 151804 or HD 152408. Here, one can measure the dominance of hydrogenic N III (8–7) 2.116 μm emission over the He I 2.112–3 μm multiplet (which is generally either in absorption or filled in; see Hanson & Conti 1994) in Of spectra. Emission from the N III line is expected by virtue of emission at 4634,40 Å in both Of stars (a classification criterion) and W-R stars. But in cases of higher Of star wind densities, intrinsic line broadening of the N III emission line may be heavily blended with the He I line, which could also be in emission under the WN-like conditions apparent in, e.g., HD 16691 and HD 190429. Further, the resolution needed to separate contributions (~ 150 km s^{-1}) may be overtaken by the range of velocities where these lines are formed in thicker winds.

3.2. *The Ofpe/WN9 Stars*

The K- and H-band spectra of Ofpe/WN9 stars are shown in Figure 2 and Figure 3. WR 122 (alias NaSt1) and WR 85a (alias LSS 4005) are located in the Galaxy; the remaining stars are members of the LMC. Equivalent widths of the primary emission lines are given in Table 4.

3.2.1. *WR 122 and WR 85a*

The Of/WN status of WR 122 and WR 85a is not certain: Crowther, Hillier, & Smith (1995a) have considered these objects good candidates for WN9–WN11 classification given their He I–II and N II–III optical emission but also suggest a possible B[e] classification because of emission by Fe II–III and various unusual forbidden lines. We cannot

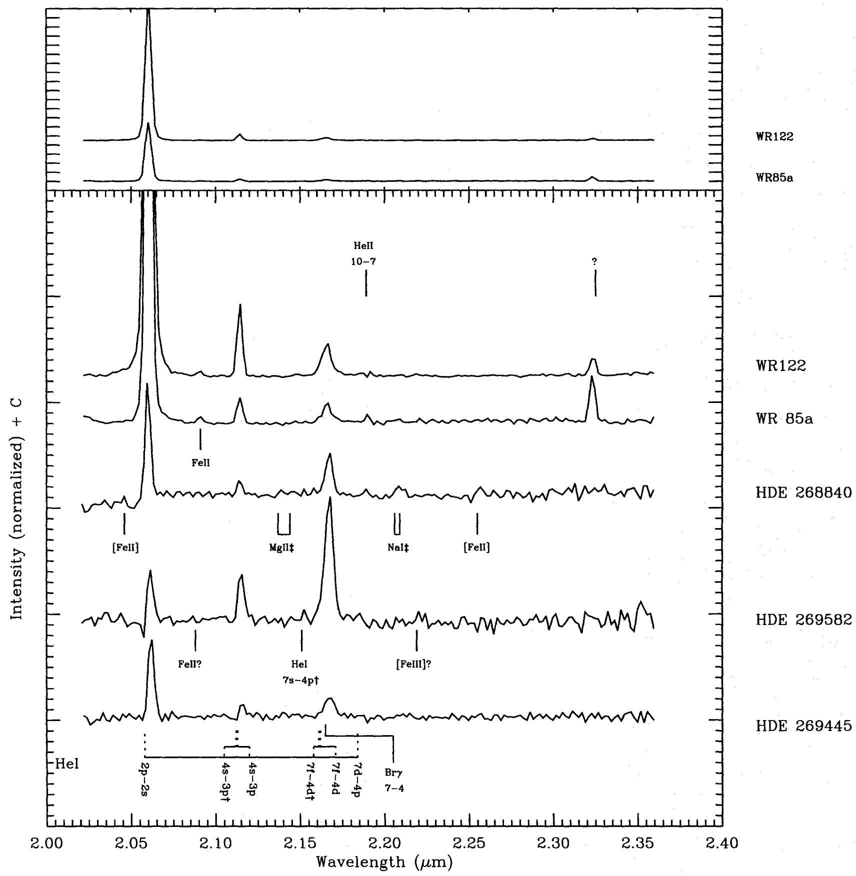

FIG. 3.—Ofpe/WN9 stars at low resolution ($R \simeq 550$) in the H window. Symbol: dagger, triplet.

make the distinction between Ofpe/WN9 and WN10–11 on the basis of N II emission. Weak He II 2.189 μm (10–7) emission seen in WR 85a, and suggested in WR 122, is also weakly present in both WN9 stars WR 108 (Fig. 1) and WR 105 (Crowther & Smith 1996). He II 4686 Å (5–4) emission is present but weak in WN10–11 (see, e.g., Smith et al. 1994), and we would not expect higher level He II emission in these subtypes.

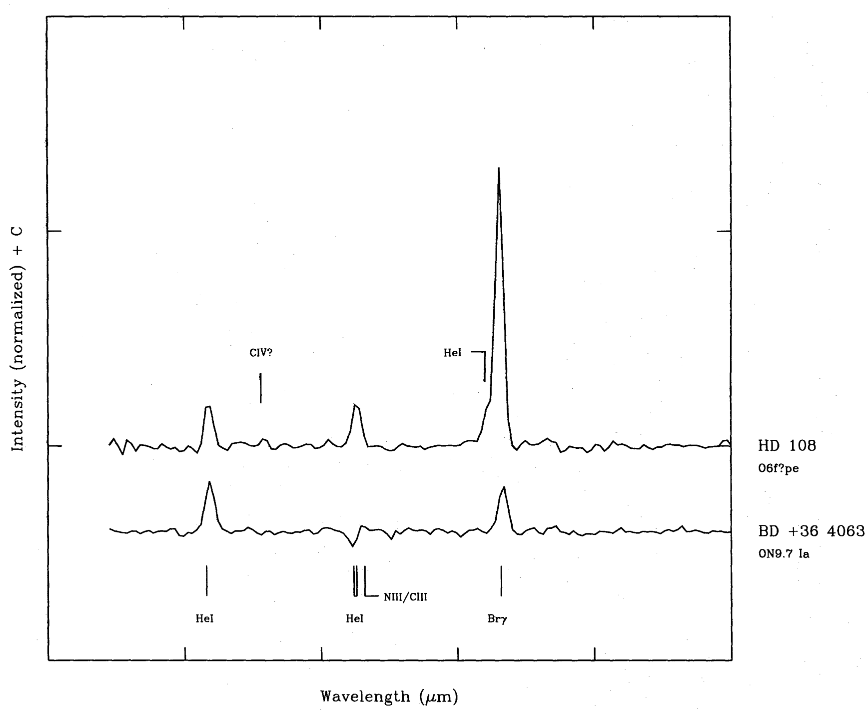

FIG. 4.—K-band spectra ($R \simeq 800$) of the O supergiants BD +36 4063 (ON9.7 Ia), and HD 108 (O6f?pe) with He I 2.058 μm in emission. Compare HD 108 with HDE 269582 (Fig. 2).

TABLE 4

Ofpe/WN9 Stars: Line Identifications and Equivalent Widths (Å)[a]

λ (μm)	Transition[b]	WR 122 (NaSt1)	WR 85a (LSS 4005)	HDE 268840	HDE 269582	HDE 269445
1.473......	? C III $7d^3D$–$6f^3F^o$	...	...	5.7	p	...
1.476......	He II 9–6	14.2	4.7[c]	...	...	...
1.488......	He II 14–7	3.7	1.8	4.8	...	...
1.504......	H I 23–4	5.8	5.4	8.7	1.9	1.1
1.508......	He I $4p^1P^o$–$3s^1S$	20.2	7.8	5.4	7.0	2.6
	+H I 22–4 1.508 μm	bl	bl	bl	bl	bl
1.513......	H I 21–4	<2[d]	1.7	3.7	...	1.1
1.519......	H I 20–4	0.9	1.5	3.7	...	2.2
1.525......	H I 19–4	1.4	1.7	3.7	3.4	2.8
1.528......	?	...	...	...	3.5	...
1.534......	H I 18–4	3.6	3.5	7.0	...	3.4
	+[Fe II] $a^4F_{9/2}$–$a^4D_{5/2}$ 1.533 μm	...	...	bl	bl?	...
1.543......	H I 17–4	2.8	2.9	10.0	3.2	6.7
1.555......	H I 16–4	7.2	7.7	11.4	5.1	6.6
1.569......	H I 15–4	9.1	11.8	18.1	5.1	5.5
	+He II 13–7 1.572 μm	bl	bl	bl	...	...
1.575......	? N III+C III 13–9	p	p	p	...	...
	?+Fe II $z^2I^o_{11/2}$–$3d^54s^2$ $I_{11/2}$ 2 1.576 μm	bl?	bl?	bl?	...	...
1.588......	H I 14–4	8.0	9.2	21.0	12.1	8.0
1.599......	[Fe II] $a^4F_{7/2}$–$a^4D_{3/2}$	...	...	3.5	p?	...
1.611......	H I 13–4	10.1	14.4	23.0	14.2	11.1
1.615......	[Fe II] $a^4H_{11/2}$–$a^2F_{5/2}$	p	p?	p	p	...
1.641......	H I 12–4	11.0	8.0	16.1	12.6	10.5
	+[Fe II] $a^4F_{9/2}$–$a^4D_{7/2}$ 1.643 μm	bl	bl?	bl?	...	...
1.653......	?	p?	p	...	p?	...
1.668......	?	p	p	2.9	p?	...
1.677......	[Fe II] $a^4F_{7/2}$–$a^4D_{5/2}$	...	...	p?	p?	p
1.681......	H I 11–4	13.2	10.3	15.6	19.4	10.1
1.688......	Fe II $z^4F_{9/2}$–$c^4F_{9/2}$	7.6	5.7	p	...	...
	?+He II 12–7 1.692 μm	p	bl	p?	...	...
1.700......	He I $4p^3P^o$–$3s^3S$	112.3	34.4	12.0	29.4	6.9
1.711......	[Fe II] $a^4F_{5/2}$–$a^4D_{3/2}$	...	...	p	?	...
1.736......	H I 10–4	13.0	10.5	17.9	30.6	11.9
	+Fe II $z^4D_{7/2}$–$c^4P_{5/2}$	...	...	p	p	p?
1.745......	[Fe II] $a^4F_{3/2}$–$a^4D_{1/2}$	p	p	p	6.5[c]	p
2.046......	[Fe II] $a^4_{5/2}$–$a^2P_{3/2}$	p?	...	p	...	...
2.058......	He I $2s^1S$–$2p^1P^o$	715	267	42.1	22.9	35.1
2.089......	Fe II $z^4F^o_{3/2}$–$c^4F_{3/2}$	p	p	...	p?	...
2.078......	C IV $3d^2D$–$3p^2P^o$	2.8	0.7	...	3.6[e]	2.4[e]
2.112......	He I $3p^3P^o$–$4s^3S$	26.1	10.3	6.2	22.2	6.2
	+He I $3p^1P^o$–$4s^1S$ 2.113 μm	bl	bl	bl	bl	bl
	+N III/C III 8–7 2.116	bl	bl	bl	bl	bl
2.138......	Mg II $5s^2S_{1/2}$–$5p^2P^o_{3/2}$	...	...	p	...	p?
2.144......	Mg II $5s^2S_{1/2}$–$5p^2P^o_{1/2}$	...	...	p	...	...
2.165......	H I 7–4	23.0	14.1	23.4	78.4	18.3
	+He I $7f^3F^o$–$4d^3D$ 2.161 μm	bl	bl	bl	bl	bl
	+He I $7f^1F^o$–$4d^1D$ 2.165 μm	bl	bl	bl	bl	bl
2.189......	He II 10–7	?	3.0	2.7	...	...
2.206......	Na I $4p^2P^o_{3/2}$–$4s^2S_{1/2}$	...	...	p	...	...
2.209......	Na I $4p^2P^o_{1/2}$–$4s^2S_{1/2}$	...	...	p	...	...
2.218......	? [Fe III] $^3G_4$–H_4	...	...	...	p	...
2.254......	[Fe II] $a^2G_{7/2}$–$a^2H_{9/2}$	...	...	5.1	...	...
2.324......	? C III $5p^3P^o$–$5s^3S$	8.6	18.3	...	...	...

[a] Equivalent widths are in units of Å.

[b] First entries for each feature in this column are judged to be the dominant transition in each feature according to measured central wavelengths and line transition probability. Weaker transitions are measured where resolvable, and are otherwise denoted as blended, "bl," and measured with the dominant transition as a conglomerate. The presence of weak lines (EW $\lesssim$ 2 Å) is simply indicated by "p."

[c] Uncertain continuum level.

[d] Partially blended with He I 1.508 μm.

[e] Uncertain identification of the C IV 2.078 μm feature in HDE 269582 and HDE 269445.

Both Of/WN and B[e] possibilities were left open earlier by van der Hucht et al. (1989), and again by van der Hucht et al. (1996) who prefer Ofpe/WN9 from visual ionization but caution that relatively low effective temperatures for both objects (~12,000 K) point to B[e]. Stable thermal continuum emission at $\lambda \gtrsim 2$ μm is also present around both sources (Williams, van der Hucht, & Thé 1987).

Since CO overtone emission is generally common in the spectra of luminous B[e] stars, with few known exceptions at other spectral types (see McGregor et al. 1988a; McGregor, Hyland, & McGinn 1989), no immediate association of WR 122 or WR 85a with a disk morphology can be made in the absence of CO. The disks of B[e] stars are expected to provide a sufficiently high density environment to explain CO overtone emission by collisional excitation. This does not exclude the possibility of a disk that is not traced by CO at *low* densities, however. This is already suggested by McGregor et al. (1988b) for the minority of B[e] stars without CO overtone emission. At lower luminosities, such a scenario provides a plausible explanation for absorption of Hα and emission by the H I infrared recombination line spectrum of the B0.2 V star τ Sco (Waters et al. 1993). The range of disk densities calculated for subtypes between B0 and B8 for this kind of behavior must be some 10^2–10^3 times lower than generally found in dwarf Be stars (Zaal, Waters, & Marlborough 1995). When adapted to higher luminosities and applied to ground-based spectra and planned observations with the Short Wavelength Spectrometer aboard the *Infrared Space Observatory*, the model should indicate how plausible a disk geometry is for WR 122 and WR 85a.

The intense He I emission from the two stars in the *H* and *K* windows is not likely to be nebular, since only faint knots of Hα + [N II] emission are observed near WR 122 in the CCD image (2″–5″ spatial resolution) taken by Miller & Chu (1993). WR 85a is not included in lists of recent surveys, but a literature search reveals no indication that nebulosity is present or suspected. Heated circumstellar (disk?) material is present in both objects (Williams et al. 1987; van der Hucht et al. 1989, 1996).

3.2.2. *HDE 269582, HDE 296445, and HDE 268840*

The most noticeable attribute of the Ofpe/WN9 2 μm spectra is the strength of the He I 2.058 μm emission. HDE 269582 is not dominated by this feature but fits the morphology of the Of stars closest in terms of relative Brγ and 2.112–6 μm line strengths (see Fig. 1) and is extremely similar to the supergiant star HD 108 in appearance (Fig. 4). We are reminded that HDE 269582 is a known LBV: Blum et al. (1995a) have pointed out that the 1993 September observation shown here is about a *factor of 2 stronger* in 2.058 μm emission than seen by McGregor et al. (1988b) in 1987 January, which indicates a strong change in far-UV flux levels (see below). The He I 2.112–3 μm line does not appear to have varied. In contrast, spectra of two LMC Ofpe/WN9 stars (BE 381 and HDE 269927c) and three SMC B[e] stars (R4, R50, and S18) shown by McGregor et al. (1989) exhibit little or no emission 2.058 μm at all.

Such contrasting behavior when measured by the He I lines is partly a result of differences in surface abundances for each object and may depend on geometrical effects (particularly where the B[e] stars are concerned) but could also be traced to varied temperature and density conditions yielding different levels of excitation. For the 2.058 μm line, this implies a strong susceptibility to *intrinsic* variability deep in the winds. The reason is that the 2.058 μm line is particularly sensitive to variations of flux in the far-UV portion of the spectrum: the resonance $2p\ ^1P^o$–$1s\ ^1S$ singlet transition (584.3 Å) from the same upper level is strongly favored, so the presence of 2.058 μm emission depends on an overpopulation of the $2p\ ^1P^o$ level. This could occur from variations in the radiation at 584 Å, and at 591 Å and 539 Å where interconnecting multiplet transitions from the upper levels of $2p\ ^3P^o$ and $3p\ ^3P^o$ occur. The 2.058 μm line will thus respond to even minor density enhancements near the surface of the star. For this reason, the 2.058 μm line is not particularly reliable for classification or as a diagnostic of abundance. Variations in UV flux are thought to be responsible for observed variability of the 2.058 μm line in the W-R component to the highly reddened X-ray binary Cyg X-3 (W-R + compact; van Kerkwijk et al. 1992, van Kerkwijk 1995), which otherwise fits the spectral and physical morphology of WN types. See also Eenens & Williams (1994) and Najarro et al. (1994) for discussion of this line in WC-type stars and Of/WN-type stars in the Galactic center. The He I 2.112–3 μm recombination singlet + triplet blend, on the other hand, should not be particularly sensitive to changes in far-UV flux levels, except through detailed balance of the He I level populations.

The H I Brackett series ($n - 4$, $n \geq 10$) dominates the general appearance of the Ofpe/WN9 spectra in the *H* window (Fig. 3). The gradual increase in strength with increasing wavelength (decreasing principal quantum number of increasing transition probability) is nicely illustrated in the spectra of HDE 269582 and HDE 269445. A low-resolution ($R \simeq 350$) 1.45–1.85 μm spectrum of the Of star HD 151804 published by Cotera et al. (1996), on the other hand, shows signs of weak emission from H I 1.736 μm (10–4) *only* (no obvious He I or higher H I lines), which indicates significantly different wind conditions. The Brackett edge occurs at 1.458 μm, and a continuum jump formed by this edge was not detected at the present signal-to-noise ratio before normalization of the continua.

Iron transitions (primarily those of Fe II and [Fe II]) are identified in the spectra of HDE 268840, HDE 269582, WR 122, and WR 85a. Iron lines such as those seen in HDE 268840 have been identified in the central knot (or star) in η Carinae (Allen et al. 1985; Hamann et al. 1994). These lines are likely to originate in the outer stellar envelope instead of surrounding nebulosity. The lines of moderate strength at 2.089 μm in the spectra of WR 122 and WR 85a are identified with a highly energetic Fe II line (see the Grotrian diagram in Allen et al. 1985); McGregor et al. (1988b), who observed this line in the LBV-like star HDE 316285, have suggested that it is populated by UV fluorescence.

The Mg II doublet at 2.137, 2.144 μm in HDE 268840 and (possibly) HDE 269445 has been observed by McGregor et al. (1988b) in the spectra of AG Car and HDE 316285. The Na I doublet identified in HDE 268840 is also seen in LBV stars by McGregor et al. (1988b) and in a number of other emission-line objects (Scoville et al. 1983; Lambert, Hinkle, & Hall 1981; Thompson & Boroson 1977; Ferland et al. 1979). Na I emission is not normally seen in the visual spectra of Ofpe/WN9 stars (see Bohannan & Walborn 1989), but McGregor et al. (1988b) noticed both a Na I D P Cygni line and weak Na I 2.206–9 μm emission in the spectrum of HDE 316285. The Na I D lines cannot be ascertained in HDE 268840 because of the lack of published optical spectra.[6] The Na I doublet at 1.637–9 μm ($4p^2P^o_{3/2,1/2}$–$6s^2S_{1/2,1/2}$) may be present in HD 268840 and HD 269582.

3.3. *HD 108 and BD +36 4063*

HCR and Hanson (1996) have shown that the majority of all O-type stars observed thus far in the *K* band do not normally exhibit the He I 2*p*–2*s* singlet in emission. Rare exceptions include Oe-type stars (with double-peaked profiles of disk origin), the O8 If star HDE 152408 (P Cygni profile; see Fig. 1), the ON9.7 Ia star BD +36 4063, and the

[6] Thus, the spectral subtype of HDE 268840 is somewhat ambiguous. We include it with the slash stars because of the similarity of its H and He spectrum to that of HDE 269445 but note the presence of He II 2.189 μm (see Figs. 2 and 3).

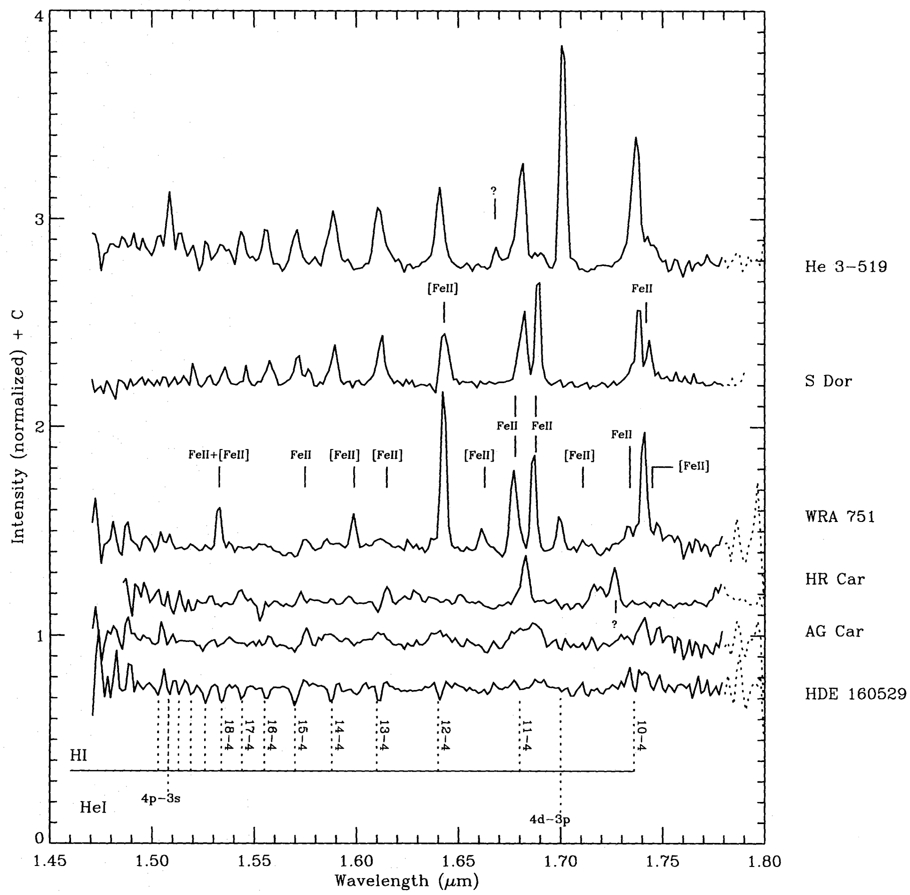

FIG. 5.—LBV stars at low resolution ($R \simeq 550$) in the K window. Symbol: dagger, triplet.

O6f?pe star HD 108. Spectra of the latter two objects are plotted in Figure 4. Identifications and equivalent width (EW) measurements of the most prominent lines are provided in Table 2.

These objects are significant in that they are morphologically similar to a number of He I emission-line sources observed within the central parsec of the Galactic center (see, e.g., Blum, Sellgren, & Depoy 1995b; Cotera et al. 1996; Tamblyn et al. 1996; Krabbe et al. 1995). Of course, HD 108 is already known to exhibit a number of unusual spectral properties at optical wavelengths (see Walborn 1972; Vreux & Conti 1979; Underhill 1994), but its similarity with the slash stars should not go unnoticed. The unresolved Galactic center point source IRS 13 bears the He I and Brγ signature of HD 108 and HDE 269582, differing only in nebular [Fe III] emission (see Libonate et al. 1995; Tamblyn et al. 1996).

Several Galactic center He I sources display the signature of BD +36 4063 as well: relatively narrow 2.058 μm emission, comparable Brγ emission, and weak He I 2.112–3 μm absorption. Tamblyn et al. (1996) have suggested that the late-type ON classification[7] may be suitable for several of these sources, as it comprises a possible minority population of evolved, luminous O-types within the central parsec.

[7] The ON classification was introduced by Walborn (1971, 1976) for those O stars with anonymously strong optical nitrogen lines. These stars have been shown to have high surface abundances of helium and nitrogen (see, e.g., Schonberger et al. 1988), which are the signs of CNO-processed material. Overabundances at the O supergiant stage are suggested to be a result of enhanced mixing or a shortened core-H burning lifetime owing to fast initial rotation.

3.4. *The Luminous Blue Variable Stars*

Line identifications and equivalent widths for our set of LBVs are given in Table 5. From Table 5 and Figures 5 and 6, we find that each spectrum is unique in terms of appearance—this is not unexpected in view of the fact that LBVs are defined solely by photometric and spectral *variability*.

Every object in Figure 5 except HD 160529 exhibits some amount of Brγ emission. In HD 160529, we suspect on the basis of the appearance of the higher Brackett lines that the 7–4 transition is just at the threshold of emission: in each of the n(upper) = 10, 11, 12, and (possibly) 13 transitions, absorption appears to be superposed on weak but broad emission features, which suggests a two-component envelope with a cool outer shell shielded from a warmer, denser inner region. This object needs to be observed at a higher signal-to-noise ratio to confirm these features. The H-Brackett absorption lines, however, are consistent with a relatively low effective temperature; Sterken et al. (1991) estimated $T_{\rm eff} \simeq 8000$ K and $\dot{M} \gtrsim 10^{-5}$ $M_\odot$ yr^{-1} at maximum light in 1982, increasing to an estimated ~10,000 K at decreased visual brightness in 1990.

He 3-519 and S Dor, on the other hand, are most pronounced in H-Brackett emission, and in this property, these stars are spectroscopically most similar to the Ofpe/WN9 stars (compare Figs. 5 and 2 and/or Figs. 6 and 3). S Dor is

TABLE 5

LBV STARS AT $RL \sim 500$–600: LINE IDENTIFICATIONS AND EQUIVALENT WIDTHS[a]

λ (μm)	Transition[b]	He 3-519	S Dor	WRA 751	HR Car	AG Car	HD 160529
1.473......	? C III $7d^3D$–$6f\,^3F^o$	<8[c]	...	<8.0[c]	<3[a]	<8[c]	p?[c]
1.476......	He II 9–6	...	p	bl	...	bl?	...
1.481......	?	...	...	5.4[c]	p?[c]	<4.5[c]	p?[c]
1.488......	He II 14–7	p?	p?	6.0	p	6.4[c]	4.1
1.496......	H I 25–4	p	p?	3.8[d]	...	2.2	p (abs)
1.504......	H I 23–4	4.1[c]	p?	3.0[d]	3.8	2.8	p (abs)
1.508......	He I $4p^1P^o$ –$3s^1S$	9.9[c]	2.6	...	p?	p (abs)	...
	+H I 22–4 1.508 μm						
1.513......	H I 21–4	5.3[c]	p?	p?	...	...	p (abs)
1.519......	H I 20–4	2.3[c]	2.7	p	p	...	p (abs)
1.525......	H I 19–4	3.3	?	p	...	2.0 (abs)	
1.528......	?	...	p	p?[c]	...	p	...
1.534......	H I 18–4	4.9	3.6	bl	...	...	2.0 (abs)
	+[Fe II] $a^4F_{9/2}$–$a^4D_{5/2}$ 1.533 μm	...	bl?	7.5	2.6	...	...
1.543......	H I 17–4	6.3	2.7	p?	...	...	p (abs)
1.555......	H I 16–4	7.4	5.7	2.0	...	...	p(abs)
	+? N I $3p^2P$–$4s^2P$ 1.558 μm	bl?	bl?	bl?	...	p	...
1.569......	H I 15–4	7.9	7.2	p?[c]	...	...	2.6 (abs)
1.575......	? Fe II $z^2I_{11/2}$–$3d^54s^2$ $I_{11/2}$ 2 1.576 μm	...	2.8	2.9[c]	3.2	3.0	p
	?+N III+C III 13–9 1.575 μm	bl?	p	p	...	...	...
1.584......	? Fe II $z^6P_{5/2}$–$c^4P_{3/2}$	bl?	bl?	3.2[c]	2.1	bl	...
1.588......	H I 14–4	13.7	8.9	p?[c]	2.7	4.4	p (abs)
1.596......	? [Fe II] $a^4F_{7/2}$–$a^4D_{3/2}$ 1.598 μm	p	p	6.0	p	p	
1.604......	?	...	...	p	p	bl	p
1.611......	H I 13–4	20.7	13.4	4.3	2.3	3.8	2.4 (abs)
1.625......	?	p	p	p	...	...	...
1.641......	H I 12–4	23.5	13.5	bl	bl	bl	2.2 (abs)
	+[Fe II] $a^4F_{9/2}$–$a^4D_{7/2}$ 1.643 μm	bl?	bl	23.0	11.8	7.1	
1.664......	[Fe II] $a^4F_{5/2}$–$a^4D_{1/2}$	...	...	4.2	p	...	...
1.668......	?	4.5	...	bl?	p	p	p
1.677......	[Fe II] $a^4F_{7/2}$–$a^4D_{5/2}$	bl?	bl?	17.9	3.8	bl	p
1.681......	H I 11–4	27.9	17.2	bl?	3.2	16.5	p[c,d]
1.688......	Fe II $z^4F_{9/2}$–$c^4F_{9/2}$	6.1	18.6	16.7	7.8	bl	...
1.700......	He I $4p^3P^o$–$3s^3S$	42.5	p	bl	...	...	p (abs)
	?+[Fe II] $a^2F_{5/2}$–$c^2G_{7/2}$ 1.700	bl?	bl?	6.8	p	...	...
1.732......	? Fe II $z^4D_{7/2}$–$c^4P_{5/2}$	p?	p?	5.0	...	4.7	...
1.736......	H I 10–4	37.6	17.0	bl	2.9	bl	2.6 (abs)
	+Fe II $z^4D_{7/2}$–$c^4P_{5/2}$ 1.736	bl?	bl	bl	...	...	...
1.743......	[Fe II] $a^4F_{3/2}$–$a^4D_{1/2}$ 1.745 μm	9.4	8.1	23.7	5.2	7.3	...
	+Fe II $z^4F_{7/2}$–$c^4F_{7/2}$ 1.741 μm	bl?	bl	bl	...	...	...
1.747......	?	bl	p	5.6	...	3.5	...
1.755......	Fe II $z^4D_{7/2}$–$c^4F_{5/2}$	p	p	3.7	...	...	...
2.043......	He I $6p^3P$–$4s^3S$	3.0[c]	2.0[c]	bl	p	p	...
	+[Fe II] $a^4_{5/2}$–$a^2P_{3/2}$ 2.046 μm	bl?	bl?	5.6	...	...	...
2.058......	He I $2s^1S$–$2p^1P^o$	260	4.0	47.1	8.0	7.9	2.0
2.068......	He I $4s^1S$–$3d^1D$	...	...	p	...	p	p?
2.089......	Fe II $z^4F^o_{3/2}$–$c^4F_{3/2}$	p?	7.8	10.5	2.9	3.5	p?
2.100......	? N V 11–10	3.2	...	p	...	p?	p?
2.112......	He I $3p^3P^o$–$4s^3S$	22.6	p	5.3	...	...	p?
	+He I $3p^1P^o$–$4s^1S$ 2.113 μm	bl	bl	bl	...	...	bl?
	+N III/C III 8–7 2.116 μm	bl?	...	...	...	...	...
2.138......	Mg II $5s^2S_{1/2}$–$5p^2P^o_{3/2}$	3.1	2.5	9.0	2.6	3.3	2.2
2.144......	Mg II $5s^2S_{1/2}$–$5p^2P^o_{1/2}$	3.0	p?	5.3	2.2	2.3	p
2.150......	He I $7s^3S$–$4p^3P$	p	...	2.1	p?	...	p?
2.159......	He I $7p^1P4d^1D$	bl?	...	p	p?	p?	p
2.165......	H I 7–4	92.2	56.0	15.3	16.8	13.8	p?
	+He I $7f\,^3F^o$–d^3D 2.161 μm	bl	bl?	bl?	bl	bl	
	+He I $7f\,^1F^o$–$4d^1D$ 2.165 μm	bl	bl?	bl?	bl	bl	bl
2.178......	?	p?	p?	2.9	2.0	p	p?
2.185......	He I $7d^1D - 4p^1P$	3.3	...	...	...	...	...
2.189......	? He II 10–7	p	p?	2.5	p	p	...
2.206......	Na I $4p^2P^o_{3/2}$–$4s^2S_{1/2}$	...	...	...	4.5	4.9	4.5
	+Na I $4p^2P^\circ{}_{1/2} - 4s^2S_{1/2}$ 22.209 μm	...	...	...	bl	bl	bl
2.228......	? He I $7s^1S$–$4p^1P$	p?	...	bl	p	p?	...
	+[Fe II] $a^2G_{9/2}$–$a^2H_{11/2}$ 2.224 μm	...	...	5.8	...	...	...
2.240......	Fe II $z^4D_{3/2}$–$c^4P_{3/2}$	2.6	...	5.8	p?	...	...
2.254......	[Fe II] $a^2G_{7/2}$–$a^2H_{9/2}$	...	p?	4.7	p?	p	p

[a] Equivalent widths are in Å and refer to emission lines, except where denoted by "abs."

[b] First entries for each feature in this column are judged to be the dominant transition in each feature according to measured central wavelengths and line transition probability. Weaker transitions are measured where resolvable and are otherwise denoted as blended, "bl," and measured with the dominant transition as a conglomerate. The presence of weak lines (EW $\lesssim$ 2 Å) is simply indicated by "p."

[c] Uncertain continuum level.

[d] Probably blended with unidentified emission.

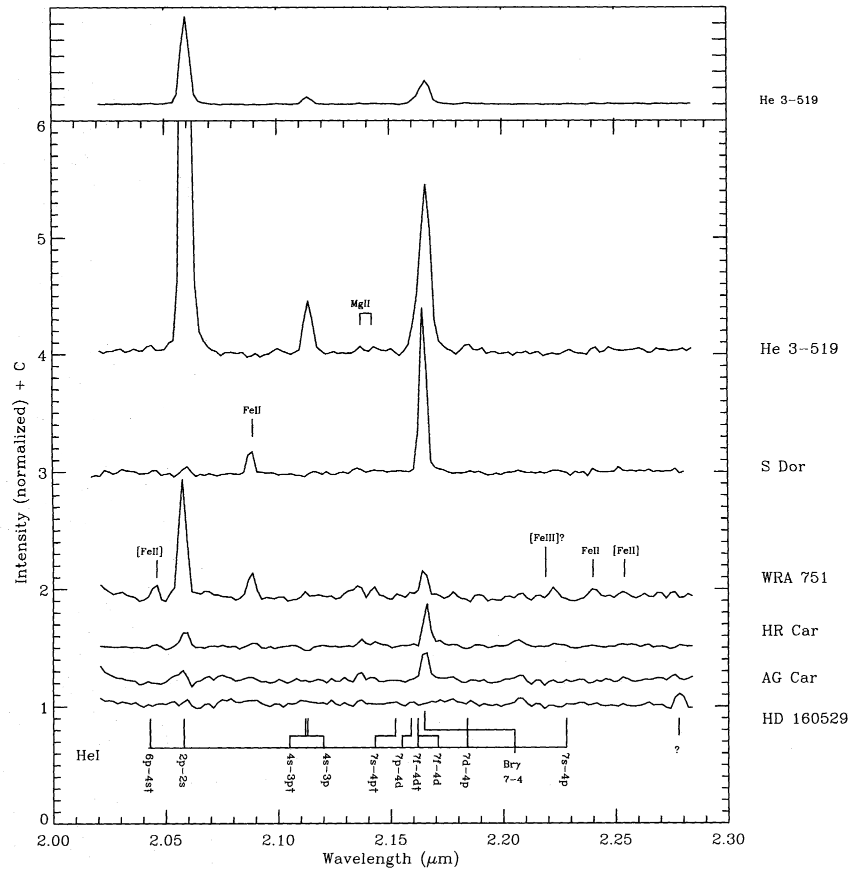

FIG. 6.—LBV stars at low resolution ($R \simeq 550$) in the H window. WRA 751 exhibits a spectrum dominated by Fe II and [Fe II] emission.

set apart by its apparent lack of He I emission. Ignoring the He I 2.058 μm line (which is highly susceptible to optical depth effects), He 3-519 has relative H I and He I line strengths quite similar to HDE 269582. He 3-519 also bears a strong resemblance to HDE 268840, which exhibits the Na I and Mg II doublets in emission. He 3-519 is, in the *infrared*, an Ofpe/WN9 star.

Davidson et al. (1993) have noted close similarities between optical spectra of He 3-519 and HDE 269582, chiefly in the prominent lines of H I and He I with P Cygni profiles as well as emission from He II 4686 Å, Si III 4551 Å, and weak N II 4601–43 Å. HDE 269582 has been confirmed as an LBV (Humphreys & Davidson 1994) because of the variation of the star between high- and low-ionization states (Shore & Sanduleak 1984; Stahl 1987); a spectrum published by Bohannan & Walborn (1989), obtained in 1986 December, shows HDE 269582 in its "fully developed" Of/WN state. It is this spectrum to which He 3-519 is compared by Davidson et al. (1993).[8] Smith et al. (1994) have argued, however, that He 3-519 is not an Ofpe/WN9 because it does not show the N III 4097, 4634–42 Å or Si IV 4089, 4116 Å features characteristic of the Of/WN stars; instead, they have suggested a classification of WN11 for He 3-519 at visual minimum, which reflects its low ionization and low hydrogen content. This spectroscopic distinction cannot be made in the H or K window, but it is probably unimportant as far as the parameters of stellar temperature, luminosity, and wind outflow velocity are concerned, as values estimated for He 3-519 by Smith et al. (1994) are very similar to those of Ofpe/WN9 stars (see Schmutz et al. 1991; Crowther et al. 1995a). The chief difference appears to be manifested in the stronger lines of He3-519 and consequently the mass-loss rate, which is about an order of magnitude higher here ($1.3 \times 10^{-4}\ M_\odot$; Smith et al. 1994) than generally observed in Ofpe/WN9 stars.

AG Car in its visual minimum is also classified by L. J. Smith et al. (1994) as WN11 rather than Ofpe/WN9 as previously done by Stahl (1986) and Walborn (1990). AG Car was observed to be at visual minimum in 1989 and was then observed to brighten and cool toward the end of 1990 (Leitherer, Neto, & Schmutz 1992; see also the discussion by Smith et al. 1994). An optical spectrum obtained in 1991 August has AG Car evolving to a B-type star with P Cygni Hα absorption. In no "normal" B-type star has Brγ been seen in emission or self-absorbed; He I 2.112–3 μm is absent or self-absorbed in B3 III and B3 V stars and is weakly absorbed in early-type B supergiants (HCR; Hanson 1996). Our high-resolution 1995 K-band spectrum of AG Car (Fig. 7) bears extremely close resemblance to the luminous ($\log L/L_\odot = 5.2$) B[e] star GG Car, ignoring the ^{13}CO disk

[8] We note in passing that no iron emission from He 3-519 is detected in our H and K spectra, and so we are not able to confirm the tentative identification of the 3008 Å emission feature by Davidson et al. (1993) as Fe III $3d^5(^4G)4p\ ^5F^o$–$3d^5(^4F)4s\ ^5F$. Smith et al. (1994) have suggested that the feature may be a conglomerate of Fe II transitions.

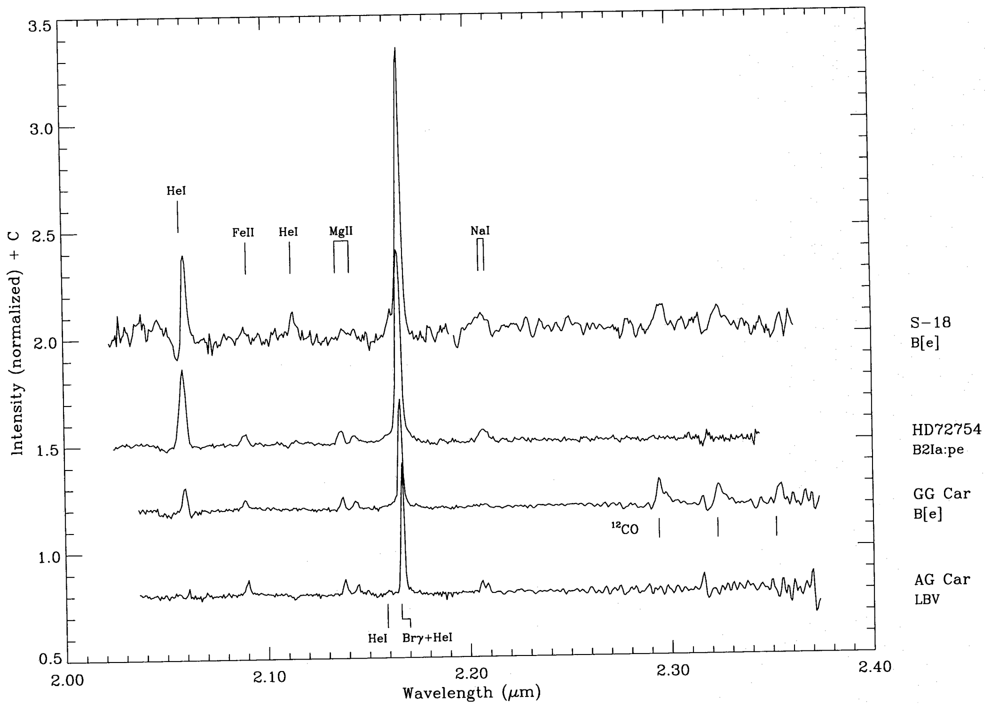

FIG. 7.—High-resolution ($\lambda/\Delta\lambda \simeq 1600$) K-band spectra of the LBV AG Car (1995 May), the B[e] object GG Car (1995 May), the B2 Iape star HD 72754 (1995 November), and the B[e] star S18 (1995 November). The He I 2.058 μm and 2.112–3 μm, and ^{12}CO emission in the S18 spectrum are new. AG Car previously (1984–1985) exhibited 2.058 μm and 2.112–3 μm emission; the "ripples" at long wavelengths are real.

emission from the latter, and to the peculiar B2 Iape star HD 72754; this similarity is discussed in more detail below. AG Car exhibited 2.058 μm emission in excess of Brγ in the 1984 spectrum published by McGregor et al. (1988b). The 2.058 μm emission is all but absent in our spectrum. Except for weak He I 2.043 μm and 2.058 μm emission, the low-resolution K-band spectrum of HR Car is similar to that of AG Car; the increased prominence of Fe II and [Fe II] in the H-band spectrum of HR Car causes some difficulty in measuring the higher Brackett lines.

HR Car is also similar to WRA 751 (=He 3-591, not to be confused with He 3-519) in the K band. Astonishing detail is more apparent in the spectrum of WRA 751, shown in Figure 8 at high resolution. Line identifications are given in Table 6. Quite clearly the He I transitions of 4–3 (2.112–3 μm) and 7–4 (2.150 μm, 2.160–2.166 μm, 2.185 μm) are in absorption in WRA 751, and the He I $2p$–$2s$ 2.058 μm singlet is in strong emission. Several strong iron transitions, already observed at different strengths in the spectrum of η Car (McGregor et al. 1988b; Hamann et al. 1994), are easily identified: [Fe II] 2.046 μm, Fe II 2.089 μm, Fe II 2.117 μm. Emission from Fe II may also be present at 2.060 μm. The Mg II 2.038–44 μm doublet is clearly visible. The strong feature at 2.134 μm is unidentified. In the H window, the low-resolution spectrum is dominated by lines of Fe II and [Fe II] (or candidates of each); [Fe II] $a^2F_{5/2}$–$c^2G_{7/2}$ 1.700 μm probably contributes to the He I line. HR Car and S Dor also display emission from allowed transitions of Fe II. Brackett emission is obvious only in He 3-519 and S Dor, probably with a large contribution from surrounding nebulosity. Weak Brackett emission may be present in the spectra of AG Car and HR Car, but not all transitions between the upper levels of $n = 25$ and $n = 10$ can be confirmed at the lower resolution and signal-to-noise ratio of these data.

3.5. *B[e] and Be Stars GG Car, S18, HD 72754, and the LBV AG Carinae. Is S18 an LBV?*

3.5.1. *GG Car*

GG Car was first classified by Carlson & Henize (1979) as Bep, showing emission from H, He I, Fe II, and [Fe II]. Only recently has weak P Cygni absorption been detected in the H-Balmer lines (Gosset et al. 1985; Lopes, Neto, & DeFreitas-Pacheco 1992), as well as emission from [O I] and Si II. The object is listed as an eclipsing binary with a period of 31.020 days (Hernandez et al. 1981; Gosset et al. 1985).

In a 1985 January 2.0–2.4 μm spectrum published by McGregor et al. (1988b), GG Car exhibited the only obvious line emission from Brγ and ^{12}CO. They measured the He I 2.058 μm equivalent width to be less than 2 Å (emission), if present at all. The equivalent width is at least twice that amount in our 1995 May spectrum (Fig. 8). The depression centered at 2.049 μm is P Cygni absorption, taking into account our confidence in the telluric correction and its presence in a spectrum obtained in 1995 November with the same instrument and at the same resolution. Brγ emission appears to have remained unchanged (EW = 14–16 Å), but no emission from Fe II 2.089 μm, the Mg II doublet at 2.138–44 μm, or Na I 2.206–9 μm were detected in the 1985 spectrum. This spectrum then has much the same appearance of the SMC B[e] stars R4, R50, and S18 as observed in 1987–1989 (McGregor et al. 1989). The authors also tabulated (but did not discuss) line strength measurements of a perplexing 1984 April spectrum in which

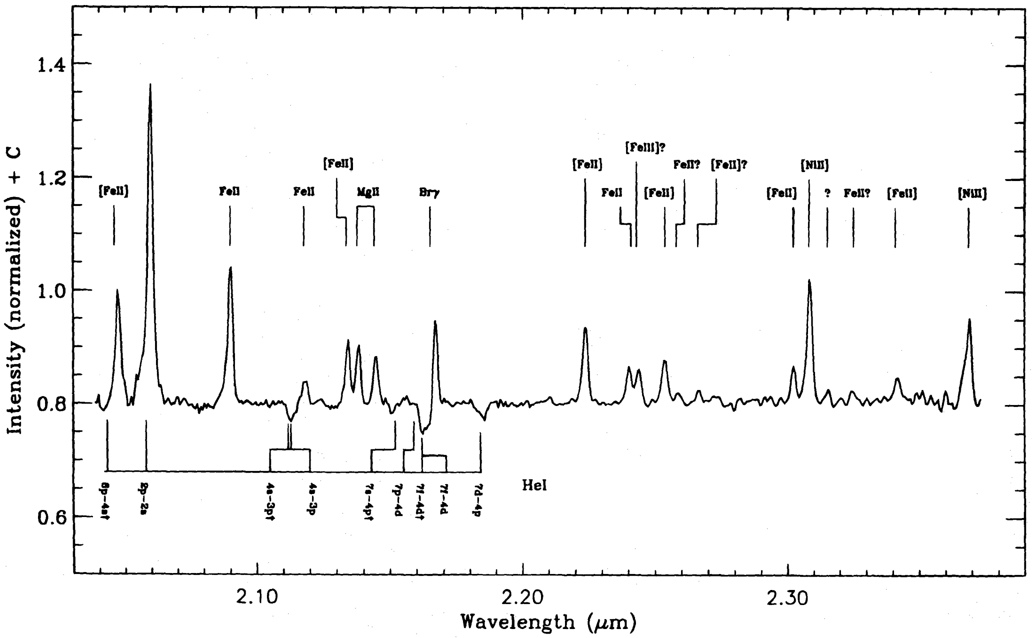

FIG. 8.—High-resolution ($\lambda/\Delta\lambda \simeq 1600$) *K*-band spectrum of the LBV WRA 751

the Na I 2.206–9 μm and a very high excitation He I line at 2.307 μm are the dominant emission features, much stronger than Brγ, and ^{12}CO emission was substantially enhanced. He I 2.112–3 μm was not present in either 1984 or 1985 spectra (this has not changed), and no difference in the He I 2.058 μm line was noted.

3.5.2. *S18*

Spectral variations in B[e] stars are not particularly unusual. The visual spectrum of the SMC B[e] star S18 has been observed by Shore, Sanduleak, & Allen (1987) to vary in the C IV and N IV resonance lines and in the characteristic Of emission line He II 4686 Å. Zickgraf et al. (1989) reported the actual disappearance of the He II line in a 1987 spectrum. A *K*-band spectrum of S18, obtained in 1995 November at high air mass (> 2), is shown in Figure 8.

This spectrum has changed dramatically from the spectrum published by McGregor et al. (1989). In addition to a sharp increase in the strength of the He I 2.058 μm line (essentially unmeasurable in the McGregor et al. spectrum), we have for the first time seen an *enhancement in the* He I *μm* 2.112–3 line in an object other than AG Car; no emission was previously present in S18. There are only two other B stars we know of in any luminosity class to exhibit 2.112–3 μm emission: the LMC B[e] star HD 38489, which is weak in He I 2.058 μm emission (see McGregor et al. 1988a), and the quiescent LBV P Cyg (see HCR), which is visually classifiable as B1 Ia^+. He I 2.112–3 μm emission, present in the spectra of some late-type O supergiant stars and common in Of/WN star spectra, was observed in AG Car in the period 1984 March–1985 January (McGregor et al. 1988b), when He I 2.058 μm was approximately twice its present strength. *Remember that AG Car has been classified as Ofpe/WN9* (*or WN11*) *at visual minimum.* The absorption of He I 2.112–3 μm now seen in AG Car and HD 72754 (discussed below) is normal for early B stars, irrespective of luminosity class (see Hanson et al. 1996; Hanson & Conti 1994).

We also see ^{12}CO band head emission in S18, not previously detected by McGregor et al. (1989). This is important since they expected to see CO features on the basis of TiO emission at 6159 Å (Zickgraf et al. 1989). If the TiO emission is produced by collisional excitation, then it should trace even higher densities than the CO-emitting region. We can now confirm the presence of CO emission in S18, which brings the total of Magellanic Cloud supergiants with this structure to eight. Our detection does not actually confirm what might be expected from collisional excitation of TiO and CO molecules in a disk, as new conditions in the CO-emitting gas may be related to the changes we see in the helium emission-line region(s). Additional monitoring of S18 is needed to characterize fully recent changes in energy output.

The source of the current instabilities in S18 might be related to the possible presence of a companion, noted above. Shore et al. (1987) proposed a model for S18 in which material from the wind of the supergiant is accreted onto a companion, which may be an ordinary main-sequence star. High-temperature radiation from an optically thin shock in the excretion flow could explain the variability seen in the He II, C IV, and N IV emission lines. Zickgraf et al. (1989) support this model, postulating further that the companion is moving in and out of the cool, dense excretion disk of S18 in order to explain the disappearance of He II 4686 Å emission from their 1987 spectrum. But since the nature of the He II emission region is not known, variable outflow in the equatorial region might account for the changes in He II emission, if the line is emitted from an inner portion of the disk or from a single region in the disk.

The resolution of our IRS spectra is not high enough at 180 km s^{-1} to determine if the new He I emission arises from a disk, where velocities measured from narrow allowed and forbidden lines in S18 are typically 30–60 km s^{-1}, compared to 750 km s^{-1} from optical Balmer and He I P Cygni absorption (Zickgraf et al. 1989). We measure the

TABLE 6

WRA 751 Line Identifications and EW: 2.0–2.4 μm

λ	Transition[b]	EW
2.046......	[Fe II] $a^4_{5/2}$–$a^2P_{3/2}$	5.8
	+He I $6p^3P$–$4s^3S$ 2.043	bl (abs?)
	+? [Fe II] $b^2P_{1/2}$–$b^2F_{5/2}$ 2.0496 μm	bl
	+? [Ni II] $4F_{5/2}$–$2F_{5/2}$ 2.0492 μm	bl
2.054......	Fe II $c^4F_{3/2}$–$z^4D^o_{1/2}$	1.2
2.058......	He I $2s^1S$–$2p^1P^o$	16.8
	+Fe II $c^4F_{5/2}$–$z^4F^o_{3/2}$ 2.061 μm	bl?
2.089......	Fe II $z^4F_{3/2}$–$c^4F_{3/2}$	6.3
	+? [Fe II] $a^4D_{3/2}$–$a^4P_{5/2}$ 2.086 μm	bl
2.112......	He I $4s^3S$–$3p^3P^o$	0.7 (abs)
	+He I $3p^1P^o$–$4s^1S$ 2.113 μm	bl (abs)
2.118......	Fe II $c^4P^o_{3/2}$–$z^4D^o_{5/2}$	1.2
2.124......	? Fe II $e^4G_{9/2}$–$e^4G^o_{7/2}$ 2.1245 μm	0.4
2.134......	[Fe II] $a^2P_{3/2}$–$a^4P_{3/2}$	2.1
2.138......	Mg II $5s^2S_{1/2}$–$5p^2P^o_{1/2}$	2.2
2.144......	Mg II $5s^2S_{1/2}$–$5p^2P^o_{1/2}$	1.9
	+[Fe III] $3d^6{:}^3G_3$–H_4 2.146 μm	bl
2.150......	He I $4p^3P$–$7s^3S$	0.2
2.156......	? Ni II $4D^o_{7/2}$–$4F_{5/2}$ 2.1564 μm	0.3
2.162......	He I $4d^1D$–$7f^1F$	1.8 (abs)
	+He I $4d^3D$–$7f^3F$ 2.161	bl[c] (abs)
2.166......	H I 7–4	2.9[c]
	+He I $4f^1F$–$7d^1D$ 2.165	bl[c] (abs)
	+He I $4f^3F$–$7d^3D$ 2.166	bl[c] (abs)
2.185......	He I $4p^1P$–$7d^1D$	0.8 (abs)
2.210......	[Fe II] $b^4P_{1/2}$–$b^2P_{1/2}$ 2.2104 μm	0.2:
2.224......	[Fe II] $a^2H_{11/2}$–$a^2G_{9/2}$	3.5
2.240......	[Fe II] $z^4D_{3/2}$–$c^4P_{3/2}$	1.7
2.244......	[Fe II] $a^4P_{1/2}$–$a^2P_{3/2}$	1.5
	?+[Fe II] $a^4H_{7/2}$–$b^2H_{11/2}$ 2.243 μm	bl?
	?+[Fe III] $3d^6{:}^3G_4$–H_4 2.243 μm	bl?
	?+[Fe II] $b^2P_{1/2}$–$b^4D_{5/2}$ 2.2445 μm	bl?
2.254......	[Fe II] $a^2G_{7/2}$–$a^2H_{9/2}$	2.3
2.258......	? Fe II $e^4G_{7/2}$–$G^o_{7/2}$ 2.2580 μm	0.5
2.267......	? [Fe II] $b^2H_{9/2}$–$b^2G_{7/2}$ 2.2661 μm	0.5
2.302......	[Fe II] $a^4G_{7/2}$–$a^4H_{5/2}$	1.5
2.308......	[Ni II] $4F_{3/2}$–$2F_{5/2}$	5.8
	?+[Fe II] $a^4G_{5/2}$–$b^2G_{9/2}$ 2.30718 μm	bl
2.315......	?	0.6
2.325......	? Fe II $z^4D^o_{1/2}$–$c^4P_{3/2}$ 2.3247 μm	0.7
2.341......	[Fe II] $a^4H_{7/2}$–$a^4G_{7/2}$	1.2
2.369......	[Ni II] $4F_{7/2}$–$2F_{7/2}$	4.6
	+[Fe II] $a^4H_{9/2}$–$a^4G_{9/2}$ 2.3670 μm	bl

[a] Equivalent widths are in Å and refer to emission lines, except where denoted by "abs."

[b] First entries for each feature in this column are judged to be the dominant transition in each feature according to measured central wavelengths and line transition probability. Weaker transitions are measured where resolvable and are otherwise denoted as blended, "bl," and measured with the dominant transition as a conglomerate. The presence of weak lines (EW $\lesssim$ 2 Å) is simply indicated by "p."

[c] Strongest absorption is centered at 2.162 μm, comprising the He I 4D–7F singlet+triplet blend. The 2.165 μm component comprises the 4F–7D singlet+triplet and is partially blended with Brγ emission. The entire He I conglomerate is measured as a single absorption feature.

velocities of Brγ and the He I 2.112–3 μm lines to be in the range of 190–210 km s^{-1}. The blue edge to the absorption component of He I 2.058 μm is placed at about 700 km s^{-1} from laboratory line center. It seems evident, then, that the new He I 2.112–3 μm emission does *not* arise from the wind but more likely from the disk as a result of a recent density enhancement that also gives rise to the CO overtone emission.

3.5.3. *HD 72754*

Shown also in Figure 8 is a spectrum of the peculiar Be star HD 72754, a binary system whose optically visible component is B2 Iape (Thackeray, Tritton, & Walker 1973), or BN2pe var according to Walborn (1976), taking into account variability ($\Delta V \simeq 0.2$ mag) and overabundance of nitrogen in the optical spectrum (Thackeray 1971). The binary nature of HD 72754 is of the complex β Lyrae type, where a higher mass but lower luminosity companion (probably B2 Ib) fills the Roche lobe. A circumstellar shell component corresponds to the strong He I 3964 Å ($2s^1S$–$2d^1D^o$) shell line reported by Thackeray (1971) and probably contributes to the largest part of the strong He I 2.058 μm emission ($2s^1S$–$2p^1P^o$), as the lines share the same lower level. By accounting for a number of observed properties of β Lyrae itself, it has been proposed that an opaque accretion disk created by mass transfer may conceal the more massive component (see Huang 1963). Clearly, a cool disk of sufficient density to excite CO ($N_H > 10^{10}$ cm^{-3}) is *not* present around HD 72754. This could support either a low-mass accretion disk model proposed by Hubeny, Harmanec, & Shore (1994) for β Lyrae or that stellar radiation completely dissociates CO throughout the accretion flow without sufficient shielding, or a combination of both.

3.5.4. *AG Car et al.*

In the previous section we noted the apparent changes in the 2 μm spectrum of AG Car between 1984 and 1985 in its Of/WN state of ionization and late 1995 in a B2 Ie–like state. What is particularly remarkable about Figure 8 is the close correspondence between the Be or B[e] stars and AG Car in spectral appearance. Hillier (1992) has remarked on the similar characteristics of η Car and B[e] stars in the visual region.

The ripples at $\lambda > 2.25$ μm in AG Car are not instrumental but are probably due to the surrounding dust shell. This behavior is reproduced in an unpublished 1995 November spectrum at $R \sim 1600$ with IRS on the CTIO 4 m telescope. This would not appear as CO overtone emission if densities in the expanding shell (~50 km s^{-1}) have declined to $N_H < 10^{10}$ cm^{-3}.

The differences between GG Car, AG Car, and HD 72754 in CO overtone and Na I 2.206–9 μm emission are significant: McGregor et al. (1988b) remarked that since the excitation energies of CO and Na I are low (11.1 eV and 5.1 eV, respectively) and thus require shielding from the stellar radiation field, the Na I– and CO-emitting regions could be related. Appropriate conditions could be found in a cool circumstellar shell or disk. Referring now to Figure 8, the spectra of HD 72754, GG Car, and AG Car show that ^{12}CO and Na I emission are not found together, and from this we would conclude that the level of shielding from the stellar radiation field is not the same. Evidently, the Na I in AG Car and HD 72754 arises from a region that is not related to a dense circumstellar disk, if this is where density and shielding conditions are most plausible for CO emission. On the other hand, the Na I emission could originate from shells that exist around AG Car and HD 72754, as long as the excitation temperatures are much lower than the stellar effective temperatures. Otherwise, the LTE result that McGregor et al. (1988b) demonstrated is that the line fluxes are vastly overpredicted, assuming that Na I lines are pumped by the Balmer continuum in a spherically symmetric wind with a linear velocity structure.

To summarize this section, we conclude that while the similar morphology shown above might be somewhat superficial from the point of view that each object has its *definite* differences in energy output and structural properties, direct evidence for LBV phenomena can be recognized in the 2.0–2.4 μm region. This statement rests on the following:

1. The appearance of AG Car, which previously exhibited an Of/WN spectrum and is now indistinguishable from HD 72754 and similar to GG Car, apart from the susceptible He I 2.058 μm line.

2. The spectral evolution of the SMC B[e] star S18, which now has strong He I emission at 2.058 μm and new He I emission at 2.112–3 μm. These lines have varied in AG Car, during excursions in ionization between Of/WN and early B, where 2.058 μm is now absent and 2.112–3 μm has gone from emission to weak absorption. Only two other B stars are presently known to have the 2.112–3 μm line in emission, namely, the LMC B[e] star HD 38439, and the LBV P Cygni (B1 Ia^{+}). The atomic spectral morphology of S18 follows that of P Cyg (see Hanson et al. 1996) and the LBV-Ofpe/WN9 object HDE 269582 (Fig. 2).

3.6. *The SMC Eclipsing WN Binary HD 5980*

An LBV-like outburst in late 1994 by the SMC object HD 5980, an eclipsing binary with a 19.266 day orbital period (Breysacher & Perrier 1980), has been reported by Barbá et al. (1995). According to Niemela (1988), HD 5980 is a WN + WN binary, with an O7 I star in the line of sight contributing to the total light. At present, the binary nature of HD 5980 and the role of the O star is unsettled (see, e.g., Koenigsberger et al. 1995). The object brightened in the visual region by 1 mag over a period of several months, preceded by a number of remarkable UV and optical spectral variations that have been recorded since 1978 (Niemela 1988; Koenigsberger et al. 1994; Barbá & Niemela 1994).

In the period from 1978 to 1993, HD 5980 underwent remarkable variations in WN spectral subtype: Koenigsberger et al. (1994) showed with *IUE* UV and optical data a transition from WN4 to WN6; Barbá & Niemela (1994) then showed how the optical spectrum had "evolved" to WN8 by 1993 November, then back to WN6 only 2 months later. Barbá et al. (1995) next reported a sudden LBV-like outburst by HD 5980 in 1994 November, brightening at *V* by 1 mag over a period of several months or by some 2.3 mag over several years. In this same period, the W-R–type line emission measurably weakened, whereas strong P Cygni emission due to He I and He II and weaker emission due to N II, Si II–III, and Fe III (indicative of circumstellar ejecta) have emerged.

Koenigsberger et al. (1995) have followed the optical observations of Barbá et al. (1995) with new *IUE* UV spectrophotometry, providing evidence with line profile measurements of non–spherically symmetric structures in the outflow. They have further concluded from measurements of profile variations, changing degree of ionization, and the properties of the atmospheric eclipses that it is the *primary* (WN4) star that has undergone the eruption. Since hydrogen is present in the wind of HD 5980 (Breysacher & Perrier 1991), the scenario of Langer et al. (1994) for the LBV phase following hydrogen-rich WN stars is supported, *provided* the hydrogen is in the envelope of the primary star as determined by Breysacher & Perrier (1991).

In Figure 9*a* we present new high-resolution (∼1600) *K*-band spectra of HD 5980 and (for comparison) the LBV He 3-519, obtained on the evening of 1995 May 11 at the CTIO 1.5 m telescope. See also HD 269445, WR 122, and WR 85a in Figure 2 for additional comparison. Curious asymmetries are present in the 2.058 μm and 2.166 μm fea-

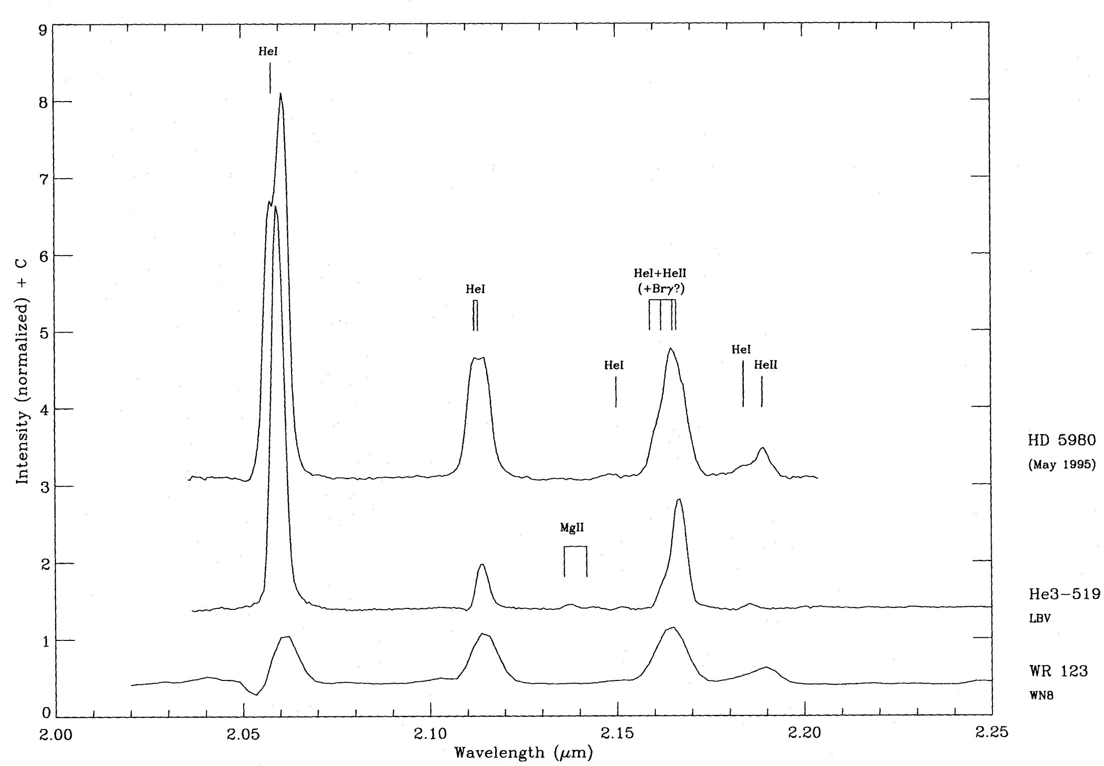

FIG. 9.— Spectra at 2 μm of the SMC WN binary star HD 5980, the Galactic LBV He 3-519 ($R \simeq 1600$), and the Galactic WN8 star WR 123 ($R \simeq 600$)

TABLE 7

COMPARISON OF Of AND WNL STAR PARAMETERS

Star	Type	T_{eff} (10^3 K)	log L ($L_\odot$)	R ($R_\odot$)	log $\dot{M}$ ($M_\odot$ yr^{-1})	v_∞ (km s^{-1})	H/He (by number)	References
HD 151804......	O8Iaf	27	5.8	34	−4.9	1445	4.0	1
HD 152408......	O8:Iafpe	28	5.8	29	−4.6	955	1.5	1
HD 16691.......	O4.5 If$^+$	42	5.8	14	−5.1	3450	...	2
HD 190429......	O4.5 If$^+$	42	6.1	20	−5.2	2300	5.7	3
WR 22[a]..........	WN7+abs	31	5.8	27	−4.3	1785	3.2	4
WR 158.........	WN7	29	5.8	27	−4.4	900	1.4	5
WR 156.........	WN8	27	5.5	25	−4.4	660	1.5	4
WR 108.........	WN9+abs	29	5.9	32	−4.4	1170	1.5	6

[a] WR 22 is a single-lined spectroscopic binary (van der Hucht et al. 1988) with a massive ($\gtrsim 72\ M_\odot$) WN7 primary, orbited by a mid- to late-type O star with $M_{WR}/M_O = 2.78$ (Rauw et al. 1996).

REFERENCES.—(1) P. Crowther, private communication; (2) Leitherer 1988; (3) Lamers & Leitherer 1993; (4) Crowther et al. 1995b; (5) Hamann et al. 1995; (6) Crowther et al. 1995a.

tures of HD 5980. These asymmetries as well as the flat-topped shape of the 2.11 μm feature are real and provide further evidence of nonspherical structure around the emitting source.

We believe the primary contribution near 2.11 μm to be from He I 2.112–3 μm since we are at high enough resolution (~1600) to separate easily the 2.112–3 μm component from N III emission at 2.116 μm (see, for example, the O8 If spectra in Fig. 1 and other examples in HCR where at similar resolution each contribution is resolved).

Barbá et al. (1995) have pointed out the morphological similarity of the LBV-like optical spectrum of HD 5980 to that of He 3-519 shown by Davidson et al. (1993). This similarity clearly holds up at 2 μm as well. Both HD 5980 and He 3-519 have very strong lines, with similar 2.058 μm emission (see again Fig. 9*a*), indicating outflows of high density. The 2.166 μm feature is probably dominated by He I 7–4 transitions in both objects. Recalling that circumstellar matter is evident from optical and UV spectra and the He I line profile asymmetries seen here, metal lines such as Fe II, [Fe II], and Mg II are not present. The lower metallicity environment of the SMC probably does not play a role in this, given the presence of these lines in the SMC B[e] star S18 (Fig. 8). The issue for the formation of the circumstellar features at 2 μm is more likely to be one of the dynamical timescale required, which is at least 1 yr after outburst.

An important difference between HD 5980 and either He 3-519 or HDE 269445 occurs in He II 2.189 μm emission. This emission and the near-equal strengths of the 2.112–3 μm and 2.166 μm features are like those of WR 123, which is hydrogen poor (Crowther et al. 1995b). One may also compare the 2 μm spectrum of the WN8 star WR 147 published by Churchwell et al. (1992) to find like similarity, as this star has the same *K*-band appearance as WR 123 and is also H-deficient (Hamann et al. 1995). Since WN8 stars exhibit much stronger 2.165 μm emission (relative to 2.058 μm, 2.112–3 μm, and 2.189 μm emission) when they are hydrogen rich, the outbursting component of HD 5980 would, *at first glance*, appear to be in an evolved state of hydrogen *deficiency*. The atmosphere of He 3-519 is also very hydrogen poor, as determined from detailed modeling by Smith et al. (1994), so that the 2.166 μm feature is mostly due to He I emission with a nebular contribution that likely accounts for the Brackett emission in Figure 6. The *K*-band spectrum of HD 5980 thus appears (at least superficially) as something intermediate to hydrogen-poor WN8 and hydrogen-poor LBV. An *H*-band spectrum would help to resolve the hydrogen abundance question.

4. DISCUSSION

The Of stars plotted in Figure 1 are recognized to have extreme wind properties, closely related to those of the least extreme W-R stars. The fact that their *K*-band spectra are not easily distinguished bears heavily on observations of highly reddened regions in which similar emission-line sources may be found. We now discuss the issues of evolutionary status and classification in the context of the previous comparisons.

4.1. *Evolution*

The strengths of the dominant features in Figure 1 scale in a gradual way between Of and WNL types. Table 7 indicates how the stellar parameters, as taken from the literature, proceed between the Of and WNL stars. A comparison between HD 152408 and WR 108 has been already made by Crowther et al. (1995a), who concluded from the physical and optical spectroscopic similarities of the two stars that WR 108 is an extreme example of Of star with slightly higher wind density and, thus, mass-loss rate. Because the chemistry (H/He and C/N abundance ratios) of WR 108 is also very similar to that of HD 152408, it is sensible to conclude that this WN9 star has evolved directly from the Of stage without having passed through an LBV (or RSG) phase.

WN8 stars, on the other hand, are considered to be likely descendants of LBV or RSG stars (where the extent of redward motion across the H-R diagram depends on initial mass) because of their LBV-like properties: spectral and photometric variability and the increased frequency of ejected material, for example. The WN8 stars have further been demonstrated to have winds that are transitional between WNL and WNE stars in terms of outward extension of the continuum-forming layers (Morris & Lamers 1996), where the WNE star winds are the most extended (tens of stellar radii between the point at which the continuum is optically thick and the point at which it starts to become thin, at around $\tau_{Ross} \sim \frac{2}{3}$). By using the evolutionary tracks of Schaller et al. (1992) at $Z = 0.020$, Crowther et al. (1995c) have predicted current masses in the range of 8–25 $M_\odot$ for the WN8 stars, with roughly half of their initial mass having been ejected. These properties are all consistent with a phase of wind instabilities prior to becoming an early-type WN star.

However, no telltale nebulosity is detected around the WN8 star WR 156 (Miller & Chu 1993), but such nebulosity (if ever present) may have been dissipated by the strong stellar wind. If WR 156 has, in fact, passed through a phase of shell ejection (LBV or RSG), then this fact is not immediately apparent from its *K*-band spectrum, which is nearly identical to that of HD 152408—even more so than WR 108 with regard to the He I 2.058 μm P Cygni profile. We might have guessed that a WN8 star with a *K*-band spectrum like that of WR 156 is directly linked in its evolution to O8 If stars, in which case predictions of $M_{\rm WR\,156} \simeq 35\ M_\odot$ would be taken as an upper limit from comparison of *M* and *L* for O supergiants (Howarth & Prinja 1989) and $M_{\rm WR\,156} = 13\ M_\odot$ (using the tracks of Schaller et al. 1992) would be a lower W-R limit set by a post–shell ejection phase. The current masses of HD 152408, HD 151804, and HD 190429 are estimated from the evolutionary tracks of de Loore, de Grève, & Lamers (1977) and de Loore, de Grève, & Vanbeveren 1978a, 1978b) by Howarth & Prinja (1989) to be 63, 79, and 77 $M_\odot$, respectively.

The primary component of HD 5980, by comparison, "evolved" from an early-type WN star to a late-type WN star (WN4 → WN6 ↔ WN8; see Koenigsberger et al. 1995) in the 15 yr prior to the 1994 November eruption. The morphology of the 2 μm spectrum obtained in 1995 May *appears* hydrogen deficient (by comparison to the hydrogen-poor objects He 3-519, WR 123, and WR 147). The inference of hydrogen deficiency is consistent with the observed fact that WNE-type stars are largely hydrogen poor (Maeder & Conti 1994). HD 5980 is obviously a unique system, however, and may not have reached its WN4 ionization state through what would otherwise be considered "normal" avenues of evolution from H-abundant (primarily in the WN 6–11 types) to H-deficient (mostly in the WN2–5 types) via mass loss. The component responsible for the substantial amount of hydrogen detected in the wind of HD 5980 by Breysacher & Perrier (1991) is all the more uncertain. If it does not belong to the primary (as our *K*-band spectrum would seemingly suggest), then the evolutionary scenario of H-rich WN → LBV → H-poor WN (see Langer et al. 1994) is not applicable to HD 5980. This assumes, of course, that the short timescales of the activity do not exclude HD 5980 from evolutionary consideration. The possible effects of mass transfer and unstable modes of oscillation in the primary (caused by high orbital eccentricity) hamper a straightforward comparison between observation and current theory.

We turn now to the WN7 stars, which are distinguished from WN8 stars (as far as classification is concerned) by weaker He I emission (Smith 1968). This distinction appears in Figure 1 (see also Hillier et al. 1983). The fact that no WN7 or WN7 + abs stars are observed to be surrounded by nebulae led Crowther et al. (1995c) to the conclusion that evolution may proceed directly from the Of stage to WN7 (or more precisely, Of → WN7 + abs → WN7). The close similarity between either of the extreme Of stars and the example of least extreme WN star in Figure 1*b* (where "extremeness" has previously referred to visual and ultraviolet spectra; see Willis & Stickland 1980; Conti et al. 1995) is not inconsistent with this scenario. The higher current masses ($\gtrsim 20\ M_\odot$) and surface H/He abundances ($\gtrsim 1$) of the WN7 + abs and WN7 stars as well as WR 108 also support the direct evolution without any LBV or RSG excursion.

In contrast to Figure 1, where a degree of "degeneracy" is demonstrated among *K*-band spectra of stars of *different* spectral subtype (i.e., optical ionization state and wind density), the Ofpe/WN9 stars of Figure 2 all display rather dissimilar appearances (relative line strengths), tracing different physical conditions. We must bear in mind that classification from *K*-band spectra may be confused by the increased visibility of nebular or circumstellar contributions compared to optical spectra, altering the relative strengths of all features but He II 2.189 μm used in *K*-band classification studies of OB-type stars (see HCR; Hanson 1996).

The "Ofpe/WN9" classification itself has proved tenuous from the point of view that the visual ionization of this subclass hints at intermediacy between Of and extreme WNL wind temperatures and densities but is naturally not calibrated to any specific values. Nearly all Ofpe/WN9 stars subjected to more detailed observational scrutiny have been reconsidered as examples of the most extreme late-type WN (WN9–11), primarily on the basis of slightly higher wind densities than counterpart Of-type stars of *similar* optical ionization (see, e.g., Crowther et al. 1995a). These subtle differences in classification are not immediately noticeable in the *H* and *K* band spectra but may surface in careful analyses of these lines to predict the stellar and wind parameters. Nor does reclassification lead to any particular improvement in spectral continuity: Crowther et al. (1995a) reclassify HDE 269227c from Ofpe/WN9 to WN9, but the McGregor et al. (1989) spectrum shows only Brγ emission, not characteristic of WR 108 (WN9), WR 105 (WN9, previously WN8; Smith et al. 1995), or Of/WN stars without He I 2.112–3 μm or 2.058 μm emission. In this regard, HDE 269227c is unique in the *K* band. Only the weakness of its Brγ emission distinguishes it from the SMC B[e] star R50, which is some 15 times stronger.

4.2. *Classification of Luminous Emission-Line Objects at 2 Microns*

Compared to OB-type stars that fall into luminosity classes V–II, the 2 μm spectra of supergiants from the Be, B[e], Of, Of/WN, and WNL categories are considerably less unique. We have demonstrated among *well-known* objects that at least one star from each of these categories can be found to match closely the spectroscopic properties of another. Criteria using the main features of Brγ, He I 2.112–3 μm, N III 2.116 μm, and He II 2.189 μm to distinguish normal OB-type stars by their optical classifications (see HCR) will not be reliable here—a problem that arises, in part, by the already well-known deficiencies of two-dimensional classification of stars with strong or unusual outflows. This is a sobering situation in which observations of luminous emission-line sources in highly reddened regions are concerned. However, with suitable observations and accessible methods of spectral analysis appropriate for stars with hot winds, the most important physical properties may be determined. This is the subject of a subsequent paper.

A *general* summary of spectral behavioral by the present transition stars in the 2 μm region can still be useful as a guide to observations of luminous sources not observable at optical wavelengths. This behavior is shown in Table 8, where we include generalized properties for normal OB-type stars based on the studies of HCR. The reader is referred to this study for more details on the 2 μm appearance of normal OB stars.

TABLE 8

SPECTRAL PROPERTIES OF OB, Be–B[e], Of, Of/WN, AND WN8–9 STARS AT 2 μm[a]

Spectral Class	Brγ 2.166	He I 2.112–3	N III 2.116	He I 2.185	He II 2.189	Fe II 2.089	Mg II 2.138–42	Na I 2.206–9	CO Overtone
B0–9 V	Ab	ab	n	n	n	n	n	n	n
B0–3 III	Ab	ab	n	n	n	n	n	n	n
B0–9 I	Ab	ab	n, ab	n	n	n	n	n	n
B[e], Be	Em–EM	ab (Em)	n	n	n	n, em	n, em	n, em	n, em–Em[b]
O3–5 V	Ab	em	em	n	ab	n	n	n	n
O6–9.5 V	Ab	ab	em	n	ab	n	n	n	n
O4–8 III	Ab	n	em	n	ab	n	n	n	n
O8.5–9.5 III	Ab	ab	n	n	n	n	n	n	n
O3–7 I	Ab	n	em	n	ab	n	n	n	n
O7.5–O8.5 I	Ab	ab	em	n	ab	n	n	n	n
O8.5–9.5 I	Ab (em)	ab	n	n	n, ab	n	n	n	n
Of I	em–Em	em	em	n	ab (em)	n	n	n	n
Of/WN[c]	Em–EM	em	em	n, em	n, em	n, em	n, em	n, em	n
WN8–9	Em–EM	em	em	n, em	em	n	n	n	n

[a] Entries correspond to absorption or emission equivalent width in Å: ab < 1.5, Ab 1.5–10, em < 1.0, Em 1.0–10, EM > 10, n = not present (or filled in). Exceptional cases are noted in parentheses. Entries for the OB stars in rows (1)–(3) and (5)–(11) are based on Hanson & Conti 1994 and Hanson 1996.

[b] Presence and absence of CO emission occurs in both Be and B[e] stars.

[c] Here, we do not distinguish between the Ofpe/WN9 and WN10–11 classifications of, e.g., Smith et al. 1994; see text.

Note that the He I 2.058 μm line is excluded from Table 8. To reemphasize, the line is not reliable as a guide to classification since it (1) may be uncertain because of difficult correction for telluric CO_2 absorption, (2) may be variable owing to its susceptibility to optical depth effects, (3) does not uniquely distinguish between OB or W-R subtypes, and (4) is not a reliable indicator of luminosity class. To clarify this last point, 2.058 μm *emission* may be identified with luminosity class I, but in reverse there are a number of known exceptions.

4.3. *The Be/B[e]-LBV Connection*

Concerning an evolutionary connection between the Be or B[e] stars to the LBV (and thus Ofpe/WN9 and extreme WNL) phase, we have demonstrated a very close correspondence in 2 μm morphology of new spectra of the B[e] stars GG Car and S18, the B2 Iape star HD 72754, and the well-known LBVs AG Car and P Cyg, which are in turn similar to published spectra of η Car. Were no information other than a *K*-band spectrum available for Be/B[e] stars, the temptation would be particularly strong to classify these objects as LBVs, as has been increasingly done in recent literature with other luminous Be-type objects. (To take this tendency to its extremum, we could consider *nearly every star in this study as an LBV candidate*, justifying this with overlapping spectral morphology.)

However, we prefer to take a less superficial approach and consider candidacy based on the required criterion of observed variability. While none of the *known* LBVs were initially identified by large photometric or spectroscopic variations outside of visual or ultraviolet wavelengths, the 2 μm spectra of AG Car obtained in 1984–1985 and 1994–1995 offer observational proof that LBV phenomena (i.e., the visual spectroscopic variations between Of/WN and early-type B ionization states) are recognizable at 2 μm.

We then turn to the case of the SMC B[e] star S18, which in the period of 1987–1989 to late 1995 has undergone a dramatic change in its He I lines at 2.112–3 μm and 2.058 μm and has seen the appearance of ^{12}CO overtone emission as well as emission from Fe II, Mg II, and Na I. The atomic line spectrum of S18 is now like that of LBVs P Cyg and HDE 269582, each object thus sharing the 2 μm signature of Of/WN stars. AG Car and S18 are the only two objects we know of to have varied in the He I 2.112–3 μm line, though an ever-increasing number of observations at these wavelengths could reveal variability in other luminous sources. Only one other B star of any luminosity class, the LMC B[e] object HD 38489, is known to have 2.112–3 μm emission. In any case, *spectroscopic variability at this level, and the close morphological relationship to P Cyg and AG Car, justify S18 as an LBV candidate.*

S18 presents the strongest case for a direct B[e]-LBV connection, bearing in mind that its instabilities might not be arising from a single star. Future investigations of its possible binarity may help distinguish LBV-like (or HD 5980–like) activity from the LBV phenomenon itself. This separation may not be of much use, unfortunately, for candidate objects discovered in highly reddened regions like the Galactic center, where candidacy is often based on a *single* spectrum due to observational limitation.

One Galactic center object that is identical to HD 72754 at 2 μm, outside of weaker He I 2.058 μm emission, was recently discovered in the cluster AFGL 2004 and is referred to as a "serendipitous" source by Moneti, Glass, & Moorwood (1994). Cotera et al. (1996) studied a number of emission-line objects in AFGL 2004 and suggested a classification of B[e] for the serendipitous source by comparison to He 3-1191. Figer, McLean, & Morris (1995), who reported the discovery of two new W-R stars in the cluster, pointed out that He 3-1191 has been reclassified as a pre–planetary nebula (Le Bertre et al. 1989) and proposed that the AFGL 2004 source is instead an LBV on the basis of spectral appearance and high luminosity ($L \simeq 10^{6.3} L_{\odot}$).

Under strict adherence to the only criterion that defines an LBV, we would favor a Be or B[e] classification of the serendipitous source. A range of luminosities can be found among Galactic B-type stars, where (log $L/L_{\odot}$) = 4.62–6.26 among the more peculiar types, which include B[e] (see, e.g., Lopes et al. 1992). The LMC B[e] star R126 is at the Humphreys-Davidson limit, surpassed in luminosity by only two LBVs, R127 and η Car. With monitoring, the AFGL 2004 source may yet prove to be an LBV that is in an ionization state like that of HD 72754 or AG Car, but the only certainty for this and similar luminous sources is the said ionization state.

Spectral appearance and LBV candidacy may be regard-ed as more than a semantic issue, however. LBVs are tied to the Ofpe/WN9 (or extreme WNL) stars through classification, remembering that (1) AG Car had been classified as either Ofpe/WN9 or WN11 during visual minimum and (2) the Ofpe/WN9 star R127 entered a phase of intense variability to identify itself with the LBV phase. In addition, the present B[e]-like spectrum of AG Car supports previous suggestions of a link between LBVs and B[e] stars, and the significant spectroscopic variability of the B[e] star S18 and the morphological similarities of this variability to P Cyg and AG Car further strengthen the connection. No evidence to contradict this connection can be seen in comparisons of GG Car and HD 72754 with AG Car.

5. SUMMARY

In comparing various Of, Ofpe/WN9, WNL, LBV, Be, and B[e] spectra at 2 μm and (Ofpe/WN9 and LBV only) 1.6 μm, we have found at least one example from each group that can *easily* be associated with other types of objects through near-infrared spectral morphology. These results, summarized below, have important implications for infrared classification and the suspected evolutionary relationship of these objects.

1. A close spectral morphology in the *K* band occurs between several extreme Of stars and late-type WN stars (Fig. 1). In particular, there exists a very similar morphology between certain (*a*) late-type Of stars (HDE 151804 and HDE 152408) and H-abundant WN8 and WN9 stars (WR 156 and WR 108) and (*b*) early-type Of stars with He II 2.189 μm in emission (HD 16691 and HD 190429) and WN7 and WN7 + abs stars (WR 158 and WR 22).
2. Likewise, examples may be found in Figures 2 and 3 that link the transition Ofpe/WN9 stars in spectral appearance to (*a*) the O supergiants or WNL stars of Figure 1 (HDE 269582 vs. HD 152408 or WR 156, for example) and Figure 4 (HDE 269582 vs. HD 108) and (*b*) the LBVs of Figure 5 (HDE 268840 and HDE 269445 vs. He 3-519).It should be remembered that the Ofpe/WN9 star HDE 269582, with similar morphology to Of and WNL stars in Figure 1*a*, is also an LBV in a decreased brightness, high-temperature state.
3. Now in a visually brightened state, the LBV AG Car exhibits the 2 μm spectrum of an early-type emission-line B supergiant, with emission from Brγ, Fe II, Mg II, and Na I, and in the absorption of He I 2.112–3 μm that is normal for B stars. He I 2.058 μm is absent. While in its level of minimum visual brightness, AG Car passed through the Ofpe/WN9 ionization state in the optical region (Stahl 1986), and at 2 μm (McGregor et al. 1988b) where, in addition to the metal lines, He I 2.112–3 μm and strong He I 2.058 μm were both in emission.
4. The SMC B[e] star S18 has spectroscopically evolved at 2 μm to an Of-like state since the 1987–1989 observations of McGregor et al. (1989). Notably, He I emission at 2.112–3 μm and 2.058 μm (strong) have appeared, in addition to the metal lines of Fe II, Mg II, and Na I. The width of the 2.112–3 μm line, possibly unresolved at $\sim$180 km s^{-1}, indicates that it is not formed in the wind, for which we measure a velocity of $\sim$700 km s^{-1} from P Cygni absorption at 2.058 μm. Overtone emission from ^{12}CO is newly detected as well.
5. The only known B star with the atomic line morphology of S18 is the quiescent LBV P Cyg (B1 Ia$^+$). The LBV and Ofpe/WN9 star HDE 269582 also shares the 2 μm appearance of S18. AG Car and S18 are the only two objects observed to vary in the 2.112–3 μm line. This variability in S18, and the close morphological connections to P Cyg, HDE 269582, and AG Car, justify S18 as a strong candidate to be an LBV. S18 therefore provides the strongest case for a connection to LBV phenomena by a well-known B[e] star.
6. No contradictive evidence for a B[e]-LBV connection can be found in the 2 μm spectra of GG Car or HD 72754, which are highly consistent with the present appearance of AG Car.
7. We showed close correspondence between new 2 μm spectra of the LBV He 3-519 and the SMC WN binary HD 5980, which recently underwent an LBV-like outburst. These are both similar in appearance to the weaker lined Ofpe/WN9 star HDE 269445 and to the WN8 star WR 123. The similarities to the hydrogen-poor objects He 3-519 and WR 123 would *superficially* suggest that the outbursting component of HD 5980 is hydrogen deficient.
8. Finally, the substantial overlapping of morphological properties (spectroscopic) of the transition groups results in serious difficulties for 2 μm classification. Only the most general spectroscopic properties of each group may be used as a guide to classification, subjected to considerable uncertainty.

Although subtle distinctions may be found (given data of sufficient resolution and signal-to-noise ratio), one cannot help but be impressed by the overlap in spectral morphology among these allegedly "transitional" objects. We support the notion that *all* stars in this paper are closely related in their evolutionary status. Under the supposition that the Of stars are *core*-hydrogen burning lead us to suggest further that the objects that exhibit hydrogen at their *surfaces* (including the WN7+abs, WN8, and WN9 stars of Fig. 1) are not yet in a state of core-helium burning. We suggest that the remaining H-abundant objects are late core- or shell-hydrogen burning and in various modes of instability and point to the work of Rauw et al. (1996) as strong independent evidence for this.

We further suspect that the only distinction between the B[e] stars and other transition objects is a stronger degree of nonspherical (disk) symmetry in the winds of the B[e] stars, as inferred by Schulte-Ladbeck et al. (1993), due to higher rotational velocities. The presence of CO overtone emission may indicate where this disk symmetry is strongest, tracing the highest density regions. Shell ejection is not expected to sustain high enough densities for CO emission explaining the lack of CO emission from LBVs (e.g., AG Car) where shell ejection has occurred. As this occurs, the spectra of B[e] stars without CO emission (explained either by a low-density disk or similar shell ejection) and LBVs appearing to pass through the B[e] stage (AG Car to wit) are practically indistinguishable.

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APPENDIX

In this Appendix we provide notes concerning features of the spectra plotted in the figures shown in the text. These notes pertain to line identification, profile shape, and blending.

A1. Of STARS

λ2.058.—Emission at 2.058 μm is highly uncertain in the O4.5 If$^+$ stars HD 16691 and HD 190429 because of difficult telluric corrections here.

λ2.105.—N V 11–10 occurring at 2.100 μm has been identified by Hillier et al. (1983) in the WN5 star HD 50896, but identification of the 2.105 μm feature with N V is not certain here. A possible (but unlikely) alternative is the C III 5*p*–5*s* 2.108 μm singlet.

λ2.165.—The main contribution in OB stars is from Brγ; lesser contribution by the He I multiplet (2.162 μm) is responsible for the asymmetry easily seen in the red side of the profiles. There is probably some blending with He II 14–8 absorption in all but HD 108 and BD +36 4063. Assuming this transition to be optically thin, the EW contribution is ∼0.5 Å (absorption) in HD 151804 and HD 152408 and ∼2 Å (emission) in HD 190429 and HD 16691, on the basis of the He II 15–8 EWs and the transition probabilities given by Wiese et al. (1966). The He II lines are probably not affected by emission from Brγ since H I transitions are expected to be formed in the outermost layers of the wind.

λ2.112–6.—The strongest contribution is a blend of hydrogenic N III and (to a lesser extent) C III in all but BD +36 4063. Optical emission lines of both species are seen in the spectra of HD 108, HD 152408, and HD 16691. No optical C III is detected in HD 151804 or in HD 190429 (Conti 1973). Absorption at 2.112–3 μm in BD +36 4063 is due to He I; detection of N III emission of less than about 1 Å in equivalent width is possible but highly uncertain at this particular resolution and S/N (see Table 1).

The lack of any substantial absorption or emission at 2.058 μm in the O4.5 If$^+$ stars suggests that He I ($3p^1P^o$–$4s^1S$, $3p^3P^o$–$4s^3S$) does not contribute much to this feature. The triplet configuration has a particularly strong transition probability, and the upper level is populated by absorption at 4713 Å ($2p^3P^o$–$4s^3S$) in the optical spectra of both stars, so some contribution seems possible, accounting for the bump in the red side of the 2.114 μm profile at least in HD 190429.

λ2.189.—The features at 2.189 μm, 2.346 μm, and (possibly) 2.038 μm in HD 16691 and HD 190429 are the first detections of *subordinate* He II emission in Of-type stars (Conti et al. 1995). Other Of stars observed in the *K* band (e.g., HD 14947 [O5 If+] and HD 15570 [O4If+]) are in better accord with their optical classifications and exhibit only absorption of subordinate He II transitions. Weak absorption of He II (10–7) may be present in HD 108.

Inspection of the spectrum of HD 190429 reveals He II emission not only by the 10–7 and *n*–8 ($15 \leq n \leq 13$) series, but also possible very weak emission by the *n*–9 ($20 \leq n \leq 24$) series and by He I 2.184 μm ($4p^1P^o$–$7d^1D$). This emission may also be present in the spectrum of HD 16691, but higher quality spectra of both stars are needed.

A2. Ofpe/WN9 AND LBV STARS

λ2.058.—A contribution from Fe II 2.060 μm (z^4F^3–c^4F_5) is possible in WR 22, WR 85a, and HDE 268840, given the presence of other Fe II lines (see below).

λ2.114–2.116.—Similar to "normal" Of supergiant stars, the feature centered at 2.12 μm is a blend of primarily He I, with contribution by hydrogenic N III and possibly hydrogenic C III. The N III contribution seems assured by its presence in Of-type stars, where resolution permits separate identification of the He I and N III features; see the O8 If stars of Figure 1, for example, and the work of Hanson (1996). Optical N III lines and (occasionally) C III emission present in Of stars (see, e.g., Conti 1973) and Ofpe/WN9 stars (Bohannan & Walborn 1989) suggest a possible contribution here. Weak Fe II 2.117 μm (z^4D_5–c^4P_3) emission is suspected in stars for which other Fe II lines are identified.

λ2.165.—Only weak He I 7–4 emission may be present. Since He II 2.038 μm (15–8) and 2.346 μm (13–8) are not readily visible, He II 2.165 μm (14–8) is mostly absent as well. This feature is therefore mostly H I (Brγ) emission.

Other emission.—Line emission at 2.325 μm in the spectra of WR 122 and WR 85a is suggested by Blum et al. (1995a) to be nebular in origin. Otherwise, it may *possibly* be attributed to the C III 5*p*–5*s* triplet, identified in the spectra of WC-type stars (Eenens et al. 1991). Since many Of-type stars do exhibit C III emission lines in the visual region, the C III triplet is a strong possibility; there are no other reasonable candidates from which to choose. The carbonaceous material observed to surround these two stars (Williams et al. 1987) is too cool at ∼1100 K to be the source of this fairly energetic emission ($E_{5p^3P} \simeq 3.44 \times 10^5$ cm^{-1} $\simeq$ 290 Å), so collisional excitation in the wind is a likely formation mechanism. We do not have adequate wavelength coverage to check for the presence of the C III triplet at 1.199 μm ($4p^3P$–$4s^3S$) to confirm the C III 2.325 μm identification.

Identification of the feature at 2.22 μm as [Fe III] 2.218 μm in the spectrum of HD 269582 is ambiguous. Lutz, Krabbe, & Genzel (1993) showed that [Fe III] emission at 2.218 μm originating in the wind-driven bubble near Sgr A* is accompanied by emission from three other [Fe III] transitions with similar ^3G_J–^3H_J spectral terms, at 2.145, 2.242, and 2.348 μm. The lines of lower transition probability at 2.145 and 2.242 μm would not be detected in our spectrum of HD 269582, but emission at 2.348 μm should be nearly as strong as that at 2.218 μm. We do not consider the large bump at 2.35 μm as suitable verification.

The Mg II doublet in the spectra of HDE 268840 and (possibly) HDE 269445 as well as the LBVs and the B[e] star GG Car (Figs. 5–7) are easily excited by Lyβ fluorescence owing to the close proximity of the Lyβ, $5p^2P_{3/2}$, and $5p^2P_{1/2}$ frequencies (McGregor et al. 1988b). The two weak bumps between the Mg II doublet and the 2.165 μm feature are centered at 2.152 and 2.158 μm; we suspect these to be lines of He I 2.150 μm ($7s^3S$–$4p^3P$) and 2.159 μm ($7p^1P$–$4d^1D$).

The emission mechanism for the weak Na I doublet observed in HDE 268840 and in the low-resolution spectra of the LBVs WRA 751, HR Car, AG Car, and HD 160529 is not clear. It is probably fluorescence, pumped by 3300 Å photons from the stellar continuum, or possibly from the Balmer continuum of a dense circumstellar H II region if the Na I–emitting region is shielded from direct stellar radiation (Scoville et al. 1983; McGregor et al. 1988b).

REFERENCES

Allen, D. A., Jones, T. J., & Hyland, A. R. 1985, ApJ, 291, 280
Barbá, R. H., & Niemela, V. S. 1994, IAU Circ., 6099, 1
Barbá, R. H., Niemela, V. S., Baume, G., & Vazquez, R. A. 1995, ApJ, 446, L23
Bashkin, S., & Stoner, J. O., Jr. 1975, Atomic Energy Levels and Grotrian Diagrams, Vol. 1 (Amsterdam: North-Holland)
———. 1978, Atomic Energy Levels and Grotrian Diagrams, Vol. 2 (Amsterdam: North-Holland)
Blum, R. D., DePoy, D. L., & Sellgren, K. 1995a, ApJ, 441, 603
Blum, R. D., Sellgren, K., & DePoy, D. L. 1995b, ApJ, 440, L17
Bohannan, B., & Walborn, N. R. 1989, PASP, 101, 520
Breysacher, J., Moffat, A. F. J., & Niemela, V. S. 1982, ApJ, 257, 116
Breysacher, J., & Perrier, C. 1980, A&A, 90, 207
———. 1991, in IAU Symp. 143, Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies, ed. K. A. van der Hucht & B. Hidayat (Dordrecht: Kluwer), 229
Carlson, E. D., & Henize, K. G. 1979, Vistas Astron., 23, 213
Chiosi, C., & Maeder, A. 1986, ARA&A, 24, 329
Churchwell, E., Bieging, J. H., van der Hucht, K. A., Williams, P. M., Spoelstra, T. A. T., & Abbott, D. C. 1987, ApJ, 393, 329
Conti, P. S. 1971, Mem. 8° Soc. Roy. Liège, 5ieme Sér., 261
———. 1973, ApJ, 179, 181
———. 1976, Mem. 9° Soc. Roy. Liège, 6ieme Sér., 193
———. 1994, in Evolution of Massive Stars: A Confrontation between Theory and Observation, ed. D. Vanbeveren, W. van Rensbergen, & C. de Loore (Dordrecht: Kluwer), 37
Conti, P. S., Hanson, M. M., Morris, P. W., Willis, A. J., & Fossey, S. 1995, ApJ, 445, L35
Cotera, A. S., Erickson, E. F., Colgan, S. W. J., Simpson, J. P., & Allen, D. A. 1996, ApJ, 461, 750
Crowther, P. A., Hillier, D. J., & Smith, L. J. 1995a, A&A, 293, 172
———. 1995b, A&A, 293, 403
Crowther, P. A., & Smith, L. J. 1996, A&A, 305, 541
Crowther, P. A., Smith, L. J., Hillier, D. J., & Schmutz, W. 1995c, A&A, 293, 427
Davidson, K., et al. 1993, ApJ, 411, 336
de Loore, C., de Grève, J. P., & Lamers, H. J. G. L. M. 1977, A&A, 61, 251
de Loore, C., de Grève, J. P., & Vanbeveren, D. 1978a, A&A, 67, 373
———. 1978b, A&AS, 34, 363
DePoy, D. L., Gregory, B., Elias, J., Montane, A., & Perez, G. 1990, PASP, 102, 1433
Eenens, P. R. J., & Williams, P. M. 1994, MNRAS, 269, 1082
Eenens, P. R. J., Williams, P. M., & Wade, R. 1991, MNRAS, 252, 300
Ferland, G. J., Lambert, D. L., Netzer, H., Hall, D. N. B., & Ridgway, S. T. 1979, ApJ, 227, 489
Figer, D. F., McLean, I. S., & Morris, M. 1995, ApJ, 447, L29
Fowler, A. M., & Heynssens, J. B. 1993, Proc. SPIE, 1946
Garcia, J. D., & Mack, J. E. 1965, J. Opt. Soc. Am., 55, 654
Gosset, E., Hutsemékers, D., Surdej, J., & Swings, J. P. 1985, A&A, 153, 71
Hamann, F., DePoy, D. L., Johansson, S., & Elias, J. 1994, ApJ, 422, 626
Hamann, W.-R., Koesterke, L., & Wessolowski, U. 1995, A&A, 299, 151
Hanson, M. M. 1996, Ph.D. thesis, Univ. of Colorado, Boulder
Hanson, M. M., & Conti, P. S. 1994, ApJ, 423, L139
Hanson, M. M., Conti, P. S., & Rieke, M. J. 1996, ApJS, in press
Hernandez, C. A., Lopez, L., Sahade, J., & Thackeray, A. D. 1981, PASP, 93, 747
Hillier, D. J. 1987, ApJS, 63, 947
———. 1992, in ASP Conf. Proc. 22, Nonisotropic and Variable Outflows from Stars, ed. L. Drissen, C. Leitherer, & A. Nota (San Francisco: ASP), 155
Hillier, D. J., Jones, T. J., & Hyland, A. R. 1983, ApJ, 271, 221
Hiltner, W. A., & Schild, R. E. 1966, ApJ, 143, 770
Howarth, I. D., & Prinja, R. K. 1989, ApJS, 69, 527
Hu, J. Y., de Winter, D., Thé, P. S., & Perez, M. R. 1990, A&A, 227, L17
Huang, S.-S. 1963, ApJ, 138, 342
Hubeny, I., Harmanec, P., & Shore, N. 1994, A&A, 289, 411
Humphreys, R. M., & Davidson, K. 1994, PASP, 106, 1025
Hutchings, J. B. 1979, PASP, 91, 361
Koenigsberger, G., Guinan, E., Auer, L., & Georgiev, L. 1995, ApJ, 452, L107
Koenigsberger, G., Moffat, A. F. J., St-Louis, N., Auer, L. H., Drissen, L., & Seggewiss, W. 1994, ApJ, 436, 301
Krabbe, A., et al. 1995, ApJ, 447, L95
Lambert, D. L., Hinkle, K. H., & Hall, D. N. B. 1981, ApJ, 248, 638
Lamers, H. J. G. L. M. 1989, in IAU Symp. 113, Physics of Luminous Blue Variables, ed. K. Davidson, A. F. J. Moffat, & H. J. G. L. M. Lamers (Dordrecht: Kluwer), 135
Lamers, H. J. G. L. M., & Leitherer, C. 1993, ApJ, 412, 771
Lamers, H. J. G. L. M., Maeder, A., Schmutz, W., & Cassinelli, J. P. 1991, ApJ, 368, 538
Langer, N., Hamann, W.-R., Lennon, M., Najarro, F., Pauldrach, A. W. A., & Puls, J. 1994, A&A, 290, 819
LeBertre, T., Heydari-Malayeri, M., Epchtein, N., Gouiffres, C., & Pierrier, C. 1989, A&A, 225, 417L
Leitherer, C. 1988, ApJ, 326, 356
Leitherer, C., Neto, A. D., & Schmutz, W. 1992, in ASP Conf. Proc. 22, Nonisotropic and Variable Outflows from Stars, ed. L. Drissen, C. Leitherer, & A. Nota (San Francisco: ASP), 366
Libonate, S., Pipher, J., Forrest, W. J., & Ashby, M. L. N. 1995, ApJ, 439, 202
Livingston, W., & Wallace, L. 1991, National Solar Observatory Technical Report 91-001
Lopes, D. F., Neto, A. D., & DeFreitas-Pacheco, J. A. 1992, A&A, 261, 482
Lutz, D., Krabbe, A., & Genzel, R. 1993, ApJ, 418, 244
Maeder, A. 1991, A&A, 242, 93
Maeder, A., & Conti, P. S. 1994, ARA&A, 32, 227
Maeder, A., & Meynet, G. 1994, A&A, 287, 803
Martin, M. C. 1987, Phys. Rev., 36, 3575
Mathys, G. 1989, A&AS, 81, 237
McGregor, P. J., Hillier, D. J., & Hyland, A. R. 1988a, 334, 639
McGregor, P. J., Hyland, A. R., & Hillier, D. J. 1988b, 324, 1071
McGregor, P. J., Hyland, A. R., & McGinn, M. T. 1989, A&A, 223, 237
Meynet, G., Maeder, A., Schaller, G., Schaerer, D., & Charbonnel, C. 1994, A&AS, 103, 97
Miller, G. J., & Chu, Y.-H. 1993, ApJS, 85, 137
Moneti, A., Glass, I., & Moorwood, A. 1994, MNRAS, 268, 194
Morris, P. W., & Lamers, H. J. G. L. M. 1996, ApJ, submitted
Najarro, F., Hillier, D. J., Kudritzki, R. P., Krabbe, A., Genzel, R., Lutz, D., Drapatz, S., & Geballe, T. R. 1994, A&A, 285, 573
Niemela, V. 1988, in ASP Conf. Proc. 1, Progress and Opportunities in Southern Hemisphere Optical Astronomy, ed. V. M. Blanco & M. M. Phillips (San Francisco: ASP), 381
Nota, A., Pasquali, A., Drissen, L., Leitherer, L., Robert, C., Moffat, A. F. J., & Schmutz, W. 1996, ApJS, 102, 383
Rauw, G., Vreux, J.-M., Gosset, E., Hutsemékers, D., Magain, P., & Rochowicz, K. 1996, A&A, 306, 771
Schaerer, D. 1995, Ph.D. thesis, Univ. of Geneva
Schaerer, D., & Schmutz, W. 1994, A&A, 288, 231
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Schmutz, W., Hamann, W.-R., & Wessolowski, U. 1989, A&A, 210, 236
Schmutz, W., Leitherer, C., Hubeney, I., Vogel, M., Hamann, W.-R., & Wessolowski, U. 1991, ApJ, 372, 664
Schonberger, D., Herrero, A., Becker, S., Eber, F., Butler, K., Kudritzki, R. P., & Simon, K. P. 1988, A&A, 197, 209
Schulte-Ladbeck, R. E., Leitherer, C., Clayton, G. C., Robert, C., Meade, M. R., Drissen, L., Nota, A., & Schmutz, W. 1993, ApJ, 407, 723
Scoville, N. Z., Kleinmann, S. G., Hall, D. N. B., & Ridgway, S. T. 1983, ApJ, 275, 201
Shore, S. N., & Sanduleak, N. 1984, ApJS, 55, 1
Shore, S. N., Sanduleak, N., & Allen, D. A. 1987, A&A, 176, 59
Smith, L. F. 1968, MNRAS, 138, 109
Smith, L. F., Shara, M. M., & Moffat, A. F. J. 1996, MNRAS, in press
Smith, L. J., Crowther, P. A., & Prinja, R. K. 1994, A&A, 281, 833
Smith, L. J., Crowther, P. A., & Willis, A. J. 1995, A&A, 302, 830
Stahl, O. 1986, A&A, 164, 321
———. 1987, A&A, 182, 229
Stahl, O., Wolf, B., Klare, G., Cassatella, A., Krautter, J., Persi, P., & Farrari-Toniolo, M. 1983, A&A, 127, 49
Sterken, C., Gosset, E., Jüttner, A., Stahl, O., Wolf, B., & Axer, M. 1991, A&A, 247, 383
Tamblyn, P., Rieke, G. H., Hanson, M. M., Close, L. M., McCarthy, D. W., Jr., & Rieke, M. J. 1996, ApJ, 456, 206
Thackeray, A. D. 1971, MNRAS, 154, 103
Thackeray, A. D., Tritton, S. B., & Walker, E. N. 1973, MmRAS, 77, 199
Thompson, R. I., & Boroson, T. A. 1977, ApJ, 216, L75
Underhill, A. B. 1994, ApJS, 420, 869

van der Hucht, K. A. 1995, in Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, ed. K. A. van der Hucht & P. M. Williams (Dordrecht: Kluwer), 301
van der Hucht, K. A., Hidayat, B., Admiranto, A. G., Supelli, K. R., & Doom, C. 1988, A&A, 199, 217
van der Hucht, K. A., & Koornneef, J. 1994, An Infrared Spectral Line List of Astrophysical Interest (2.4–200 μm), Document ISO 94-94
van der Hucht, K. A., Williams, P. M., van Genderen, A. M., Mulder, P., & Zealey, W. J. 1989, in IAU Symp. 113, Physics of Luminous Blue Variables, ed. K. Davidson, A. F. J. Moffat, & H. J. G. L. M. Lamers (Dordrecht: Kluwer), 301
van der Hucht, K. A., et al. 1996, in preparation
van Kerkwijk, M. H. 1995, in IAU Symp. 163, Wolf-Rayet Stars: Binaries, Colliding Winds, Evolution, ed. K. A. van der Hucht & P. M. Williams (Dordrecht: Kluwer), 527
van Kerkwijk, M. H., et al. 1992, Nature, 355, 703
Vreux, J. M., & Conti, P. S. 1979, ApJ, 228, 220
Walborn, N. R. 1971, ApJ, 164, 267
———. 1972, AJ, 77, 312
———. 1973, AJ, 78, 1067
Walborn, N. R. 1976, ApJ, 205, 419
———. 1982, ApJ, 256, 45
———. 1989, in IAU Symp. 113, Physics of Luminous Blue Variables, ed. K. Davidson, A. F. J. Moffat, & H. J. G. L. M. Lamers (Dordrecht: Kluwer), 27
———. 1990, in ASP Conf. Proc. 7, Properties of Hot Luminous Stars, ed. C. D. Garmany (San Francisco: ASP), 23
Waters, L. B. F. M., Marlborough, J. M., Geballe, T. R., Oosterbroek, T., & Zaal, P. 1993, A&A, 272, 9
Wiese, L. L., Smith, M. W., & Glennon, B. M. 1966, Atomic Transition Probabilities, Vol. 1, National Standard Reference Data Series (Washington: NBS)
Williams, P. M., van der Hucht, K. A., & Thé, P. S. 1987, A&A, 182, 91
Willis, A. J., & Stickland, D. J. 1980, MNRAS, 190, 27P
Wolf, B., & Stahl, O. 1982, A&A, 112, 111
Wolf, B., Stahl, O., Smolinski, J., & Cassatella, A. 1988, A&AS, 74, 239
Zaal, P. A., Waters, L. B. F. M., & Marlborough, J. M. 1995, A&A, 299, 574
Zickgraf, F.-J., Wolf, B., Stahl, O., & Humphreys, R. M. 1989, A&A, 220, 206