THE ASTROPHYSICAL JOURNAL, 330:766–775, 1988 July 15

WOLF-RAYET STARS IN THE MAGELLANIC CLOUDS. V. BINARIES IN THE SMALL MAGELLANIC CLOUD

ANTHONY F. J. MOFFAT[1]
Département de physique, Université de Montréal
Received 1987 October 29; accepted 1988 January 13

ABSTRACT

With the present spectroscopic data, a systematic radial velocity study of all eight Wolf-Rayet (W-R) stars in the Small Magellanic Cloud (SMC) is now available. Two of these stars are of the late, cool WN subclass (WNL), with one possibly an extreme Of star; one is definitely, the other probably, constant in radial velocity. Five early, hot WN stars (WNE) all exhibit O-type spectral lines, two of type O4: and three of type O6–7 I:; four of the five WNE stars are definitely spectroscopic binaries. The eighth star belongs to the rare oxygen sequence (WO) and has an orbiting O4 V companion.

The binary frequency of the six hydrogen-poor WNE/WO stars appears to be high (83–100) ± 42%, but cannot be labeled abnormal at the ~1 σ level by Galactic standards. SMC W-R stars appear to have more massive progenitors than do Galactic W-R stars; the higher luminosity implied may be a necessary prerequisite for a strong W-R type stellar wind, to compensate for the low SMC metallicity.

Spatial correlations of spectral subclasses for the SMC W-R population are compatible with the evolutionary scenario WNL → WNE → WCE/WO in a low-metallicity environment, with most W-R stars appearing in the bottleneck WNE phase.

Subject headings: galaxies: Magellanic Clouds — stars: binaries — stars: Wolf-Rayet

I. INTRODUCTION

The SMC is an ideal laboratory to study the effects of low metal abundance ($Z/Z_{\odot} \approx 0.1$) on stellar evolution, especially of massive stars, whose mass-loss rates may be strongly affected by their initial metal content. In particular, it appears that details concerning the formation of Wolf-Rayet (W-R) stars (e.g., spectral character, relative number compared to other stars, distribution of different subtypes, ...) are very sensitive toward Z (cf. Azzopardi, Lequeux, and Maeder 1987).

Azzopardi and Breysacher (1979; hereafter AB) have cataloged a total of eight W-R stars in a complete survey of the Small Magellanic Cloud (SMC). The eight stars are listed in Table 1 and plotted as they appear on the sky in Figure 1. According to AB, *all* eight W-R stars appear to have spectroscopically visible or inferred OB companions. AB's W-R subtypes are dominated by the early, hot nitrogen sequence, WNE (i.e., WN2–5), with one star (WC4) of the early, hot carbon sequence, WCE (i.e., WC4–6).

The possibility that W-R stars formed in metal-poor environments may all be binaries has been noted in support of the necessity of an additional mechanism besides wind mass loss to expose the observed products of nucleosynthesis seen in the winds of W-R stars (cf. Hidayat, Admiranto, and van der Hucht 1984). The tidal force of a close OB companion is supposed to enhance the mass-loss rate of the primary, or lead to mass transfer from the initially more massive star to the secondary. The initial primary then evolves into a W-R star, which it might not do as a single star with a weaker wind in a low metallicity situation.

However, in the case of the SMC, the fact that the presence of an OB companion in three cases was only *inferred* by AB on the basis of absolute magnitudes (i.e., not directly observed in the spectrum), justifies a search for more compelling evidence of duplicity, such as orbital motion. To do this, one needs repeated spectra over days, and weeks if possible, in order to reveal any periodic radial velocity (RV) variation in at least one star of the binary. If found, this would imply the undeniable presence of a binary companion; if not found, this would discredit the binary hypothesis.

In this paper, I report on repeated spectroscopic observations of the five faintest W-R stars in the SMC (AB 1, 2, 3, 4, and 7). These same spectra are also averaged to derive more precise estimates of the spectral types. The remaining W-R stars in the SMC (AB 5, 6, and 8) are brighter, and have already been reported in Papers II, I, and III, respectively, by Breysacher, Moffat, and Niemela (1982), Moffat (1982*b*), and Moffat, Breysacher, and Seggewiss (1985). Paper IV in this series (Moffat and Seggewiss 1986) deals with the peculiar LMC triple system R130 [WN6 (+O) + B1 Ia].

II. OBSERVATIONS

The present spectra were obtained during three observing runs at the Cerro Tololo Inter-American Observatory (CTIO), Chile: 12 nights in 1980 December, and nine nights in 1982 January, at the 1 m telescope; and four nights in 1982 January at the 4 m telescope. At both telescopes, a Carnegie image tube was employed at a dispersion of ~45 Å mm^{-1} in the range λλ3700–5000. The spectra were widened to ~0.7 mm. A spectral resolution of ~1.5 Å was attained with the baked IIaO plates used at the 1 m, where AB 4 and AB 7 were bright enough to be observed, and ~1.0 Å with the baked IIIaJ plates at the 4 m, where the faintest stars, AB 1, 2, and 3 were observed. Wavelengths were calibrated by Ne-Ar lines.

All plates were digitally scanned using the PDS machine in photographic density mode at the David Dunlap Observatory. For this, a scanning slit of 10 μm width was used, with 5 μm sampling interval along the direction of dispersion. All further

[1] Visiting Astronomer, Cerro Tololo Inter-American Observatory, Chile, National Optical Astronomical Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

TABLE 1

SPECTRAL AND PHOTOMETRIC PROPERTIES OF THE SMC W-R STARS

AB	Other	Sp(AB)[a]	Adopted Sp	V(AB)	M_v(AB)	RV Var	Ref (sp)
1	...	WN3 + OB	WN3 + O4:	15.48	−3.9	Const:	1
2	...	WN4.5 + O4	O3 If*/WN6-A	14.43	−5.0	Const:	2, 1
3	...	WN3–4 + O4	WN3 + O4:	14.55	−4.8	SB2	1
4	Sk 41	WN4.5 + (O4–6 V–III)	WN6 − A	13.43	−6.0	Const	3, 1
5	HD 5980	WN3p + (OB)	WN4 + O7 I:	11.88	−7.5	SB2	4
6	R31, Sk 108	WN3 + O7 Ia	WN3 + O6.5 I:	12.36	−7.1	SB2	3, 5, 6
7	...	WN3p:(+OB)	WN3: + O7:	13.16	−6.3	SB2	1
8	Sk 188	WC4? + O4	WO4 + O4 V	12.97	−6.:	SB2	7

[a] Parentheses indicate presence of OB companion *inferred* by AB from absolute magnitudes M_v(tot) observed and M_v(W-R) from the W-R subtype.

REFERENCES.—(1) present work; (2) Walborn 1984; (3) Walborn 1977; (4) Breysacher, Moffat, and Niemela 1982; (5) Moffat 1982*b*; (6) Hutchings *et al.* 1984; (7) Moffat, Breysacher, and Seggewiss 1985.

NOTES. AB 1, 2, 3—visual companion not evident, but would be difficult to see with 4-m TV monitor.

AB 4—observed with ~1.5 mag fainter, 4″ companion along the spectrograph slit.

AB 7—faint, 2″ companion just outside slit.

AB 5, 6, 8—look single in 1″ seeing.

analysis was done in photographic density rather than converting to intensity or log intensity, since photometric precision is most nearly independent of exposure level in density mode.

III. SPECTRAL CLASSIFICATION

Using the classification criteria of Smith (1968), revised by van der Hucht *et al.* (1981) for W-R stars, and the M-K criteria (cf. Schmidt-Kaler 1982) for O stars, each of the five stars was classified on the basis of the digitized mean (cf. Fig. 2) of all the 4 m spectra for AB 1, 2, and 3, and the 1980 1 m spectra for AB 4 and 7. The adopted types are given in Table 1. Some detailed remarks for each star follow.

AB 1.—(*a*) emission lines: N IVe 4057 ≪ N Ve 4603, no N IIIe 4640 → WN3 for the W-R component; (*b*) absorption lines: He IIa 4200 ≪ Hδa or Hγa, i.e., strongly alternating Pickering series → significant hydrogen abundance → absorption from an OB companion star, since WNE stars normally have undetectable H/He (cf. Maeder and Meynet 1987). He Ia 4471/He IIa 4541 ≈ 0.0 ± 0.2 → O4: for the OB component.

AB 2.—(*a*) N IVe ≳ N IIIe, N V present but weak (absorption), relatively narrow N IVe, He IIe lines → WN6 if W-R. Very narrow nebular Hβ, [O III] emission visible; (*b*) well-developed absorption line spectrum with alternating Pickering lines → could be a single WN6/O3:f star or WN6 + OB binary. Walborn (1986) gives O31f*/WN6-A.

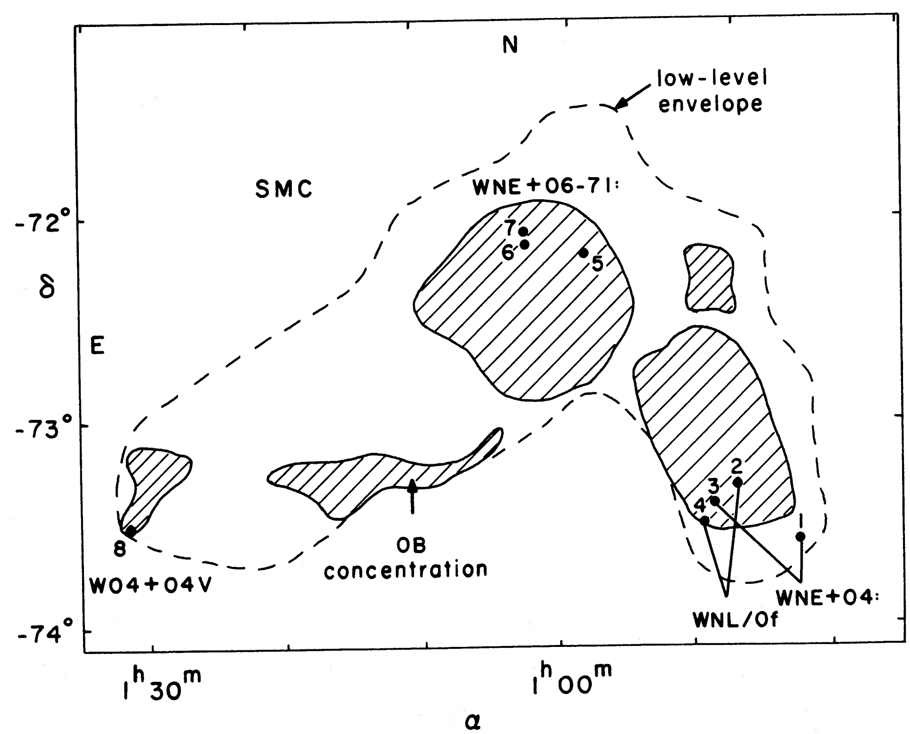

FIG. 1.—Spatial plot of the eight W-R stars in the SMC, showing schematic concentrations of OB stars, based on the work of AB. The AB numbers are shown along with the adopted spectral types from Table 1.

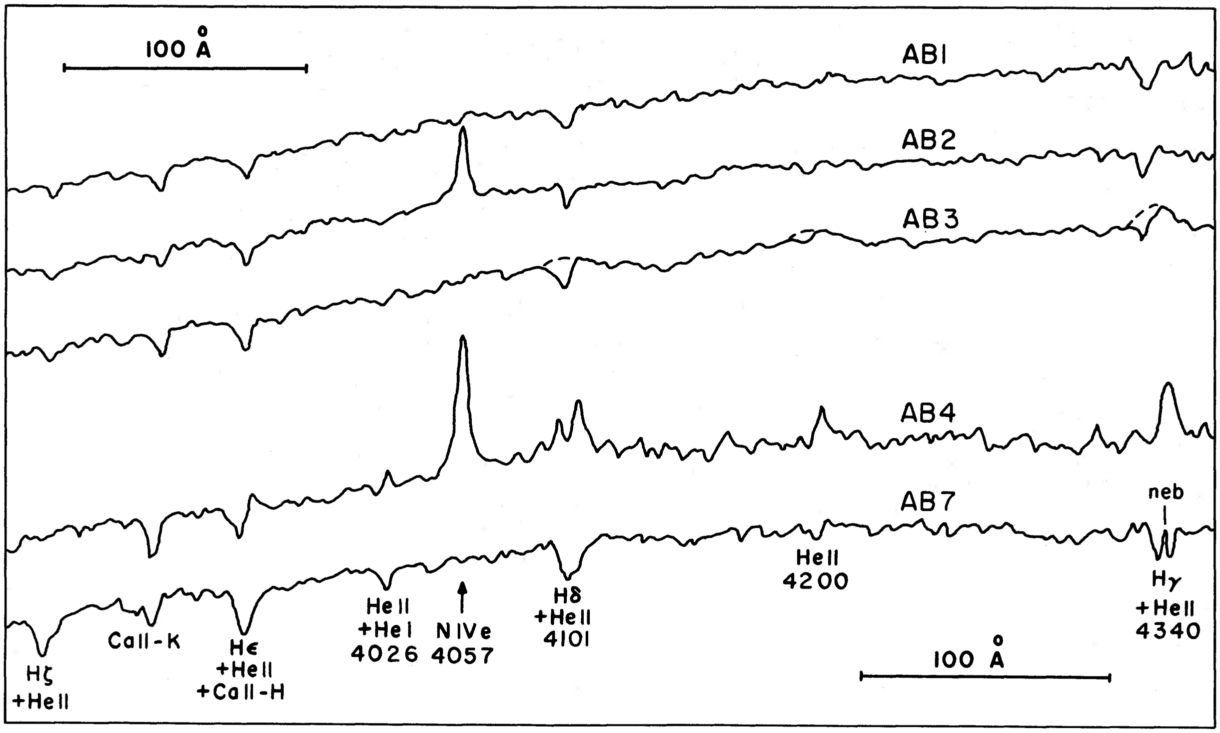

FIG. 2a

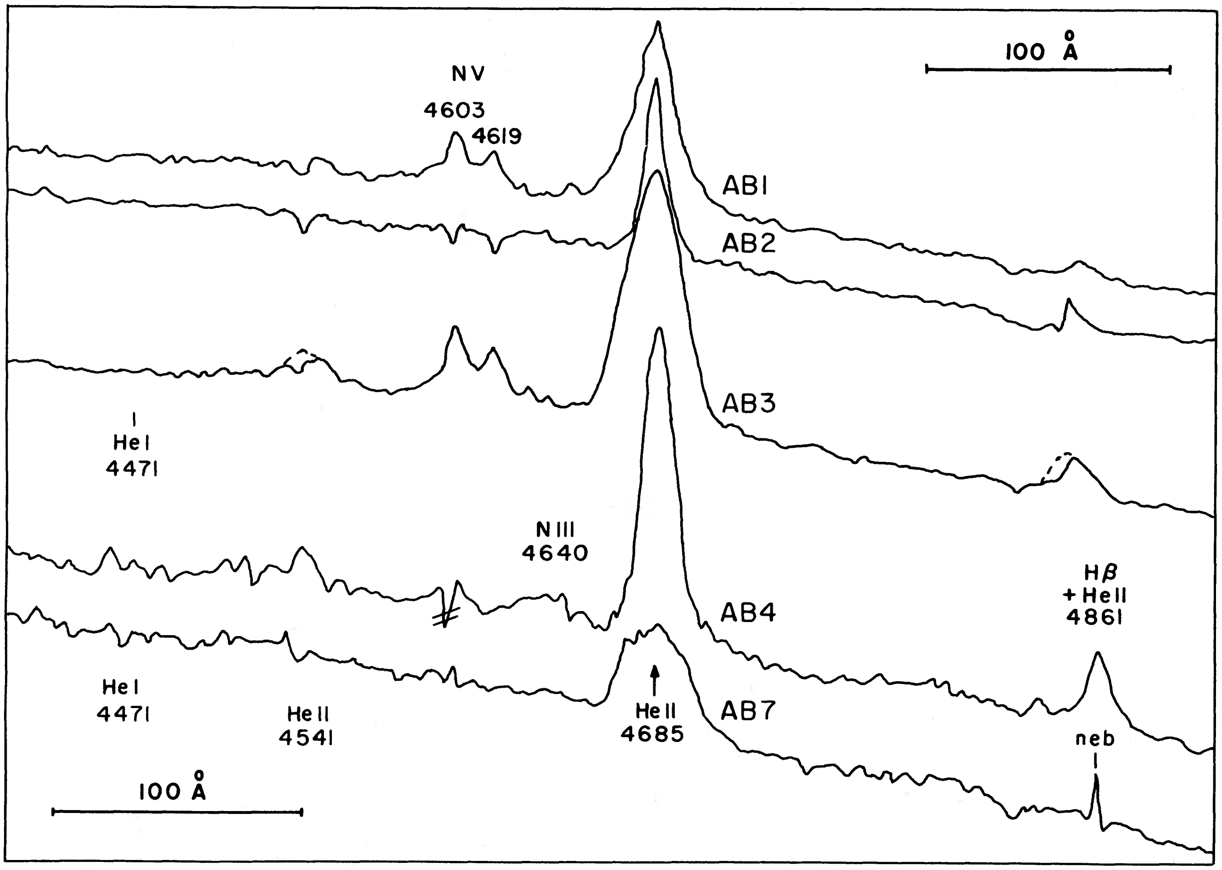

FIG. 2b

FIG. 2.—Mean PDS spectra of the five W-R stars observed here. For each of AB 1, 2, and 3, the means are based on the four IIIaJ spectra from the 4 m; for each of AB 4 and 7, the 10 IIa0 1980 spectra from the 1 m. The abscissa is nearly linear in wavelength; the ordinate is proportional to photographic density (~log intensity for most of the spectra). Both scales are the same for the data from each telescope, but differ between the two sources. (*a*) From H8 to Hγ; (*b*) from He I 4471 to Hβ. The two groups coincide at N IV 4057 in (*a*) and He II 4685 in (*b*).

TABLE 2

IMAGE-TUBE HELIOCENTRIC 4 m RADIAL VELOCITIES OF AB 1, AB 2, AND AB 3

JD-2,444,000	H10a 3797.900	H9a 3835.386	H8a 3889.051	Hεa 3970.074 (+Ca II)	Hδa 4101.737	Hγa 4340.468	He IIa 4541.590	N Va 4603.730	N Va 4619.980	N IVe 4057.759	N VE 4603.730	N Ve 4619.980	mean N Ve	He IIe 4685.682	Ca IIa IS 3933.664	[O III]e 4958.9	[O III]e 5006.8	Hβe 4861.332
					(AB1)										(AB1)			
983.588	...	...	70	0	59	−55	...	...	...	...	215	152	184	255	73	...	...	...
984.583	...	...	6	−4	50	82	161	...	...	...	189	174	182	275	73	...	...	...
985.590	...	...	90	36	72	13	−20	...	...	...	125	257	191	264	64	...	...	...
986.547	...	...	83	−86	50	−48	32	...	...	...	260	98	179	287	103	...	...	...
mean	...	...	62	−14	58	−2	58	...	...	...	197	170	184	270	78	...	...	...
σ	...	...	38	52	10	64	93	...	...	...	56	66	5	14	17	...	...	...
					(AB2)										(AB2)			
983.610	236	111	102	10	100	−74	72	43	145	147	...	...	...	205	70	165	113	(neb.) 261
984.544	85	57	−39	9	42	−52	84	...	227	112	...	...	...	202	60	156	96	174
985.619	146	149	107	54	−41	−76	94	59	161	141	...	...	...	251	65	142	111	161
986.569	52	94	71	24	8	−90	32	63	112	121	...	...	...	215	96	154	106	189
mean	130	103	60	24	27	−73	70	55	161	130	...	...	...	218	73	154	106	196
σ	81	38	68	21	59	16	27	11	48	16	...	...	...	23	16	9	8	45
					(AB3)										(AB3)			
983.626	...	...	81	−96	...	−123	...	...	...	...	310	305	308	387	84	...	...	(stell.) 521
984.559	...	...	−60	−3	56	−130	...	...	...	...	240	216	228	317	97	...	...	539
985.555	...	...	22	−48	−49	−211	...	...	...	...	219	203	211	284	94	...	...	435
986.588	...	...	26	+66	−88	−459	...	...	...	...	175	115	145	170	146	...	...	424
mean	...	...	17	−20	−27	−231	...	...	...	...	236	210	223	290	105	...	...	480
σ	...	...	58	69	74	157	...	...	...	...	56	78	67	90	28	...	...	59

AB 3.—similar to AB 1, except that the emission lines are stronger and absorption lines are weaker in AB 3.

AB 4.—similar to AB 2, except that the emission spectrum is more prominent compared to the absorption lines, which are strongly violet-shifted; the spectrum is only slightly hotter than that of the WN7 star HD 151932 in the Galaxy (cf. spectral atlas of Smith and Kuhi 1981) → WN6 without Of option. Walborn (1977) gives WN6-A.

AB 7.—(*a*) similar to AB 6 (cf. paper I) with broad, diluted He IIe 4685 and a trace of N ve 4603/4619 → WN3. H II region nebular emission lines visible; (*b*) absorption lines weaker than in AB 6 but significant H-abundance indicated. He Ia/He IIa ≈ 1 → O7:.

In AB 5, 6, and 8, H absorption lines are clearly seen (cf. Papers II, I, and III, respectively). Indeed, all three stars are spectroscopic binaries with O-type companions which provide the source of H absorption.

IV. RADIAL VELOCITIES

RVs were obtained for the strongest lines by bisecting parabolic fits in rectified photographic density to the central line cores, which were chosen to include ~3/4 of the total line width (FWZM). The RVs are given in Table 2 for AB 1, 2, and 3; Table 3 for AB 4; and Table 4 for AB 7.

Among the three stars observed during only four consecutive nights (AB 1, 2, 3), only AB 3 shows clear RV variations (cf. Fig. 3), although not in a complete orbital cycle. The lower Balmer absorption lines (Hγ, δ) appear to move with the emission lines, while the upper lines (Hϵ, 8) tend to vary in antiphase. This may mean that we are seeing either (*a*) photospheric absorption lines of both the W-R star (He) and the O companion (H + He), or, more likely, (*b*) spurious variations of Hγ, δ due to the perturbing effects of the dominant emission for these lines.

On the basis of the partial orbit observed for AB 3, one has the constraint $P \gtrsim 6$ d, $K_{\text{W-R}} \gtrsim 100$ km s^{-1} and $K_0 \gtrsim 50$: km s^{-1}. On the basis of the nearly linear RV variations with time, the assumption that $K_{\text{W-R}} \approx 100(P/6\ \text{d})$ km s^{-1} and $K_0/K_{\text{W-R}} \approx 0.5$, leads to $M_0 \sin^3 i \approx 1.4, \ldots, 71\ M_\odot$ for $P = 6, \ldots, 16$ d, respectively. Further observations are required to tie the orbit down; the important point to note here is that AB 3 *is* a double-line spectroscopic binary.

The stars AB 1 and AB 2 both show little if any RV variation during the four nights. However, AB 1 may reveal a hint of change, supported independently by the mean RV for He IIe 4685, which is ~50 km s^{-1} higher than the systemic velocity of the same line in the well-behaved stars AB 2, 4, and 6, but similar to AB 3 (cf. Fig. 5 below). This deviation may be the result of a long-period orbit, assuming that He IIe 4685 is not intrinsically shifted more in AB 1 than other WNE stars in the SMC.

For both AB 4 and AB 7, there are sufficient data (two 10-day intervals separated by about a year) to qualify their binary status with some confidence. Clearly, AB 4 appears to be a single star: not only are the well-measured emission lines of He II 4685 and N IV 4057 ~ constant in RV [e.g., RV (He IIe) = 211 ± 8(σ) km s^{-1} in 1980; = 212 ± 8(σ) km s^{-1} in 1982], but also their mean values are very similar to those of AB 2. This supports the single nature of both AB 2 and AB 4, which also have similar spectra.

With σ(RV) ≈ 120 km s^{-1} for He IIe 4685 in AB 7, even if this line is strongly diluted, there is no doubt that this star is varying. For comparison, the three nebular emission lines of [O III] and Hβ reveal σ(RV) ≈ 13–20 km s^{-1}, with $\overline{\Delta \text{RV}}$ (1980–1982) ≈ +6 ± 5 km s^{-1}. A period search among the RVs of He IIe and the mean absorption (cf. Table 4), yields periods in the range 13–18 d. Unfortunately, the emission and absorption lines do not yield the same best period; thus, Table

TABLE 3

IMAGE-TUBE HELIOCENTRIC 1 m RADIAL VELOCITIES OF AB 4

JD-2,444,000	H9a	H8a	Hϵa +H	Hδa	N IVe	Hγe	He IIe 4685	Ca IIa IS	[O III]e neb.	[O III]e neb.	Hβe stell.
584.603	...	...	64	...	130	376	203	98	...	...	247
585.582	...	...	−25	...	98	305	220	68	...	...	281
586.594	...	...	129	...	120	336	199	46	...	...	237
587.593	...	...	65	...	96	261	209	78	...	...	283
588.651	...	...	167	...	127	312	215	180	...	...	212
589.650	...	...	133	...	80	274	221	135	...	...	208
595.554	...	...	120	...	152	329	208	124	...	...	274
596.556	...	...	64	...	140	234	219	183	...	...	317
597.576	...	...	109	...	141	250	215	109	...	...	240
599.578	...	...	136	...	168	241	200	98	...	...	239
mean	...	...	96	...	125	292	211	112	...	...	254
σ	...	...	55	...	27	47	8	45	...	...	34
974.586	...	...	141	...	122	297	217	126	...	...	268
976.617	...	...	56	...	118	344	194	104	...	...	185
977.562	...	...	84	...	114	434	216	31	...	...	193
979.573	...	...	50	...	93	357	211	78	...	...	228
980.640	...	...	85	...	115	287	217	189	...	...	192
981.581	...	...	82	...	113	311	213	144	...	...	257
982.575	...	...	28	...	107	248	216	137	...	...	231
mean	...	...	75	...	112	325	212	116	...	...	222
σ	...	...	36	...	9	60	8	51	...	...	33
Overall mean	...	...	88	...	120	306	211	113	...	...	241
Overall σ	...	...	48	...	22	54	8	46	...	...	36

NOTE.—Laboratory wavelengths as in Table 2.

TABLE 4

IMAGE-TUBE HELIOCENTRIC 1 m RADIAL VELOCITIES OF AB 7

JD-2,444,000	H9a	H8a	Hεa +H	Hδa	N IVe	Hγe	He IIe 4685	Ca IIa IS	[O III]e neb.	[O III]e neb.	Hβe neb.	mean abs H9, 8, ε[a]
584.643	119	118	83	245	...	...	223	...	200	191	193	107 ± 12
585.621	380	1	181	169	...	...	173	...	167	179	189	188 ± 109
586.626	242	204	166	172	...	...	85	...	190	180	157	204 ± 22
587.565	448	404	277	−186	...	...	113	...	207	202	152	376 ± 51
588.611	296	467	395	97	...	...	−10	...	190	195	157	386 ± 50
589.690	340	345	296	135	...	...	−60	...	173	212	158	327 ± 16
595.590	180	272	105	108	...	...	248	...	164	209	180	186 ± 48
596.597	198	287	139	78	...	...	234	...	192	197	199	208 ± 43
597.617	42	176	83	−96	...	...	235	...	173	185	...	100 ± 40
598.553	31	62	103	96	...	...	189	...	180	174	218	65 ± 21
mean	228	234	183	82	...	...	143	...	184	192	178	215 ± 49 (rms)
σ	140	149	106	129	...	...	109	...	14	13	23	114
975.603	184	41	95	−51	...	...	232	...	183	168	(−246)	107 ± 42
977.619	154	−115	73	−16	...	...	68	...	188	181	175	37 ± 80
978.575	132	174	205	184	...	...	−49	...	162	202	(−404)	170 ± 21
979.545	93	245	87	151	...	...	−25	...	171	188	182	142 ± 52
982.609	260	210	219	266	...	...	−52	...	185	181	166	230 ± 15
mean	165	111	136	107	...	...	35	...	178	184	174	137 ± 48 (rms)
σ	63	148	70	135	...	...	121	...	11	12	8	72
Overall mean	207	193	167	90	...	...	107	...	182	190	177	189 ± 49 (rms)
Overall σ	121	156	96	127	...	...	120	...	13	13	20	106

NOTE.—Laboratory wavelengths as in Table 2.

[a] Excludes Hδa which may be affected by nebular emission.

5 and Figure 4 show circular orbit parameters and fitted curves for the three best periods. Some preference can be assigned to the emission-line period (Fig. 4*c*), which gives absorption and emission RVs that are closest to being in antiphase, despite the RV (or phase?) shift in the absorption RVs between 1980 and 1982. This period also yields the most similar mass ratio compared to other known W-R binaries (cf. Abbott and Conti 1987). The best absorption-line period (Fig. 4*a*) yields a large phase shift between the 1980 and 1982 emission-line RVs. These shifts may be due to distortion effects (most likely in the relatively weak W-R wind) or to the presence of a third body. Further data are needed to clarify this.

In Figure 5 are shown mean RVs for different lines of the stars observed here. The general trend to greater negative RV for the lower Balmer absorption lines in those stars for which there are sufficient data (AB 2, 3, 7) is quite apparent. The same trend was seen in the previously observed binary AB 5 (cf. Paper II), although not in AB 6 (cf. Paper I) or in AB 8 (cf. Paper III). As seen in other luminous stars (cf. Hutchings 1976), this indicates outwardly accelerating photospheres for the hot, luminous O-type companions, although the emission lines from the W-R component may affect this in some cases.

V. DISCUSSION AND CONCLUSIONS

Despite their small number, the W-R stars in the SMC can be grouped in several meaningful ways. Spatially, they tend to cluster at the *edges* of three global OB concentrations (cf. Fig. 1). Taking W-R stars as indices of recent vigorous star formation, this suggests an age gradient, compatible with the concept of stochastic self-propagating star formation in OB associations (cf. Seiden and Gerola 1982).

The three spatial groups also differ somewhat in the spectral

TABLE 5

ORBITAL PARAMETERS FOR AB 7 ($e = 0$)

PARAMETER	BEST ABSORPTION Emis.	BEST ABSORPTION Abs.	BEST COMBINED SOLUTION Emis.	BEST COMBINED SOLUTION Abs.	BEST EMISSION Emis.	BEST EMISSION Abs.
P(d)	17.97		16.34		13.013	
γ (km s^{-1})	117 ± 31	227 ± 15	108 ± 19	213 ± 23	83 ± 11	210 ± 34
K (km s^{-1})	96 ± 33	152 ± 22	144 ± 23	128 ± 33	161 ± 12	81 ± 38
E_0 − JD 2,444,500	92.0 ± 1.5	104.2 ± 0.4	93.8 ± 0.5	87.0 ± 0.6	93.6 ± 0.2	87.7 ± 1.2
σ_{o-c} (km s^{-1})	92	45	56	68	30	90
$[E_0(\text{abs}) - E_0(\text{emis})]/P$	0.68 ± 0.09		0.42 ± 0.05		0.45 ± 0.09	
$M_{WR} \sin^3 i(M_\odot)$	17.5 ± 7.3		16.1 ± 8.5		6.4 ± 5.0	
$M_0 \sin^3 i(M_\odot)$	11.0 ± 7.0		18.1 ± 7.4		12.8 ± 4.6	
$M_{WR}/M_\odot$	1.58 ± 0.59		0.89 ± 0.27		0.50 ± 0.24	

NOTE.—E_0 is the time of γ-passage from negative to positive velocity. Emis. refers to He II 4685, abs. to the mean of H9, 8, ε.

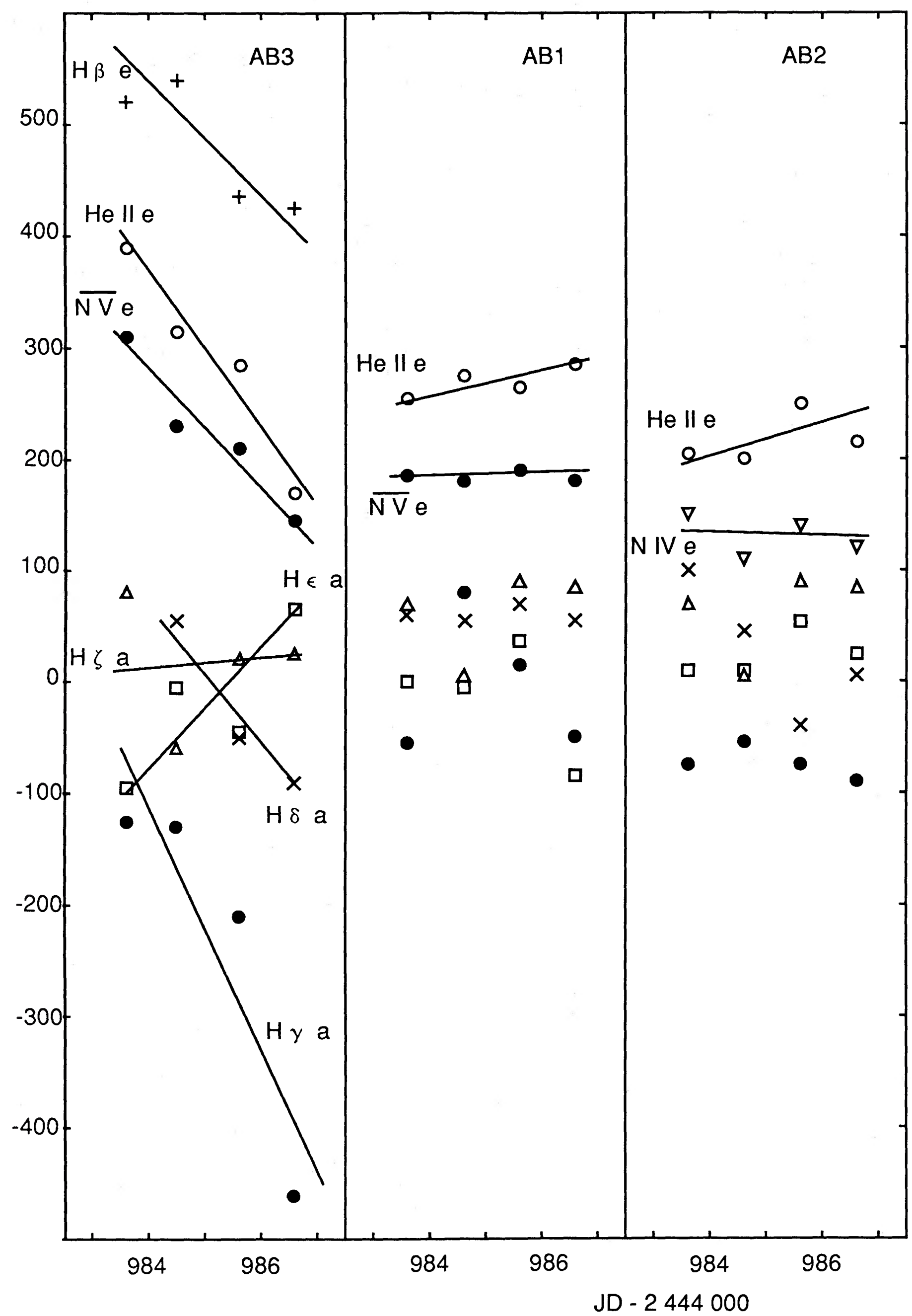

FIG. 3.—Radial velocity vs. time for various spectral lines in AB 3, 1, and 2

types of the W-R stars they contain. The two WNE + O4: binaries AB 1 and AB 3 blend with the two luminous single WN 6 or Of-like stars AB 2 and AB 4 in the southern main body of the SMC. The northern main body contains a more uniform sample of three WNE + O6–7 I: binaries, each dominated by the light of their supergiant components. The wing contains the only non-WN star, AB 8, of spectral type WO4 + O4V. These facts suggest (1) that WNL stars can evolve into lower mass, lower luminosity WNE stars (by rapid mass loss: $\sim 4 \times 10^{-5}\ M_{\odot}\ \mathrm{yr}^{-1}$ in 5×10^5 yr yields $\sim 20\ M_{\odot}$), a phase that may not reach the WC/WO phase very often for low Z, before exploding as supernovae, and (2) that the southern W-R groups are slightly younger and originate from slightly more massive progenitors, assuming that W-R star progenitors in binaries were more massive than their present secondaries and that main-sequence O4 stars are more massive than the progenitors of O6–7 I stars.

Grouping according to spectral subtype, one finds two WNL stars (one of which may be an extreme Of star), four or five WNE + O stars, and one or zero WNE + intrinsic absorption star, respectively, and one WO + O star. The binary frequency for the WNL stars is $(0 \pm 1.4)/2$, not incompatible with the W-R + O frequency in the Galaxy of ~43% (Moffat *et al.* 1986*a*). The WNE/WO stars reveal a binary frequency of $(5\text{–}6 \pm \sqrt{6})/6 = (83\text{–}100) \pm 42\%$. This is also compatible at the 1.0–1.4 σ level with the Galactic value of

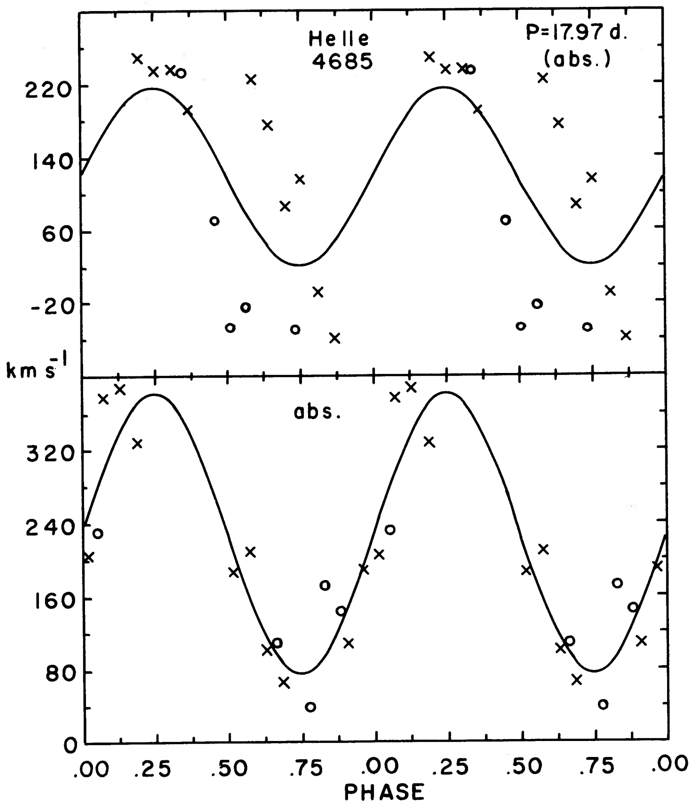

FIG. 4*a*

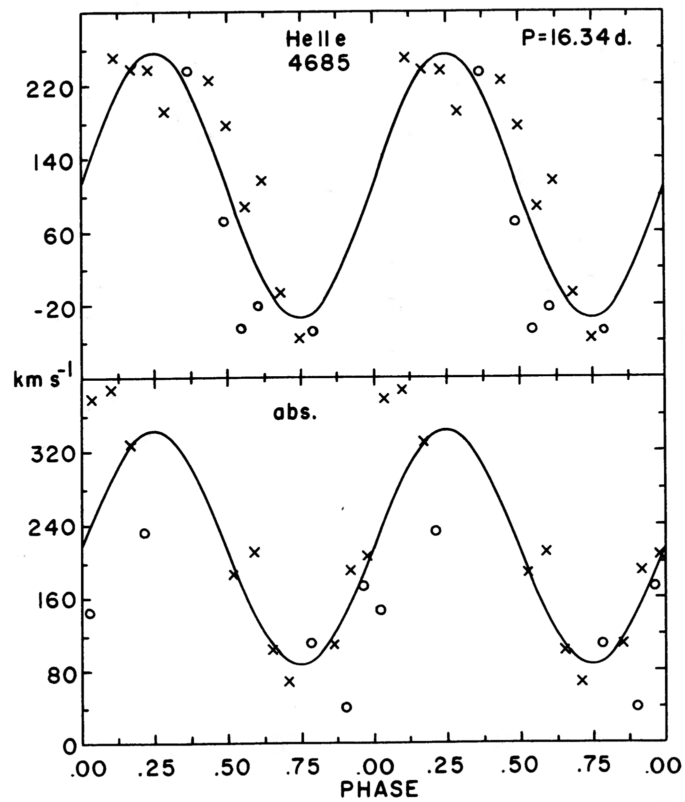

FIG. 4*b*

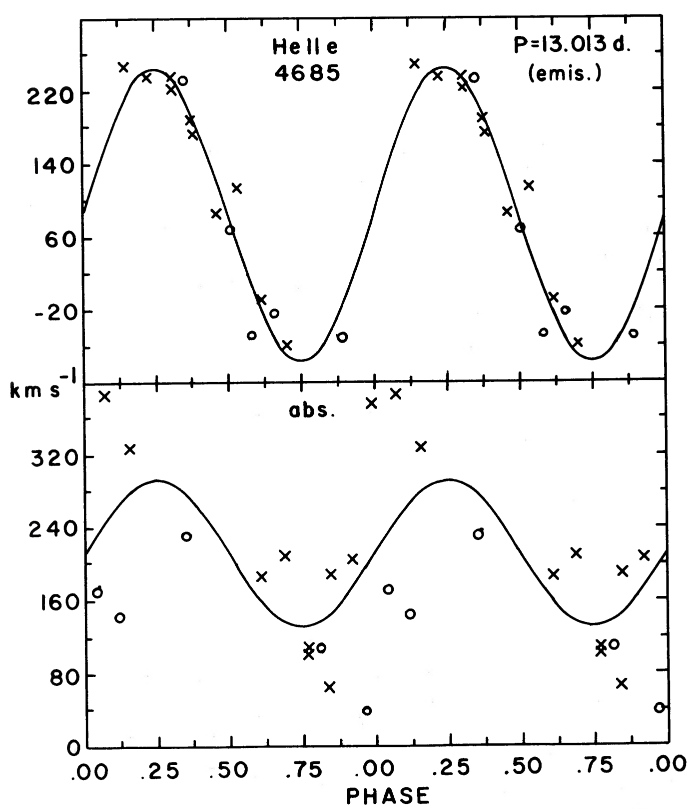

FIG. 4*c*

FIG. 4.—Circular orbit fits made independently to the He II 4685 emission line and the mean absorption (H9, 8, ε) RVs of AB 7, for three different periods: (*a*) $P = 17^{\mathrm{d}}97$ (best absorption-line period), (*b*) $16^{\mathrm{d}}34$ (best combined emission/absorption period), and (*c*) $13^{\mathrm{d}}013$ (best emission-line period). Crosses refer to 1980, circles to 1982.

43%. Compared to the LMC (cf. Moffat *et al.* 1987), the relative numbers of W-R stars of different subtypes in the SMC is entirely compatible with that found outside the active 30 Dor region, where one finds N(WNE)/N(WCE) = 3.5 and N(WNL)/N_{tot}(WR) ≈ 0.1. The numbers in the SMC are simply too small to draw significant conclusions of these ratios regarding any *clear* correlation with metallicity.

One can also arrange the SMC W-R stars into three distinct groups according to absolute visual magnitude. For $M_v < -6$, one finds the single WNL star AB 4 and the four WNE/WO + O binaries AB 5, 6, 7, and 8, in which the fainter, W-R component ($M_v \sim -4$: cf. Lundström and Stenholm 1984) is dominated by the light of the O companion. For $M_v \approx -5$, one finds the second WNL (or possibly Of) star AB 2, and the WNE + O binary AB 3. Finally, at $M_v \approx -4$ one has AB 1; its absolute magnitude is compatible with that of a *single* WNE star. However, allowing for cosmic scatter (2 $\sigma \sim 1$ magnitude in M_v, typically), there is still room for an O companion. More spectroscopic monitoring is needed to check for possible long-period binary motion in AB 1.

In Galactic star clusters, one observes near neighbors to W-R stars with spectral types as late as ~B0 (Moffat and Seggewiss 1979; Lundström and Stenholm 1984). In spectroscopic W-R binaries with established orbits (Massey 1981) the companions are as late as O9. However, in the SMC, all binaries appear to have either O4 (V?) or O6–7 I: companions. This implies that W-R stars originated from more massive progenitors in the SMC ($\gtrsim 50\ M_\odot$) than in the Galaxy ($\gtrsim$20–30 $M_\odot$), assuming (i) that the W-R progenitors in binaries were at least as massive as their *present* secondaries, and (ii) that there is a unique relation between spectral type and mass for O stars in both galaxies. Why SMC W-R stars had more massive progenitors may be due to the lower metallicity Z, and hence lower mass-loss rates, in the SMC: to reach

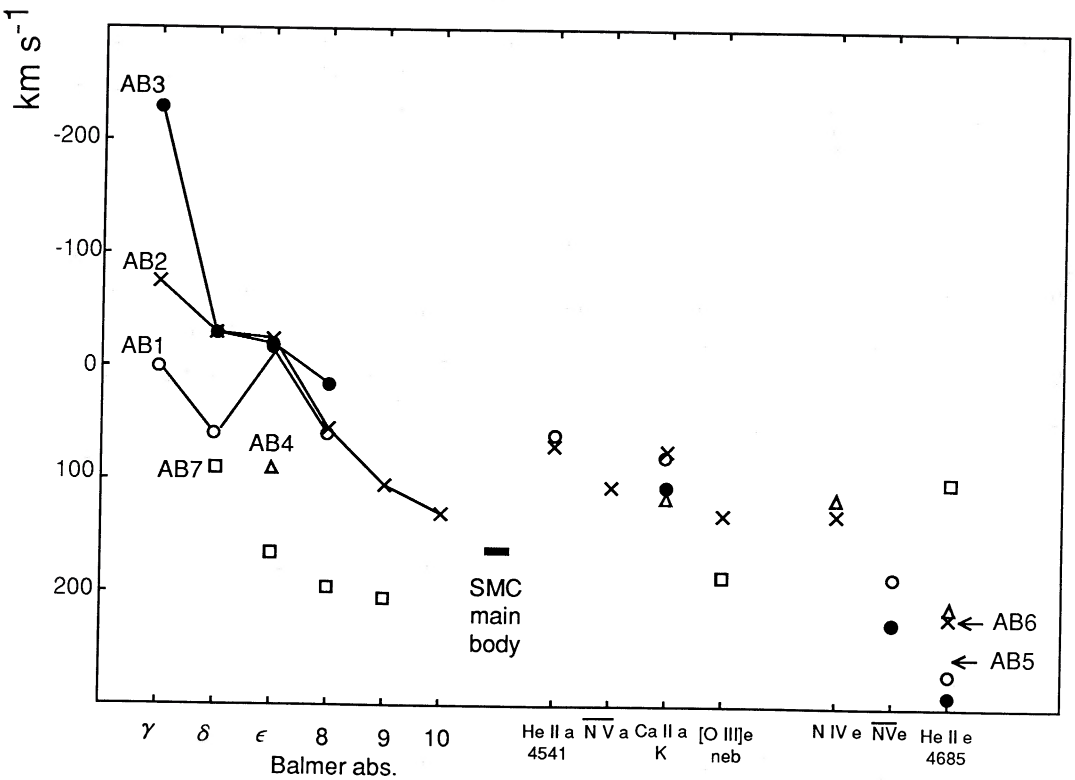

FIG. 5.—Mean or systemic γ radial velocity for different lines compared to the mean RV of the main body of the SMC, 163 ± 3 km s^{-1} (Ardeberg and Maurice 1979). Systemic velocities of He II 4685 emission (*arrows*) are also shown for the binaries AB 5 (Paper II) and AB 6 (Paper I).

the W-R stage still requires high mass loss—SMC W-R stars thus make up for their low Z by evolving only from more massive, luminous progenitors than in the Galaxy.

Originally it was hoped that the present observations would provide additional information on the mass ratio $Q = M(\text{W-R})/M(\text{O})$ in W-R binaries. However, the two newly detected binaries, AB 3 and AB 7, are problematic, while AB 5 shows anomalous behavior. There remain only the two relatively well-determined ratios for AB 6 and AB 8, with $Q = 0.17 \pm 0.03$ and $Q = 0.27 \pm 0.08$, respectively. As noted by Moffat (1981, 1982*a*) and Moffat *et al.* (1986*a*), low-mass ratios like these are typical for Galactic and Cloud WNE and WCE systems, which have probably evolved via mass loss from more massive WNL (and sometimes WCL, for the WCE stars depending on Z) progenitors. Evolution *directly* from WNL to WCE or WO (i.e., without passing through an intermediate WNE or WCL phase) appears unlikely, however, in view of the extreme difference in line widths, mass ratios, and luminosities between WNL and WCE/WO stars.

Finally, note is made of the relatively weak emission lines (other than He) generally seen in the SMC W-R stars, compared to Galactic and even LMC W-R stars of similar types. Even in some WNE stars the winds may be thin enough that we *may* be seeing photospheric absorption lines (e.g., AB 1). Evidence for differential depletion of the heavier metals in the SMC and thus lower mass-loss rates has recently been uncovered from UV observations of the wind eclipses in AB 5 (Koenigsberger, Moffat, and Auer 1987).

I have greatly appreciated the warm hospitality at CTIO, as well as the generous allotments of PDS time and support at the DDO. Financial support is greatelly acknowledged from the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

Abbott, D. C., and Conti, P. S. 1987, *Ann. Rev. Astr. Ap.*, **25**, 113.
Ardeberg, A., and Maurice, E. 1970, *Astr. Ap.*, **77**, 277.
Azzopardi, M., and Breysacher, J. 1979, *Astr. Ap.*, **75**, 120.
Azzopardi, M., Lequeux, J., and Maeder, A. 1987, preprint.
Breysacher, J., Moffat, A. F. J., and Niemela, V. S. 1982, *Ap. J.*, **257**, 116.
Hidayat, B., Admiranto, A. G., and van der Hucht, K. A. 1984, *Ap. Space Sc.*, **99**, 175.
Hutchings, J. B. 1976, *Ap. J.*, **203**, 438.
Hutchings, J. B., Crampton, D., Cowley, A. P., and Thompson, I. B. 1984, *Pub. A.S.P.*, **96**, 811.
Koenigsberger, G., Moffat, A. F. J., and Auer, L. H. 1987, *Ap. J.* (*Letters*), **322**, L41.
Lundström, I., and Stenholm, B. 1984, *Astr. Ap. Suppl.*, **58**, 163.
Maeder, A., and Meynet, G. 1987, *Astr. Ap.*, **182**, 243.
Massey, P. 1981, *Ap. J.*, **246**, 153.
Moffat, A. F. J. 1981, in *IAU Colloquium 59, Effects of Mass Loss on Stellar Evolution*, ed. C. Chiosi, R. Stalio (Dordrecht: Reidel), p. 301.
———. 1982*a*, in *IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolution*, ed. C. W. H. de Loore and A. J. Willis (Dordrecht: Reidel), p. 515.
———. 1982*b*, *Ap. J.*, **257**, 110.
Moffat, A. F. J., Breysacher, J., and Seggewiss, W. 1985, *Ap. J.*, **292**, 511.
Moffat, A. F. J., Lamontagne, R., Shara, M. M., and McAlister, H. A. 1986*a*, *A.J.*, **91**, 1392.
Moffat, A. F. J., Niemela, V. S., Phillips, M. M., Chu, Y.-H., and Seggewiss, W. 1987, *Ap. J.*, **312**, 612.
Moffat, A. F. J., and Seggewiss, W. 1979, *Astr. Ap.*, **77**, 128.

Moffat, A. F. J., and Seggewiss, W. 1986, *Ap. J.*, **309**, 714.
Moffat, A. F. J., Vogt, N., Paquin, G., Lamontagne, R., and Barrera, L. H. 1986*b*, *A.J.*, **91**, 1386.
Schmidt-Kaler, Th. 1982 in *Landolt-Bornstein*, ed. K. H. Hellwege (Berlin: Springer), New Ser., Group 6, Vol. 2b, p. 1.
Seiden, P. E., and Gerola, H. 1982, *Fund. Cosmic Phys.*, **7**, 241.
Smith, L. F. 1968, *M.N.R.A.S.*, **138**, 109.
Smith, L. F., and Kuhi, L. V. 1981, *JILA Rept.*, No. 117.
van der Hucht, K. A., Conti, P. S., Lundström, I., and Stenholm, B. 1981, *Space Sci. Rev.*, **28**, 227.
Walborn, N. R. 1977, *Ap. J.*, **215**, 53.
———. 1986, in *IAU Symposium 116, Luminous Stars and Associations in Galaxies*, ed. C. W. H. de Loore, A. J. Willis and P. G. Laskarides (Dordrecht: Reidel), p. 185.

ANTHONY F. J. MOFFAT: Département de Physique, Université de Montréal, C.P. 6128, Succ. A, Montréal, P.Q., HC3 3J7, Canada