THE ASTROPHYSICAL JOURNAL, 337:251–271, 1989 February 1

SPECTROSCOPIC STUDIES OF WOLF-RAYET STARS. IV. OPTICAL SPECTROPHOTOMETRY OF THE EMISSION LINES IN GALACTIC AND LARGE MAGELLANIC CLOUD STARS

PETER S. CONTI[1]
Joint Institute for Laboratory Astrophysics, University of Colorado and National Bureau of Standards,
Department of Astrophysical, Planetary, and Atmospheric Sciences, University of Colorado

AND

PHILIP MASSEY[1]
Kitt Peak National Observatory, National Optical Astronomy Observatories
Received 1988 April 22; accepted 1988 July 8

ABSTRACT

We present spectrophotometry of the leading emission-line features for nearly all the Wolf-Rayet stars in the Galaxy and in the Large Magellanic Cloud (LMC). These form the empirical basis of the normal relationships among the various lines. Emission lines have a *wide range* of strengths, but all lines in a given star are strong or weak together, aside from the well-understood ionization effects. We present the first extensive data of the N IV $\lambda 3480$ feature in WN stars. This line persists to earlier types than does the singlet N IV $\lambda 4057$ line, probably due to decreasing optical depth in the latter transition. Among those very few WN stars with anomalous lines, there are eight objects, mostly single stars, with inordinately strong C IV; we label them "WN/WC" and suggest that they have a "transition" composition between the WN and WC subclasses. We give quantitative descriptions of "early" (WNE; WCE) and "late" (WNL; WCL) types for the WN and WC classes, respectively. Among WC stars, the persistence of the C III $\lambda 4650$ feature to the earliest subtypes (where C III $\lambda 5696$ has already disappeared) suggests the importance of the contribution of C IV $\lambda 4658$ to the blend, *or* an anomalous triplet-singlet behavior in the C III ions similar to that observed in N IV in the WN sequence. We compare the emission-line fluxes of He II $\lambda 4686$ with the M_v for the WN stars of the LMC. Aside from the ionization effects, there is a nice correlation of these parameters since brighter stars have more continuum flux present at 4686 Å. Although WCL stars have not been found in the LMC, the line strengths of the other W-R stars are very similar in that system and in our own Galaxy.

Subject headings: galaxies: Magellanic Clouds — spectrophotometry — stars: stellar statistics — stars: Wolf-Rayet

I. INTRODUCTION

This is a continuation of a series of papers devoted to investigations of the spectra of Wolf-Rayet (W-R) stars. Our previous papers have involved analysis of the emission-line spectra of many of these same objects obtained with moderately high dispersion image-tube spectrograms. Here we present spectrophotometry of the leading emission lines of most of the known W-R stars in the Galaxy and in the LMC from instruments which are "linear detectors." The spectral resolutions are not as high as in our previous studies but are similar to those in which spectra of stars in other galaxies have been obtained (e.g., Massey, Conti, and Armandroff 1987). These studies are intended to form the basis for defining quantitatively the "normal" framework of line strengths for comparison with stars in other galaxian environments.

W-R stars are believed to be the endpoints of evolution of the most massive stars (Conti *et al.* 1983) and display very complex physical phenomena in their inordinately strong stellar winds. Their optical spectra are, in fact, dominated by the properties of the wind itself and appear to be only loosely coupled to the stellar parameters of mass and luminosity. The classification scheme for W-R stars is based upon the appearance of these optical emission lines, coming from ions of helium, carbon, nitrogen, and oxygen. These stars have been arranged into two sequences (Beals and Plaskett 1935), one in which the helium and nitrogen lines dominate (the WN classes), and one in which helium, carbon and oxygen ions are found (the WC classes). A newly identified but sparsely populated category related to the WC class, in which strong oxygen lines are found, is called WO (Barlow and Hummer 1982).

The W-R stars can be further subdivided into higher and lower excitation subtypes, depending on the strengths of various ions of helium (He I, He II), nitrogen (N III, N IV, N V), carbon (C II, C III, C IV), and oxygen (O III, O IV, O V, O VI). These range from WN 2, WN 3, ..., to WN 9, and WC 4, WC 5, ..., to WC 9 (van der Hucht *et al.* 1981). In analogy with MK terminology, the high-excitation and low-excitation subtypes are called "early" and "late" types, respectively. Presumably the ionization sequences also correspond to a run of effective temperatures, but this latter parameter is not yet well determined quantitatively.

The WN and WC sequences depict different elemental abundances, the former displaying the properties of core hydrogen-burning "CNO equilibrium" values, and the latter that of the even more highly evolved helium-burning material (e.g., Smith and Willis 1982). The absence of hydrogen in WC stars (Willis 1982) and weak appearance in less than half of the WN stars (Conti, Leep, and Perry 1983; hereafter Paper I) lends additional credence to the idea that these objects are highly evolved. Individual W-R stars exhibit different M_v, as shown by their apparent magnitudes and membership in Galactic

---

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

clusters and associations with known distances (Lundstrom and Stenholm 1984*b*) and in the Magellanic Clouds (Prevot-Burnichon *et al.* 1981; Breysacher 1986; Torres-Dodgen and Massey 1988). There is a spread of several magnitudes among the different subtypes and also one within a given subtype for the WN stars which are somewhat heterogeneous in their appearances (Paper I). There are smaller differences in the WC classes, which appear more homogeneous in their properties (Torres, Conti, and Massey 1986; hereafter Paper III).

This one-dimensional empirical spectral classification currently in use depends on the properties of the wind. A central question which is as yet unresolved is the relationship of this wind classification to the underlying star. In this paper we will discuss spectrophotometry of the strongest emission lines, which are often the only lines that can be observed in W-R stars of more distant galaxies of the Local Group (Massey, Conti, and Armandroff 1987). This paper will present the quantitative connections among the leading emission lines to define the "normal" correlations for them.

In § II we outline the observational program and discuss the data reduction procedure; in § III the data analysis is described. The main results of this investigation for the WN and WC stars are contained in § IV. There we discuss the relationships among the line strengths, expressed in terms of the [log] equivalent widths (EWs) of the leading lines in the various subtypes. In § V, we discuss the nature of the subset of so-called WN + WC stars, those objects showing emission lines of both the nitrogen and carbon sequences. We will argue that in most cases, if not all, these are single stars that have a surface (stellar wind) composition containing "CNO equilibrium" hydrogen-burned material with an admixture of helium-burned, carbon-rich matter. In addition to the equivalent width measurements, the strength of the emission features may be expressed in terms of the actual line fluxes, in units of ergs s^{-1} cm^{-2}. We give these measurements in § VI for several lines of the WN stars in the LMC and show that the flux in the He II λ4686 line is roughly proportional to M_v over a range of a few magnitudes. In § VII we briefly discuss the Galactic distribution of the WNE and WNL stars, along with the WCE and WCL objects, and compare it to what is found in other galaxies. We then consider the implications for the evolution of the W-R classes.

One of the questions we wished to address in this investigation was whether or not the emission lines of a W-R star are correlated in line strength, that is, are they all strong or weak together? We will demonstrate that, aside from well-understood differences in ionization balance in the wind, the emission features do behave in an organized fashion, with very few exceptions. We will note anomalies of individual ions to the main trends where they occur. We will also point out that the line strengths in W-R stars form a continuum from the strongest lined stars to the weakest.

II. OBSERVATIONS AND REDUCTION

The observations reported herein were obtained from 1981 to 1986 using the facilities of both KPNO and CTIO. The absolute spectrophotometry was used to discuss the continuum colors ("line-free") *ubvr* colors of the Galactic stars, and intrinsic colors and absolute magnitudes of the LMC W-R stars by Massey (1984) and Torres-Dodgen and Massey (1988), who give ample descriptions of the observational procedures and reduction techniques. Additional details can also be found in Massey, Conti, and Armandroff (1987), including a comparison of equivalent widths made with the different instrumentation. Here we will just briefly summarize the procedures.

The data on the "northern hemisphere" (generally $\delta > -25°$) were obtained primarily with the intensified reticon scanner (IRS) on the KPNO No. 1 0.9 m and No. 2 0.9 m telescopes. These data were obtained over several years with many repeated observations. The spectra measured in the current paper were the combination of the photometric data with that obtained under nonphotometric conditions added in by first applying grayshifts; these data and the reduction procedures given in Torres and Massey (1987). A very few of the fainter Galactic stars were observed with the KPNO 4 m telescope and intensified image disector scanner (IIDS), and these observations were described qualitatively by Massey and Conti (1983*a*).

The southern Galactic stars and those in the LMC were observed at CTIO using the 1.5 m and the SIT–Vidicon detector. These data were also obtained over several years and on multiple observing runs, and the data for which we describe line fluxes were all of good photometric accuracy. Recent detailed descriptions can be found in Torres-Dodgen and Massey (1988).

III. DATA ANALYSIS

The equivalent widths and the full widths at half-maximum, expressed here as log (−EW) [Å] and FWHM [Å], respectively, were derived using the interactive IRAF software package running on the JILA VAX 8600 computer in Boulder. In this package these quantities are computed by separate algorithms; the former from numerical integration over the line, the latter from fitting a Gaussian to the profile. The Gaussian approximation was found to be quite adequate for most lines in most stars by actual inspection during the interactive process. We had also found this to be true in our previous studies (Papers I and III).

In order to give consistency from one wavelength region to another in setting the continuum level, we normalized the spectra using an IRAF routine. This was accomplished by using a third-order cubic spline fitted to regions of the spectrum judged by eye to be free of lines. Several emission-line features were also measured in the LMC WN stars from unnormalized spectra in order to determine the line fluxes; the derived equivalent widths were similar to those from the normalized continua. The choice of a smooth continuum level was relatively easy and was not felt to be a critical problem in determining the parameters of the strong emission lines discussed here, even though it is the most arbitrary decision to be made. We will shortly show that the uncertainties are typically ~30%. This is potentially a more serious issue when evaluating weaker emission lines as in our previous work.

The (log) equivalent width [Å] measures of the leading emission lines in the WN types are presented in Tables 1 and 2 for the Galactic and LMC stars. The spectral types are taken from van der Hucht *et al.* (1981) for the Galactic stars, with additions or revisions by Massey and Conti (1983*b*), and those for the LMC from Breysacher (1981), with additions or revisions by Massey and Conti (1983*a*) or Paper I. A very few other revised types herein are indicated by the footnotes to the tables.

A comparison of measures of the He II λ4686 and λ5411 emission-line equivalent widths in the WN stars with the previous data (Paper I: note the published values were in units of mÅ) was instructive. With the exception of a very few "outlier"

TABLE 1

LINE STRENGTHS (log EW) IN GALACTIC WN STARS

WR#	Star	Sp	4686	FWHM^a	NIII/V	5411	CIV	HeI	NIV	Remarks
1	HD4004	WN5	2.69	42 E	1.82	1.86	1.80	1.30	1.90	
2	HD6327	WN2	2.30	63 E	-	1.52	-	-	-	
"	"	"	2.20	61 "	-	-	-	-	-	
3	HD9974	WN3+abs	1.74	42 E	1.59	0.87	n	-	0.91	
7	HD56925	WN4	2.66	32 E	1.91	1.89	1.77	p	-	
"	"	"	2.57	36 "	1.83	1.87	1.63	p	1.92	
8	HD62910	WC4/WN6	2.04	28 -	-	1.30	2.14	1.58	-	4650 2.48
"	"	"	2.00	29 -	-	1.23	2.07	1.46	1.46	4650 2.42
10	HD65865	WN4.5	1.68	22 -	BLEND	0.89	p	-	0.97	
12	MR13	WN7	1.86	20 L	1.58	1.01	-	1.40	0.72	
18	HD89358	WN5	2.62	49 E	1.83	1.81	1.80	p	-	
20	BS1	WN4.5	2.25	27 -	BLEND	1.56	1.47	0.89	1.49	
21	HD90657	WN4 + O4	1.71	30 E	0.96	0.81	0.79	-	1.06	
26	MS1	WCE/WN5	2.68	61 -	-	1.91	2.99	p	1.59	4650 2.45
28	MS2	WN7	1.73	21 L	1.20	1.04	0.67	0.48	0.64	
29	MS3	WN7	1.43	21 L	0.91	0.61	-	p	-	
31	HD94546	WN4 + O7	2.54	24 E	1.07	Blue region only			1.75	
34	LS5	WN4.5	2.22	24 -	BLEND	Blue region only			1.56	
35	MS6	WN6	1.94	21 L	1.42	1.21	0.81	0.75	0.93	
36	LS6	WN4	2.37	43 E	1.60	1.59	1.47	1.48	p	
37	MS7	WN3	2.50	44 E	1.67	1.89	1.86	p	1.89	
40	MR34	WN8	1.68	17 L	1.59	0.78	p	1.61	0.80	
43	HD97950	WN6 + abs	1.14	35 L	0.68	-	-	-	0.50	Composite
44	MR39	WN4	2.19	30 E	1.42	Blue region only			1.74	
46	HD104994	WN3p	1.97	41 E	1.78	1.28	n	n	0.66	OVI Present
47	HDE311884	WN6 + O5	1.91	26 L	1.38	1.16	0.86	0.92	0.70	
49	LSS 2979	WN5	2.14	26 -	BLEND	1.41	1.00	0.37	1.39	
51	MR45	WN4	2.05	28 E	1.35	1.31	0.96	p	1.56	
54	MR48	WN4	2.15	26 E	1.54	Blue region only			1.59	
55	HD117688	WN7	2.13	21 L	1.90	1.35	1.09	1.33	0.94	
58	MR51	WN4/WCE	2.51	36 -	1.91	1.82	2.15	p	-	
61	MR53	WN6	2.23	28 L	1.68	1.51	1.39	0.88	-	
62	NS2	WN6	2.35	36 L	1.99	Blue region only			1.98	
63	LSS 3289	WN7	1.65	20 L	1.46	1.10	0.79	1.02	1.01	
66	HD134877	WN8	1.66	21 L	1.61	0.96	-	1.29	-	
67	MR55	WN6	2.11	24 L	1.76	1.40	1.15	0.96	1.33	
71	HD143414	WN6	2.18	24 L	1.86	1.48	1.05	1.06	1.34	
74	BP1	WN7	1.84	20 L	1.85	1.15	0.90	1.26	-	
75	HD147419	WN6	2.51	49 -	BLEND	1.81	1.37	1.68	-	
82	LS11	WN8	1.88	19 L	1.83	1.09	-	1.35	0.97	
83	MR67	WN6	2.08	24 L	1.70	1.33	0.90	p	1.50	
84	LS12	WN6	1.99	20 L	1.84	1.40	1.09	1.30	1.24	
85	HD155603B	WN6	1.95	20 L	1.74	1.19	0.68	0.74	1.18	
87	LSS 4064	WN7	1.33	20 L	1.30	0.22	0.46	0.26	-	
89	LSS 4065	WN7	1.30	16 L	1.23	-	-	0.47	-	
91	StSa1	WN7	2.24	58 L	1.92	1.60	1.18	1.67	-	
94	HD158860	WN6	2.08	25 L	1.65	Blue region only			1.52	
97	HDE320102	WN3+abs	1.36	34 -	BLEND	0.57	0.53	p	0.73	
98	HDE318016	WC7/WN6	1.78	24 -	-	1.11	1.56	1.46	-	4650 2.13
100	HDE318139	WN6	2.13	31 L	1.92	Blue region only			1.45	
105	NS4	WN8	1.03	15 L	1.18	-	-	1.21	-	
"	"	"	1.23	18 L	1.35	-	-	1.26	-	
107	DA1	WN7-8	1.63	15 L	1.72	Blue region only			-	
108	LS14	WN9	0.96	13 L	1.16	-	-	0.61	-	

TABLE 1—*Continued*

WR#	Star	Sp	4686	FWHM[a]	NIII/V	5411	CIV	HeI	NIV	Remarks
"	"	"	1.03	18 "	1.10	-	-	0.81	-	
110	HD165688	WN6	2.55	58 E	1.95	1.88	1.63	1.69	-	
"	"	"	2.61	58 "	1.98	1.84	1.52	1.63	1.79	
115	MR87	WN6	2.05	24 L	1.72	1.27	1.13	1.02	-	
116	St1	WN8	1.54	21 L	1.63	-	-	1.77	-	
120	MR89	WN7	1.90	20 L	1.85	1.19	0.72	1.36	-	
123	HD177230	WN8	1.36	13 L	1.58	Blue region only			0.51	
"	"	"	1.62	17 "	1.74	0.86	-	1.58	0.66	
124	209 BAC	WN8	1.57	19 L	1.67	0.62	-	1.72	-	
127	HD186943	WN4 + O9	1.82	32 E	1.00	1.08	0.82	-	1.21	
128	HD187282	WN4	2.04	32 E	1.40	1.21	0.92	-	1.44	
129	MR96	WN4	2.27	28 -	BLEND	1.65	1.53	p	1.75	
130	LS16	WN8	1.66	20 L	1.58	0.80	-	1.27	-	
131	MR97	WN7+abs	1.59	20 L	1.26	0.88	-	0.67	-	
133	HD190918	WN4.5+O9.5I	1.33	29 E	0.57	0.75	p	p	0.76	
134	HD191765	WN6	2.64	43 -	BLEND	1.95	1.57	1.48	1.85	
136	HD192163	WN6	2.58	34 L	2.07	1.92	1.44	1.50	1.72	
138	HD193077	WN5 + abs	1.83	25 L	1.26	1.15	0.86	-	1.13	
139	V444 CYG	WN5 + O6	1.83	29 L	1.10	1.12	1.06	0.56	1.17	
141	HD193928	WN6	2.36	31 L	1.71	1.62	1.45	1.08	1.49	
145	MR111	WN/WCE	1.74	28 -	-	1.13	1.84	1.15	-	4650 1.66
147	NS6	WN8	1.50	17 L	1.36	-	-	1.74	-	
148	HD197406	WN7	1.35	15 L	1.00	0.37	-	0.73	-	
149	St4	WN6	2.30	24 L	1.69	1.75	1.60	p	-	
151	CX CEP	WN4 + O8	2.00	28 -	BLEND	1.27	1.10	0.59	1.22	
152	HD211564	WN3	2.04	33 E	1.49	1.30	0.64	-	1.51	
153	GP CEP	WN6/WCE+O	1.68	31 -	1.10	0.95	1.44	p	0.81	
155	CQ CEP	WN7 + O	1.53	23 L	1.07	0.63	-	0.27	-	
156	MR119	WN8	1.47	21 L	1.60	0.39	-	1.18	-	
157	HD219460	WN4.5 (+ B)	1.57	24 -	BLEND	0.82	0.66	-	0.87	
158	MR122	WN7	1.49	16 L	1.31	0.61	-	0.74	-	

NOTES:—WR8: OV 1.09, 5696CIII 0.96; WR37, anomalously broad CIV; WR43, WR55 Spectral type from LS; WR 61: Spectral type from Paper I; WR98 5696CIII 1.43 (Lundstrom and Stenholm 1984*a*); WR147 new spectral type; WR157 "(+abs)" spectrum from close VB companion; WR151 new spectral type (see also Massey 1984).

[a] Units of FWHM are angstroms; E is WNE type; L is WNL type.

points, which may be transcription or measuring errors or potentially attributed to variability and were thus disregarded, the random rms "scatter" seemed to be ~0.1 dex but a little larger for the λ4686 line, possibly due to it frequently being located near the edges of the image-tube plates (Paper I) where the exposure level is falling off dramatically. There was no systematic difference in the comparison of line strength measures of "single" stars and those of the "binary or composite" systems. The data being compared were taken at different times and were reduced in a completely independent manner; the fact that the line strengths are in nearly all cases typically within 30% of one another argues that spectral variability above this level is not significant for most W-R stars, even for the known binaries!

Our new data exhibit systematically larger values of line strength, by +0.15 dex for λ4686 and +0.05 dex for λ5411. One would naively expect that using the higher resolution photographic data (Paper I) would lead to choosing the continuum to have a lower relative value, due to the ease in recognizing weaker emission features. This would result in finding larger line strengths on the image-tube plates, contrary to what is observed. An explanation of the discrepancy must thus lie elsewhere. There is no systematic difference in the comparison between the Galactic and LMC values for the λ5411 feature; for λ4686, the LMC photometric values were even more (+0.05 dex) positive with respect to the photographic. We have no ready explanation for this difference. We believe that our published line strengths have associated random and systematic errors of the order of 0.10 dex or 30% each. These numbers should be kept in mind in what follows: however, all the conclusions which we will subsequently draw from the data concerning anomalies will be based on considerably larger differences than these.[2]

The FWHM were extracted from the normalized spectra using the Gaussian fits. The line widths of the WN stars were not discussed in Paper I, so a comparison of our data with the photographic results is not possible. However, the FWHM of the WC stars was given in Paper III. A comparison was carried out, with the result that the new data are some 300 km s^{-1} larger. Measurement differences such as these will not affect any of the conclusions we will wish to draw from the line widths.

---

[2] Dr. Werner Schmutz has kindly compared our data with his ESO IDS and CALAR ALTO CCD results for some 30 W-R stars in common. The systematic agreement is excellent, within a few hundreths DEX for several select lines.

TABLE 2

LINE STRENGTHS (log EW) IN LMC WN STARS

Br#	Star	Sp	4686	FWHM[a]	NIII/V	5411	CIV	NIV	HeI
1	-70 1	WN3	2.54	38 E	1.82	1.95	n	1.29	n
3	WS1	WN4	2.44	32 E	1.74	1.84	1.47	1.88	p
4	AB15	WN2	2.19	38 E	-	1.59	-	-	-
6	HD32109	WN2.5	2.65	65 E	P	1.98	1.66	1.75	p
12	HDE268847	WN4	2.52	36 E	1.77	1.83	1.72	1.90	1.36
13	HD33133	WN8	1.91	20 L	1.54	1.20	n	1.01	1.47
14	HDE269015	WN4	2.21	32 E	1.55	1.59	1.48	1.68	p
15	-70 64	WN4	2.11	29 E	1.34	1.36	1.16	1.62	n
16	HD34187	WN2.5	2.28	42 E	1.33	1.63	1.36	1.52	-
18	HDE269227	WN9	0.96	23 L	1.18	n	-	-	0.93
19	WS13	WN4	2.61	53 E	1.89	1.95	1.43	1.91	1.24
20	WS14	WN4	2.36	31 E	1.70	1.74	1.65	1.91	p
21	HDE269333	B1Ia + WN3	1.20	39 E	0.31	n	n	0.62	-
23	WS17	WN3	2.37	31 E	1.66	1.70	1.44	1.73	0.96
24	WS18	WN7	1.91	19 L	1.37	1.17	-	0.93	-
25	AB16	WN3	2.43	33 E	1.74	1.78	1.68	1.83	n
26	HD36063	WN7	2.02	24 L	1.16	1.35	1.06	1.08	1.05
27	WS20	WN3	2.29	32 E	1.68	1.62	-	1.75	-
29	HDE269485	WN3/WCE	2.48	43 -	1.61	1.72	2.78	1.88	-
33	AB1	WN3 + abs	1.87	28 E	0.87	1.09	1.24	1.16	-
34	HDE269546	B3I + WN3	1.11	60 E	-	-	-	0.23	-
35	HDE269549	WN4	2.53	29 E	1.70	1.80	1.77	1.89	-
36	WS27	WN8	1.59	15 L	1.41	0.86	n	0.64	1.04
37	WS28	WN3 + abs	2.01	28 E	1.08	Blue only		1.39	-
38	AB2	WN4	2.22	31 E	1.48	1.51	1.15	1.53	-
40	HDE269264	WN4	2.56	33 E	1.87	1.83	1.74	1.90	p
42	WS30	WN3	2.50	48 E	1.61	1.91	n	1.70	0.99
45	WS33	WN3	2.59	34 E	1.95	1.82	1.64	1.85	n
46	HDE269692	WN4	2.39	32 E	1.78	1.66	1.20	1.80	n
47		WN8	1.68	18 L	1.20	0.90	-	-	0.87
48	HDE269748	WN3 + abs	1.63	31 E	0.98	1.05	0.64	1.02	n
49	-69 183	WN3 + abs	1.63	29 E	0.76	Blue only		1.13	-
51	-66 156	WN3	2.16	30 E	1.67	1.51	-	1.65	-
52	FD47	WN4 + abs	1.90	30 E	1.02	1.00	-	1.17	-
54	-67 213	WN3	1.94	32 E	1.41	1.36	-	-	-
56		WN6	1.67	30 L	0.67	1.00	-	0.92	-
57		WN7	1.60	20 L	1.23	0.82	0.28	0.69	1.01
58		WN5-6	1.45	24 -	-	-	-	1.02	-
60	AB5	WN3	1.73	26 E	0.97	0.86	-	-	-
64	BE381	WN9	1.26	21 L	1.28	-	-	-	1.20
66	AB8	WN3	2.47	34 E	1.63	1.76	-	1.11	-
69	AB9	WN4	2.06	30 E	1.43	1.50	-	1.60	-
72	HDE269891	B1I+WCE/WN3	1.24	53 -	-	-	1.87	-	
80	R135	WN7	2.19	30 L	1.54	1.45	1.17	0.81	1.63
82	R136	OB + WN5-6	1.13	35 -	-	-	-	-	Composite
85	HDE269908	WN3-4p	2.67	53 E	1.73	1.97	1.89	1.90	n
88	R146	WN4.5 + abs	1.59	33 -	-	0.57	-	0.98	-
89	HD38282	WN6	1.93	23 L	1.07	1.05	0.68	-	0.79
90	HDE269928	WN6	1.87	23 L	1.23	1.09	0.79	0.56	0.73
92	HD38344	WN6	1.93	24 L	0.89	1.17	0.66	0.91	n
99	WS51	WN4	2.53	33 E	1.70	1.69	-	1.89	n
100	HDE270149	WN4	2.52	36 E	1.72	1.81	1.52	1.86	p

NOTE.—Br 3, Br 46, Br 56, Br 57: new spectral types.

[a] Units of FWHM are angstroms; E is WNE type; L is WNL type.

IV. LINE PARAMETERS

a) WN Stars

In Tables 1 and 2 we have presented the line strengths, in units of log EW, of the leading lines λ4686 and λ5411 of He II; the λ4604, λ4620 blend of N V or the λ4634, λ4640 blend of N III; the λ3478, λ3483 blend of N IV; and the λ5801, λ5812 blend of C IV in WN stars. We also give the FWHM of He II λ4686 since it is representative of a single feature. What relationships exist among the strengths of these various ions? Examination of the various combinations of line strengths, and line widths, will enable us to see if systematic trends are apparent so as to define what will be referred to as "normal" behavior.

In the early WN stars, the N V blend dominates the emission-line feature found immediately shortward of He II λ4686; in the late WN types, the N III blend is the stronger. In Paper I, the resolution was sufficient that these two blends could each be separately measured—in fact, the N V blend itself was resolved into its two components. With our resolution here, only the overall wavelength could be measured (to an accuracy of a few angstroms or so). The measured wavelengths of this feature ranged from 4605 to 4647 Å, with values clustering near 4610 Å for the early-type WN stars and near 4635 Å for the later types (we have ignored possible differences from the intrinsic wavelength due to the line-of-sight velocity of the star). The LMC stars fell into two very separate groups of wavelength measures in which either the N V or the N III clearly dominated. Curiously, in the Galactic stars the measured wavelengths were spread more evenly between the extrema. It was possible to assign a wavelength of 4621 Å as the largest to be associated with N V being the primary contributor, and 4628 Å as the smallest to be due to N III alone by reference to the separate nitrogen ion measures in Paper I. There were eight Galactic stars in which the blend appears to have more or less equal contribution by both ionization stages from our wavelength measures, but all LMC stars could be identified with one group or the other.

The terms WNL and WNE were first introduced by Vanbeveren and Conti (1980) as a shorthand for "late" and "early" subtypes, the former being defined as the WN 7, WN 8, and WN 9 stars, the latter the other types. Subsequently the abbreviations WNE and WNL have come into general usage, not always consistently with these precepts, particularly when discussing stellar evolution scenarios. For example, some authors define the WNL stars as those with hydrogen and the WNE as those without this element. This is demonstrably not correct. Massey and Conti (1980) and Conti, Leep, and Perry (1983) have shown that some WNL stars (e.g., HD 177230, WN 8) show no evidence of hydrogen, and some WNE (e.g., HD 187282, WN 4) clearly do have this element present as indicated by the Balmer/Pickering emission decrements. It is true that most WNL have spectroscopic evidence of hydrogen and most WNE do not, but it is not yet firmly established that the latter have no hydrogen; Conti *et al.* suggested values of H/He of 0.1 or less (by number) for the stars with no Balmer/Pickering decrement, but the actual value may not be identically zero.

In this paper, we will define the WNE and WNL types quantitatively by using the measured wavelength of the N III/N V feature: if N III dominates, we call the star WNL and use an "L" in column (6) of Table 1 or 2; if N V, we use the term WNE and the letter "E"; if intermediate, we use neither an "L" nor an "E" but use the word "blend" in column (7). Thus in our terms WN 6 are (mostly) WNL, WN 5 are split between E and L, and nearly all the rest of the stars follow the initial definitions as may be seen by inspection and comparison of columns (6) and (7) in Tables 1 and 2. These same principles to define WNL and WNE have been applied to the WN stars in the Local Group galaxies by Massey, Conti, and Armandroff (1987) and will be useful in other subsequent work on distant WN stars. In our figures to follow, the stars without an "E" or "L" in Table 1 were assigned the letter approximate to their numerical subtype.

Although N IV λ4057 is also an important classification line in WN stars (van der Hucht *et al.* 1981) on our spectra, it was often difficult to disentangle from the usually stronger He II/N III feature near λ4100 and thus not easily measured. Estimates of the line strength have been given in Paper I. In any event, we do have extensive measures of the N IV emission-line feature at 3478 and 3483 Å; this is the first time such data have been presented. The He I feature at 5876 Å is seen in a number of our stars, and its equivalent width is noted in Tables 1 and 2 but only if it was relatively strong and readily measured. In the next few figures we will show the correlation between the line strengths of the He II λ4686 emission line, compared to the He II λ5411 line, or the N V or N III or N IV blends, or the C IV blends. These are intended to establish the "normal" relationships among these leading WN features, and thus to isolate those objects which might have anomalous lines. Stars without detections are not plotted, but their behavior is noted in the text if there is some anomaly. Anticipating the results of § V, we will plot the stars with features intermediate between the WN and WC classes (here WN/WC or WC/WN) separately. The binary or composite stars are not plotted with separate symbols on these figures; in general, these objects have weaker lines than the single stars, but always there is a partial overlap in the strengths between them.

In Figure 1 the relation between the log EW [Å] measures of the two He II lines is plotted. In this and in the following figures, we find that stars with relatively strong or weak He II λ4686 have similar strengths for the other emission features. The line strength is a diagnostic of the wind density primarily, but also depends on the other parameters. The binary or composite systems have the weakest features, only one object having λ4686 stronger than 100 Å [EW], but they otherwise follow the relation of the single stars. We see a graphic demonstration in Figure 1 that the line strengths of He II λ4686 in WN stars form a *continuum* of values from the strongest to the weakest lined stars.

In just about all the stars plotted in Figure 1 the λ4686 line is typically stronger than λ5411 by a factor 5 (0.7 dex). In a few WN 8 or WN 9 stars λ5411 is not found, due to weakness of λ4686 and the low ionization state of the stellar wind. In a few other stars with weak λ4686, the absence of λ5411 is to be expected. The regression relation is along a 45° line but deviates from it at the weak-line end in the sense that λ4686 remains relatively stronger in the single stars. A straightforward explanation is that at the strong-line end both features are optically thick (Paper I), but the λ5411 line starts to become optically thin in the weaker line stars. The rms scatter from the mean relation is ~0.1 dex (30%), which is self-consistent with our expectations of the uncertainties. The agreement between the two He II features for all stars plotted gives us confidence in comparing the strength of other ions with the He II λ4686 line.

Figure 2*a* shows the line strengths of the N V blend com-

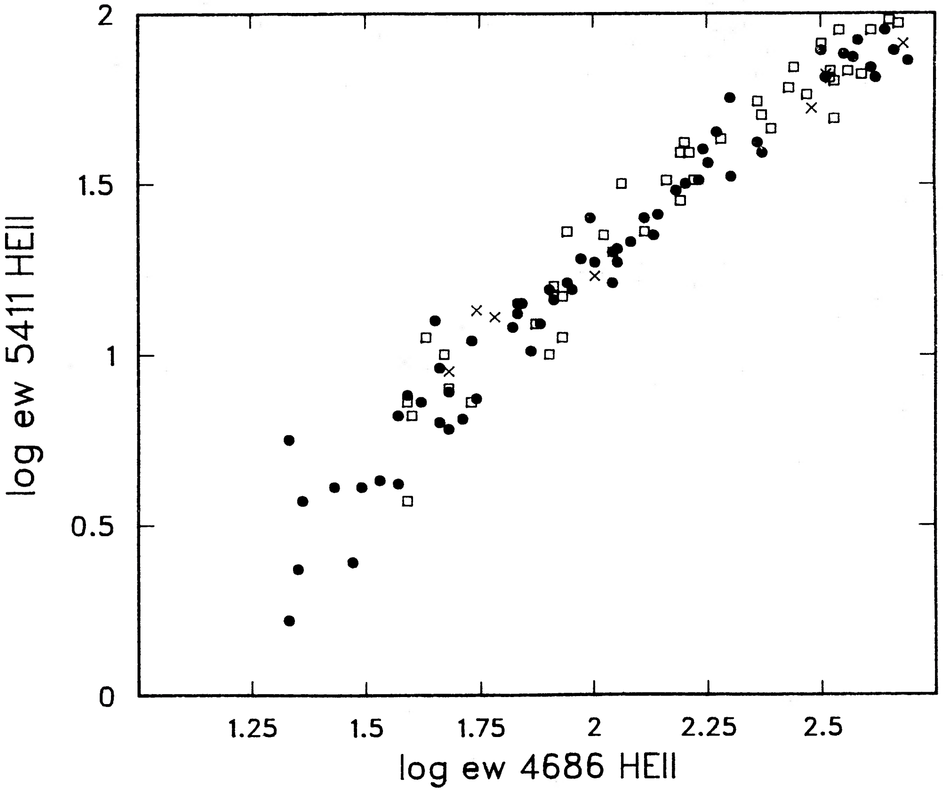

FIG. 1.—Equivalent width (log) comparisons of λ4686 and He II λ5411 in Galactic (*filled circles*) and LMC (*open squares*) WN stars. In this and in all following figures, the Galactic stars are denoted by circles and the LMC stars by squares; WN/WC stars are denoted by "X" (see text).

pared with λ4686 for the "WNE" objects. Nearly all stars fit a relatively well defined regression relation with a scatter of 0.1 dex, about as expected. In the two WN 2 types, N V is absent (a definition of the spectral type). This is an ionization effect: the emission-line spectrum in W-R stars is primarily that of recombination; thus, the population of N VI controls the N V line strength. N V will begin to disappear when the nitrogen begins to become primarily N VII. At first glance this would appear unlikely, given the ionization energy from the ground state of N VI to be 552 eV. However, ionization from the first excited state of N VI appears to be a plausible mechanism as this requires only some 100 eV, although it does require a substantial excited state population.

There are three "outlier" Galactic objects in Figure 2*a* which are sufficiently far from the mean relation that they can be considered anomalous. These include the following: (1) WR 31, having too weak a N V feature compared to λ4686. A careful examination reveals a potential problem with the He II λ4686 line in which it appears to be double. Our measure is inconsistent with the value of Paper I; unfortunately, our spectrum does not include the wavelength region of λ5411 to further check the consistency; (2) WR 46, having too strong a N V for the He II feature. This star, HD 104994, is already known to be peculiar, having a strong O VI emission-line blend at 3814 Å. We will see shortly that the N IV is weak; (3) WR 3, HD 9974, of type WN 3 + abs(orption) which also has strong N V. This is one of the earliest type WN stars in which hydrogen is present from the Balmer/Pickering decrement in the emission-line spectrum (Paper I). It has also been suggested to be a single WN since no binary motion has been found (Massey and Conti 1981).

In summary, among 19 Galactic WNE stars, two have an anomalous N V line strength and one has a peculiar λ4686 feature. Among 29 LMC objects, none appear to deviate appreciably from the normal relationship between He II λ4686 and N V λ4608.

Figure 2*b* shows the relation between He II λ4686 and N III λ4640 for the "WNL" stars which have been separated into WN 5/6/7 and WN 8/9 classes. Here there is substantial scatter compared to the previous figures, and it can be understood as being due to the ionization state of nitrogen. The N III lines weaken with advancing spectral type as the N V or N VI ionization stages begin to dominate.

In Figure 2*b* we have a mixture of subtypes in which the ionization balance of N III is changing relatively rapidly. For example, the WN 5/6/7 subtypes have relatively weak N III, while the WN 8/9 have relatively strong N III as can been seen. The large scatter in Figure 2*b*, due to the ionization effect in nitrogen, makes difficult identifying any possible objects with anomalous lines but note that generally stars with stronger He II also have stronger N III.

We have presented in Tables 1 and 2 the first extensive measurements of the triplet N IV λ3480 feature. How do these compare with the singlet N IV λ4057 line? This line is not readily measured on our spectra given their lower resolution, but we can adopt the values given in Paper I. Figures 3*a* and 3*b* give the comparisons between the triplet and singlet features for the WNE and WNL stars, respectively. There is a wide range in values between the two emission lines, which is somewhat surprising, given their origin in the same ion. In the WNL stars there is a very rough correlation but with a substantial scatter; the λ3480 emission is invariably the stronger. In the

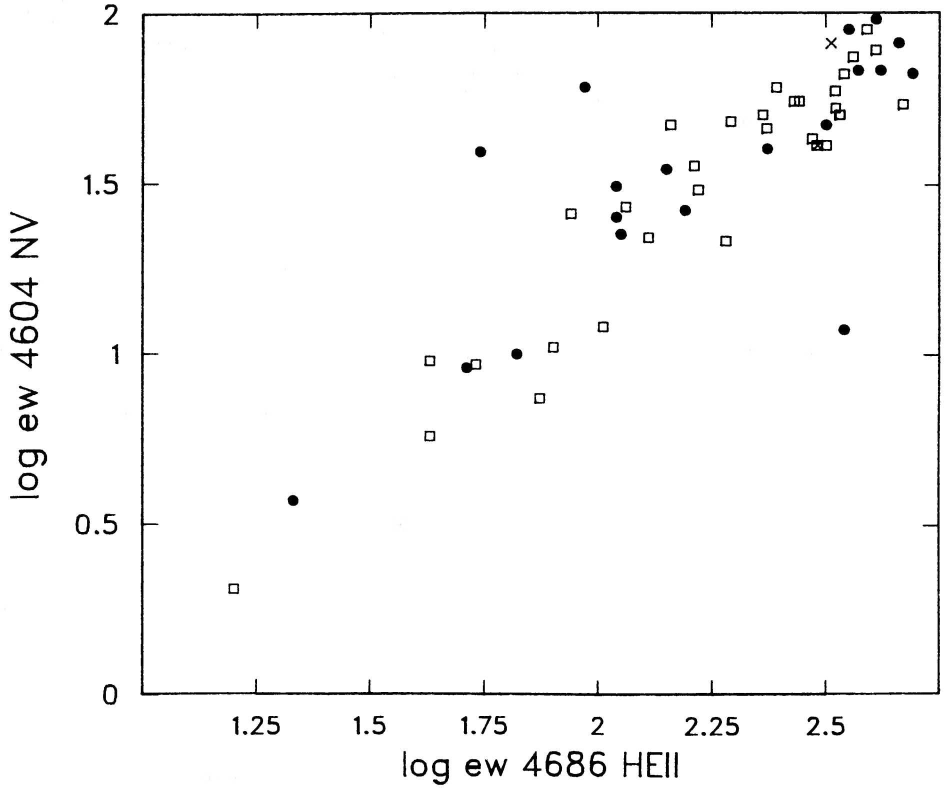

FIG. 2*a*

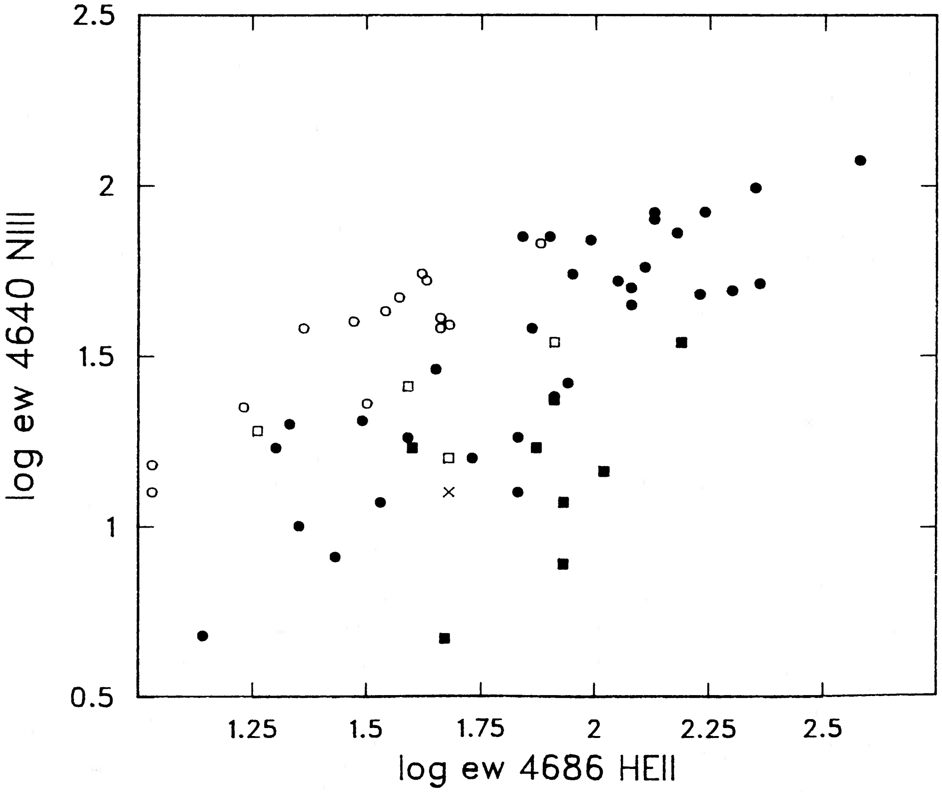

FIG. 2*b*

FIG. 2.—(*a*) Equivalent width (log) comparisons of He II λ4686 and N V λ4604 for the WNE stars in the Galaxy (*filled circles*) and the LMC (*open boxes*). The three stars diverging from the main relation are discussed in the text. (*b*) Equivalent width (log) comparisons of He II λ4686 and N III λ4640 for the WNL stars in the Galaxy (*filled circles*, WN 5/6/7; *open circles*, WN 8/9) and in the LMC (*filled squares*, WN 6/7; *open squares*, WN 8/9). In this figure, unlike the previous two, ionization differences in N III among the subtypes lead to a large scatter in the relationship.

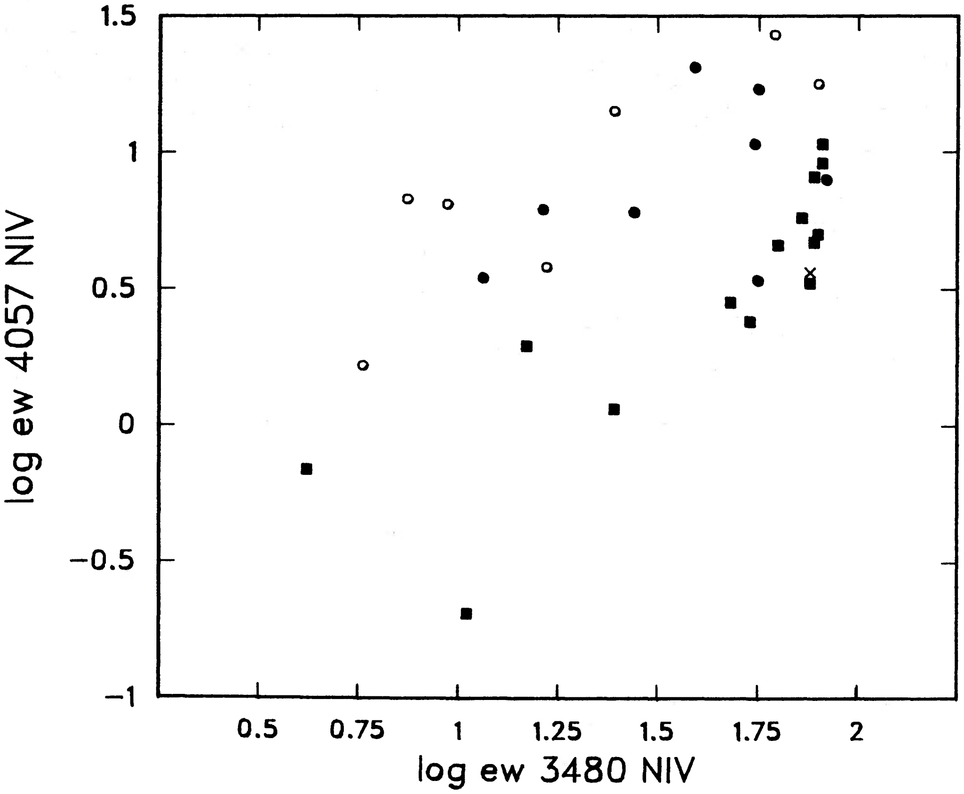

FIG. 3*a*

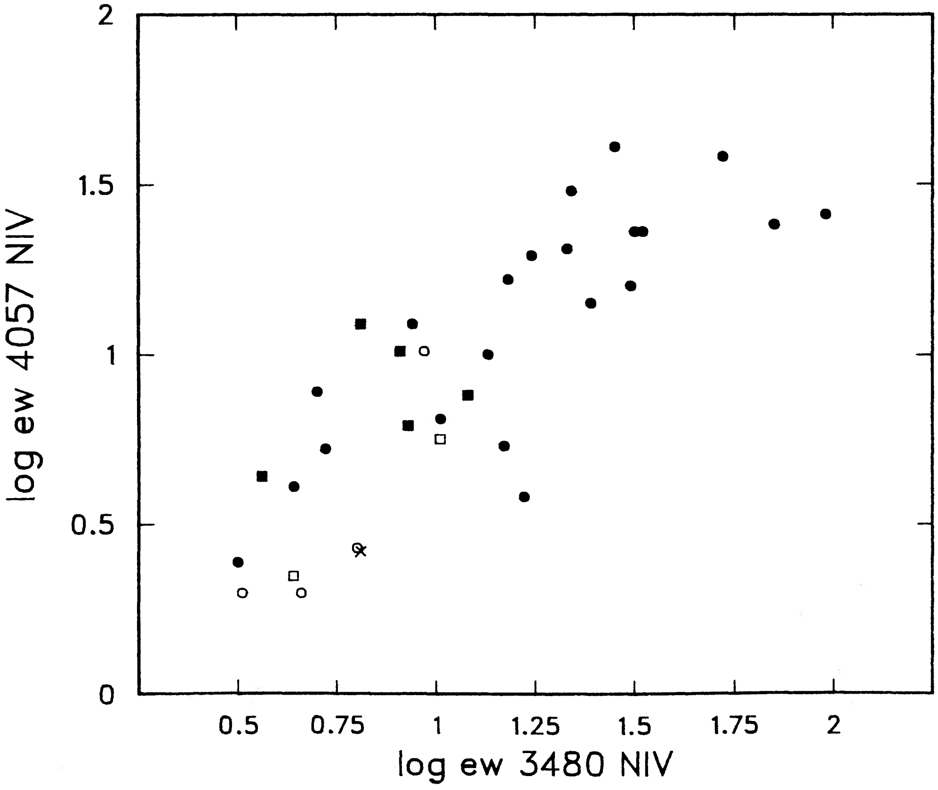

FIG. 3*b*

FIG. 3.—(*a*) Equivalent width (log) comparisons of N IV λ3480 and N IV λ4057 for the WNE stars in the Galaxy (*filled circles*, WN 4; *open circles*, WN 4.5/5) and in the LMC (*filled squares*, WN 3/4). See text. (*b*) Equivalent width (log) measures of N IV λ3480 and N IV λ4057 for the WNL stars in the Galaxy (*filled circles*, WN 5/6/7; *open circles*, WN 8) and in the LMC (*filled squares*, WN 6/7; *open squares*, WN 8).

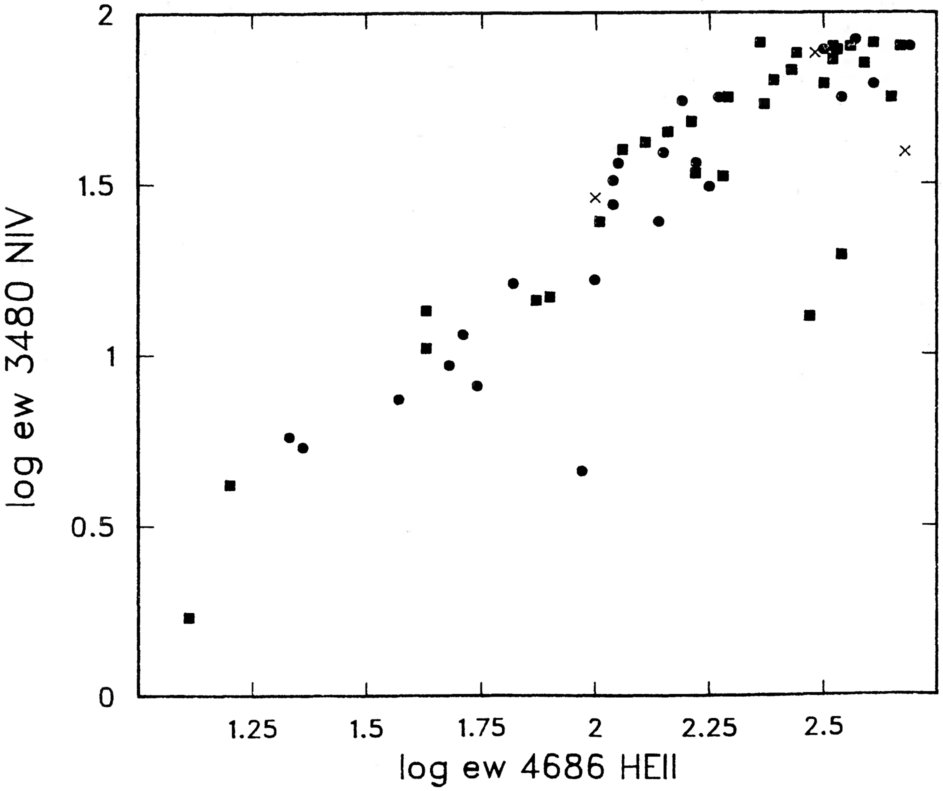

FIG. 4*a*

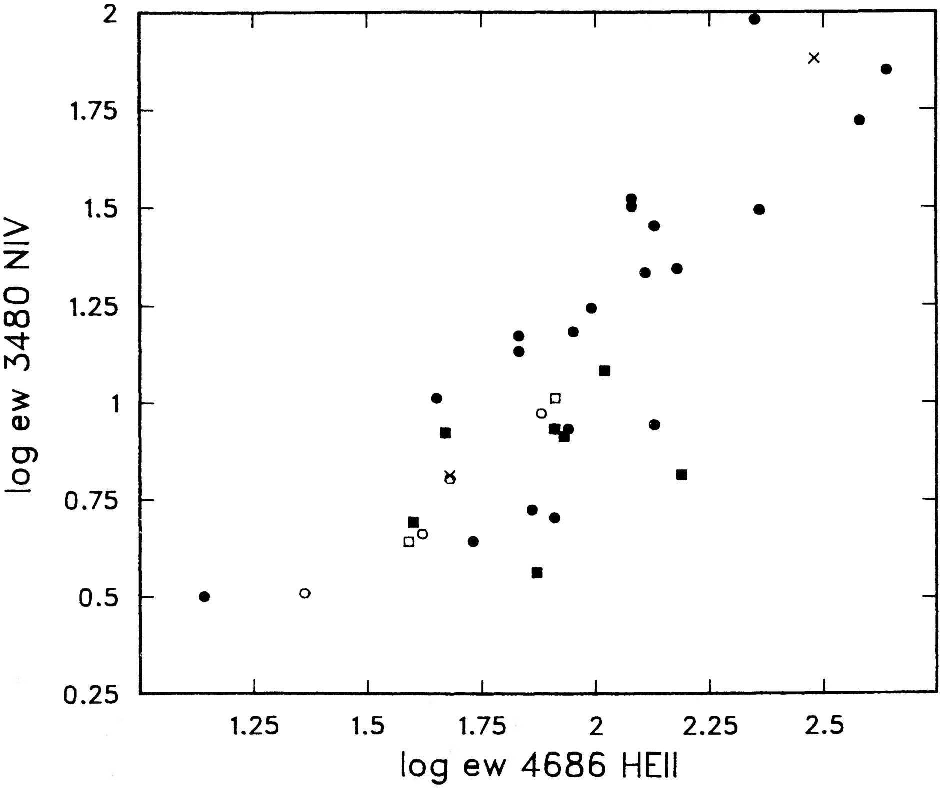

FIG. 4*b*

FIG. 4.—(*a*) Equivalent width (log) measures of He II λ4686 and N IV λ3480 for the WNE stars in the Galaxy (*filled circles*) and in the LMC (*filled squares*). The three stars divergent from the main relationship are discussed in the text. (*b*) Equivalent width (log) measures of He II λ4686 and N IV λ3480 for the WNL stars in the Galaxy (*filled circles*, WN 5/6/7; *open circles*, WN 8) and in the LMC (*filled squares*, WN 6/7; *open squares*, WN 8).

WNE stars there is even more scatter, but here a pattern begins to emerge. A careful examination of the data reveals that in the earliest WN subtypes, found mostly in the LMC, the singlet feature has weakened with respect to the triplet. Why do we assert this? Let us look at the relation of the N IV λ3480 feature with He II λ4686.

In Figures 4*a* and 4*b* we show the relationship between the N IV λ3480 features and the He II λ4686 line; we have segregated the data into the WNE and WNL stars, respectively. In Figure 4*a* there is a nice correlation of N IV and He II, with the exception of three stars, WR 46, Br 1, and Br 66 to which we will return below. Figure 4*a* demonstrates that N IV λ3480 is relatively "well behaved" over a wide range of WNE subtypes since it correlates nicely with λ4686. The relationship of λ4057 with λ4686 would show considerable scatter, since the line weakens and disappears in the WN 3 subtypes as noted by the classification. There is also a correlation of λ3480 with λ4686 in the WNL stars as shown in Figure 4*b*, but with more scatter than in Figure 4*a*. This seems unlikely to be only an ionization effect since the lowest excitation stars, the WN 8, are plotted separately and fall near the middle of the relation. We do not have a ready explanation for the range of values of λ3480 compared to λ4686 in the WNL stars, but it does seem possible to argue from Figure 3*a* that the N IV λ4057 singlet line does weaken before the N IV λ3480 triplet with advancing spectral subtype. We will return to this theme below when discussing behavior of the C III emission features in the WC stars.[3]

We have previously noted WR 46 with weak N IV as having strong N V (and the unprecedented presence of O VI). In Br 1 and Br 66, the weakness of λ3480 suggests they are of an earlier spectral type than the two WN 2.5 stars, Br 6 and Br 16, both of which have "normal" N IV on Figure 4*a*. The two WN 2 stars, WR 2 and BR 4, have neither N IV nor N V present. On this basis we should classify Br 1 and Br 66 intermediate between WN 2 and WN 2.5. This seems highly unsatisfactory in terms of the terminology. Perhaps we should call WR 2 and BR 4 with no visible optical nitrogen ions as WN 1 (the N V resonance line at 1240 Å is present), then Br 1 and Br 66 would become WN 2.

Nearly all WN stars show the presence of the C IV blend at 5801, 5812 Å. C III λ5696 is not normally found in WN stars, nor is C III λ4650. In a very few WN objects in which λ4650 is seen the stars are referred to as "WN + WC" subtypes (van der Hucht *et al.* 1981). The presence of the C IV feature in normal WN stars, and the absence of corresponding C III lines, suggests the ionization state for the wind in the nitrogen subtypes is generally more advanced than in the late WC objects as we will discuss below.

Figure 5 gives the relation between He II λ4686 and C IV λ5808 for the WN stars in which this line has been measured (Tables 1 and 2). Most stars follow a normal relation, although we note the rms scatter is 0.2, rather than the 0.1 shown by the

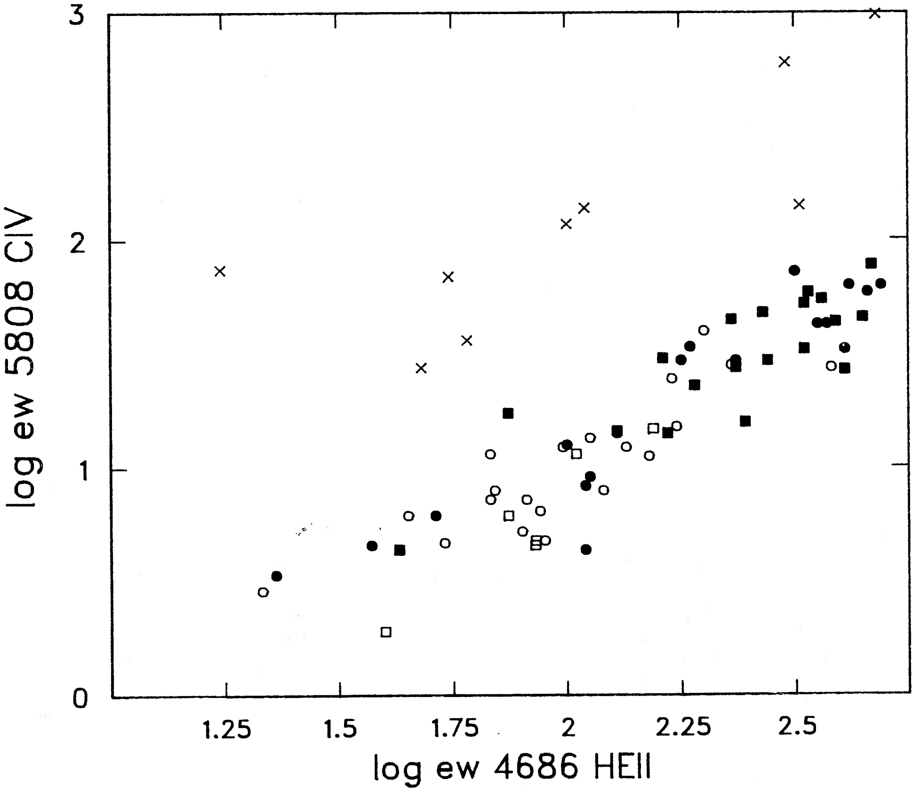

FIG. 5.—Equivalent width (log) measures of He II λ4686 and C IV λ5808 for the WN stars in the Galaxy (*filled circles*, WNE; *open circles*, WNL) and in the LMC (*filled squares*, WNE; *open squares*, WNL). Those eight stars with anomalously strong C IV are labeled with an "X" and are described in the text as WN/WC objects.

---

[3] Hillier (private communication) has kindly enlightened us with an explanation of why N IV λ4058 and N IV λ3481 should in fact be expected to behave as we have found. The λ4058 line arises from the $2s3d\ ^1D$–$2s3p\ ^1P$ transition, but the alternate transition to $2s2p\ ^1P$ is greatly favored, and we therefore should expect λ4058 to occur only if the optical depth is great (Hillier 1988). At the earliest types, presumably this transition becomes optically thin as the dominant N ion becomes N V or N VI. However, the λ3481 line arises from the most probable transition out of the $2s3p\ ^3P$ level. A similar explanation should hold equivalent for transitions of C III.

λ5411/He II (Fig. 1), the N v/He II (Fig. 2*a*), and the N IV/He II (Fig. 4*a*). There are six Galactic stars out of 40 WN objects plotted with strong C IV; similarly, two of 28 LMC stars fall well above the normal relation. Three of the Galactic stars were the previously cataloged "WN + WC" types. All eight stars have strong C IV relative to He II λ4686. We have labeled them similarly in Figure 5 and will consider their nature in § V.

The absence of C IV in the very earliest type WN stars and many of the WN 7/8/9 types is probably due to the ionization state at the extremes of the WN subtypes. A careful examination of Table 1 and 2 indicates C IV is not measured and potentially weak in WR 3, WR 10, WR 46, Br 1, Br 27, Br 42, Br 51, Br 52, Br 54, Br 66, Br 69, and Br 99 given the strength of He II λ4686. We have already seen (Fig. 4*a*) that Br 1 and Br 66 may be of relatively early WN type. In Paper I, WR 10 and Br 52 show C IV present with a measured strength that should be only marginally detectable with our data; the spectra of the other LMC stars (all but Br 69 and Br 99 of WN 3 subtype) appear to become noisier in the yellow region of the spectrum and the apparent absence of λ5808 might not be significant. Better data will be needed. In WR 46, the weakness of C IV does appear to be real, as also noted in Paper I. We have already noted its so far unique WN spectrum (O VI present, N V strong, N IV weak).

Tables 1 and 2 also contain the FWHM measures of He II λ4686. In Massey, Conti, and Armandroff (1987) these data are plotted with respect to the log EW measures of the same lines. It was shown there that the single WN types fit a well-defined relationship (called a "hockey stick") between the line width and strength, with the weakest lined stars, generally of the latest types, having the narrowest features, and the strongest lined objects, usually of the earliest types, having broader lines. The binary and composite systems have generally weaker lines for the same line width, and many of them fell outside the relationship for the normal stars. Massey *et al.* used these data to address the issue of potential binary or composite objects among the WN stars identified in some Local Group galaxies. Hiltner and Schild (1966) have introduced the letters "A" and "B" to the WN classes to indicate narrow- and broad-lined objects which had weak and strong lines. We see by the results of our figures above, and the FWHM relationship given in Massey *et al.*, that this is an oversimplification of the situation since *both* the line strengths *and* the line widths have a *continuum* of values from the strongest and broadest lined cases to the weakest and narrowest ones. The "A" and "B" nomenclature may isolate the extremes but their use should not be overinterpreted.

b) WC Stars

Tables 3 and 4 give the measurements for the leading lines in the WC stars in the Galaxy and LMC, respectively. We present the [log] EW (and FWHM) for the C IV blend at 5801, 5812 Å, the C III/C IV/He II feature at 4650 Å, the C III line at 5696 Å, the O III/O V line at 5592 Å, and the He I λ5876 line. While the λ4650 feature is the leading line in the blue region of the spectrum, it is a blend of contributions from a C III line at 4650 Å, a C IV component at 4658 Å, and the He II λ4686 feature. Because of the blending from ions of different intrinsic strength, we have thus decided to use the C IV λ5808 blend to record the FWHM.

The classification of the WC sequence comes primarily from the carbon and oxygen ion lines in the yellow, with additional criteria concerning the line widths. The spectral types listed come from van der Hucht *et al.* (1981), supplemented by Paper III where many pertinent comments concerning individual stars are recorded. Torres (1988) has subsequently derived carbon and helium abundances from the Paper III data.

It is instructive to compare the measurements made here with those of Paper III, which are partly photographic from image-tube plates, and partly from these same data sources as we have available here, although reduced completely independently. The data reported in Paper III used a software program written by Doug Perry and run by AVT on the APAS Departmental VAX at the University of Colorado. In most cases, the data in Paper III were means of these individual measurements of two kinds of spectra. Here the data are exclusively from "linear" detectors and were reduced with the IRAF by PSC. A comparison of the values of the [log] EW of C III λ4650, λ5696 and C IV λ5808 with Paper III indicate close fits to a one-to-one relation, with a rms scatter of 0.1 dex for the λ4650 and λ5808 and 0.2 dex for the λ5592 feature. We see no systematic deviations between the measurements.

There were, however, several "outlier" points in the comparisons which require comment: WR 77, which was farthest from the mean relations, a factor 4, seems to have consistently strong lines in Paper III compared to all our measures here, in which an absorption spectrum is also visible. Upon careful inspection, we realized that the close visual companion was included in the data presented here but *not* in Paper III. Two other divergent measurements, for WR 13 and Br 7, have only the C IV λ5808 feature strong; the other lines are similar here and in Paper III. The possibility of occasional "outlier" points, probably due to unevaluated measurement errors, therefore needs to be kept in mind.

The terms "WCL" and "WCE" were used in Paper III to describe the WC 9, WC 8, and WC 7 and the WC 6, WC 5, and WC 4 subtypes, respectively. Other references in the literature also use WCL and WCE as shorthand for the "late" and "early" designations. Let us put these definitions on a somewhat firmer quantitative basis. We will define the WCL stars as those in which C III λ5696 is as strong, or stronger, than C IV λ5808. The WC 7 subtype definition then embraces both the L and E designation but can now be separated by the actual measurements, or by eye inspections of the spectra. We have thus labeled the stars in column (6) of Tables 3 and 4. We see that all the LMC stars are WCE; the Galactic objects are split between the two subgroupings. We shall return to the distribution of these subtypes in § VII where we will note their rather different galactocentric distributions.

Let us now turn to the correlations of line parameters among the leading emission-line features of WC stars. In the absence of ionization effects, it is found that the emission lines are all relatively strong or relatively weak in a given star. We will use the C IV λ5808 feature as the comparison standard and in Figure 6 show the relationship between it and the C III λ5696 line. For labeling, in this and several following figures, we have segregated the WC stars into the WCE and WCL classes. In Figure 6 the WCE and WCL stars are nicely separated, as expected, from the difference in line strength of the C III λ5696 line relative to the C IV λ5808. Among the WCL stars there is a correlation between the strength of λ5808 and λ5696; however, among the WCE stars, there is no correlation. These results can be understood as being due to the relatively small change in ionization fraction of C III in the former group and the rapid change in the latter. Notice there is only one LMC star with C

TABLE 3

LINE STRENGTHS (log EW) IN GALACTIC WC STARS

WR#	Star	Sp	5808	FWHM^a	4650	5696	5592	HeI
4	HD16523	WC5	3.19	44 E	3.09	2.18	2.02	-
5	HD17638	WC6	3.06	38 E	3.05	2.03	1.75	-
9	HD63099	WC5 + abs	2.61	65 E	2.59	1.65	1.51	-
"	"	"	2.53	73 "	2.53	1.71	1.57	-
13	MR15	WC6	2.64	68 E	2.90	1.93	1.68	-
14	HD76536	WC6	2.79	43 E	2.89	2.30	1.56	1.90
15	HD79573	WC6	2.90	69 E	2.89	2.18	1.53	-
17	HD88500	WC5	2.93	46 E	2.99	1.62	1.51	-
19	LS3	WC4	2.64	85 E	2.58	-	1.90	-
23	HD92809	WC6	2.86	51 E	2.87	2.19	1.47	-
27	LS4	WC6 + abs	2.85	47 E	2.97	2.08	1.80	-
30	HD94305	WC6 + abs	2.59	50 E	2.63	1.69	0.98	-
33	HD95435	WC5	3.05	74 E	3.00	2.10	2.05	-
38	MS8	WC4	2.94	72 E	2.78	-	1.99	
39	MS9	WC6	2.08	71 E	2.03	1.69	-	-
42	HD97152	WC7 + O7	-		2.37	Blue region only		
45	LSS 2423	WC6	-		2.90	Blue region only		
50	MR44	WC6 + abs	2.47	54 E	2.58	2.13	1.48	-
52	HD115473	WC5	3.04	54 E	2.94	1.61	1.77	-
53	HD117297	WC8	2.19	31 L	2.40	2.55	0.94	-
56	LS8	WC7	2.55	39 E	2.70	2.27	1.50	1.51
57	HD119078	WC7	2.52	38 L	2.66	2.52	1.52	-
59	LSS 3164	WC9	1.68	31 L	2.17	2.19	-	1.41
60	HD121194	WC8	2.50	42 L	2.60	2.69	1.38	1.92
64	BS3	WC7	-		2.59	Blue region only		
65	LSS 3319	WC9	1.52	32 L	1.78	2.07	-	1.45
68	BS4	WC7	2.51	44 E	2.67	2.23	-	1.86
69	HD136488	WC9	-		1.95	Blue region only		
70	HD137603	WC8 + abs	1.03	40 L	1.09	1.52	-	p
73	NS3	WC9	2.20	35 L	2.28	2.66	1.25	1.73
77	MR62	WC8(+ abs)	2.10	38 L	2.02	2.36	1.05	1.41
79	HD152270	WC7 + O5	-		2.39	Blue region only		
80	LSS 3871	WC9	1.97	34 L	2.04	2.51	-	1.64
81	MR66	WC9	1.85	33 L	2.01	2.40	-	1.79
86	HD156327	WC7 + abs	2.14	39 E	2.21	1.98	1.03	1.28
88	MR70	WC9	1.75	31 L	2.06	2.22	-	1.68
90	HD156385	WC7	-		2.71	Blue region only		
92	HD157451	WC9	1.67	31 L	1.95	2.30	-	1.59
93	HD157504	WC7 + abs	2.41	51 E	2.48	2.04	-	1.86
95	MR74	WC9	1.93	37 L	2.11	2.38	-	1.65
96	LSS 4265	WC9	2.10	33 L	2.23	2.67	1.46	1.82
101	DA3	WC8	2.45	41 L	2.48	2.60	1.60	1.68
102	Sand4	WO1	2.08	127 E	2.45	-	2.10	-
103	HD164270	WC9	1.89	32 L	1.93	2.43	-	1.80
104	MR80	WC9	-		1.62	Blue region only		
106	HDE313643	WC9	1.78	32 L	1.96	2.32	-	1.72
"	"	"	1.92	31 "	2.14	2.51	-	1.95
111	HD165763	WC5	3.15	45 E	3.16	2.13	1.94	-
112	CRL 2104	WC9	1.35	32 L	-	1.73	-	0.85
113	HD168206	WC8 + O8	1.72	32 L	2.01	2.02	0.65	1.08
114	HD169010	WC5	2.80	60 E	2.91	1.95	1.73	-
"	"	"	3.17	42 E	3.06	2.18	1.99	-
117	MR88	WC8	2.39	37 L	2.53	2.87	1.54	-
118	CRL 2179	WC10	-	24 L	-	2.91	-	-

TABLE 3—*Continued*

WR#	Star	Sp	5808	FWHM[a]	4650	5696	5592	HeI
119	LS15	WC9	1.91	28 L	2.07	2.49	-	1.77
121	MR90	WC9	2.01	28 L	2.09	2.59	-	2.03
125	MR93	WC7	2.36	66 E	2.32	2.20	0.98	1.13
126	St2	WC5	2.48	45 E	2.19	-	-	-
135	HD192103	WC8	2.55	32 L	2.73	2.54	1.09	1.96
137	HD192641	WC7 + abs	2.17	36 E	2.40	1.92	1.00	1.37
140	HD193793	WC7 + abs	2.35	67 E	2.37	1.86	1.03	1.08
142	Sand5	WO2	2.53	135 E	2.60	-	2.23	-
143	HD195177	WC5	2.74	59 E	2.66	-	1.70	-
144	MR110	WC4	3.37	56 E	3.13	-	2.25	-
146	MR112	WC4	2.60	67 E	2.57	-	-	-
150	St5	WC5	3.21	61 E	3.03	1.99	1.92	-
154	HD213049	WC6	2.96	44 E	2.97	2.18	1.75	-

NOTES.—WR 77, "(+abs)" spectrum from close VB companion; WR 101 called WN 7-8 in catalog; WR 118 FWHM is for C III 5696; WR 126: Pickering series emission anomalously strong, He II λ5411 1.21.

[a] FWHM units are angstroms; E is WCE type; L is WCL type.

III λ5696 measured on our spectrograms; in Paper III with its higher resolution this line is detected in some other LMC stars.

In Figure 7 we show the relation between the C IV λ5808 blend and the λ4650 blend due to C III, C IV, and He II. We see a correlation over the entire range of line strength for both the WCL and WCE stars. In the former, the blend must be primarily due to C III, and in fact, in the WC9 stars we can usually separate out the He II λ4686 feature from the overall profile since the line widths are narrow. In the WCE stars, the correlation between the C IV λ5808 and the λ4650 feature remains. In Figure 6 we found no relation between C III and C IV in the WCE stars, but we find one between λ4650 and C IV from Figure 7. We might thus infer that the λ4650 feature is not primarily due to C III in the WCE stars but due to C IV (this has also been noted in the recent WC star atlas of Torres and Massey 1987). An experiment to confirm this by measuring the wavelength of the λ4650 feature did not pan out, probably because the difference in wavelength between the C III at 4650 Å and the C IV at 4658 Å is not sufficiently large to be detected with our spectral resolution. On the other hand, we have noted above the behavior of the singlet N IV λ4057 line with respect to the triplet N IV features in WN stars; the triplet remains strong to a higher excitation class, due to optical depth effects. The C III λ5696 line is the same isoelectronic transition as N IV λ4057; similarly, C III λ4650 is isoelectronic with N IV λ3480. Thus we would expect that emission remains strong at 4650 Å in the earliest WC subtypes not only because of a contribution by the known C IV line at 4658 Å but also because of the persistence of the triplet C III.

Figure 8 gives the relation between the strength of the C IV λ5808 blend and the O V λ5592/O III line. Here the O V line dominates in the WCE stars, the O III line in the WCL objects. We see a correlation in the strength of the carbon and oxygen features, but with somewhat more scatter than in previous diagrams. One is tempted to think this larger scatter may be due to measurement error in the weaker oxygen feature, but a comparison of these O III/O V measures to those of Paper III does not indicate any such trends. Br 50 has a relatively weak O V line given its λ5808 line strength; the measurements are similar to those given in Paper III. The WO stars are found in distinctly different parts of Figure 8 than the WC stars. Aside from WR 144, there is no clear indication that any other stars have O V (or O III) line strengths intermediate between WC and WO types. This is to be contrasted with Figure 5 which showed several WN stars with strong C IV lines. Thus, by measurement of the leading lines of C III, C IV, O and V/O III in WC stars one

TABLE 4

LINE STRENGTHS (log EW) IN LMC WC STARS

Br Number	Star	Spectral Type	5808 Å	FWHM[a]	4650 Å	5696 Å	5592 Å
7......	HD 32125	WC 4	3.26	58 E	2.86	...	1.73
8......	HD 32257	WC 4	3.23	65 E	3.07	...	2.03
10......	HD 32402	WC 4	3.19	79 E	3.13	...	2.07
22......	R90	WC 6 + abs	2.29	74 E	2.25	1.59	...
28......	HD 36156	WC 4 + abs	2.51	56 E	2.30	...	1.16
31......	HD 36402	WC 4 + abs	...		1.70	Blue region only	
32......	HD 36521	WC 4 + abs	2.37	77 E	2.11	...	1.15
43......	HD 37026	WC 4	...		3.07	Blue region only	
50......	HD 37680	WC 4	3.17	79 E	3.15	...	1.37
62......	HDE 269818	WC 4	2.70	79 E	2.44	...	...
74......	HDE 269888	WC 4	3.20	64 E	3.09	...	1.83
93......	San 2	WO 4	3.49	106 E	2.73	...	2.32

[a] FWHM units are angstroms; E is WCE type; L is WCL type.

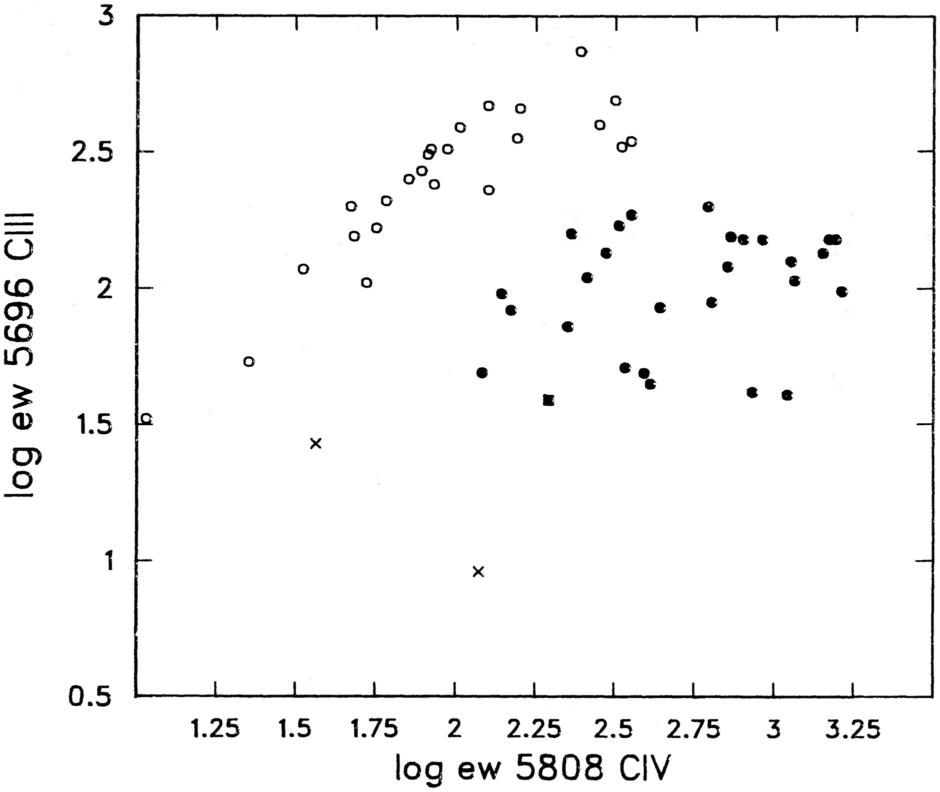

FIG. 6.—Equivalent width (log) measures of C IV λ5808 and C III λ5696 for the WC stars in the Galaxy (*filled circles*, WCE; *open circles*, WCL) and in the LMC (*filled square*, WCE).

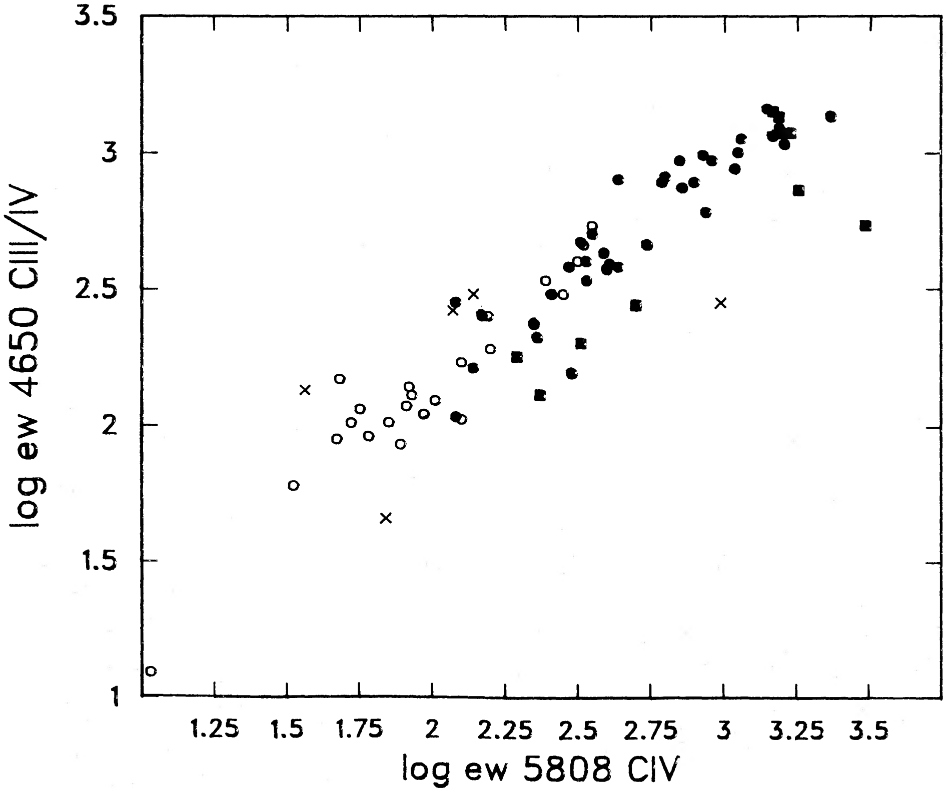

FIG. 7.—Equivalent width (log) measures of C IV λ5808 and λ4650, a blend of C III, C IV and He II (see text) for the WC stars in the Galaxy (*filled circles*, WCE; *open circles*, WCL) and in the LMC (*filled squares*, WCE).

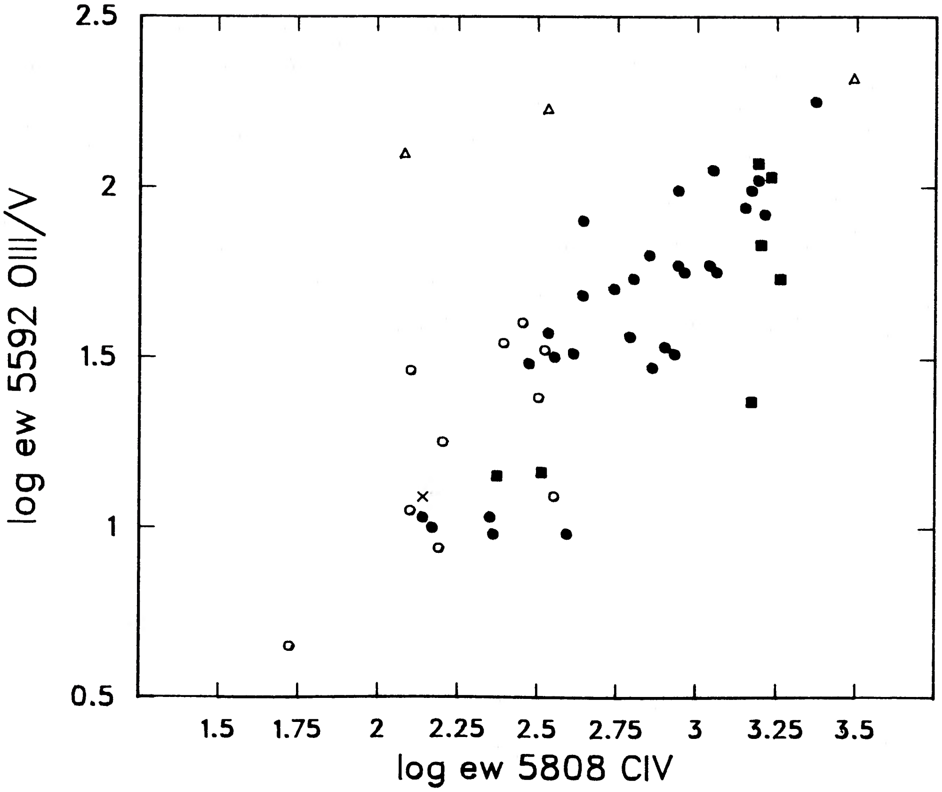

FIG. 8.—Equivalent width (log) measures of C IV λ5808 and O III/V λ5592 for WC stars in the Galaxy (*filled circles*, WCE; *open circles*, WCL) and in the LMC (*filled squares*, WCE). The triangles are WO-type stars (see text).

would infer the abundances to be relatively more homogeneous than that suggested for carbon from the C IV lines (and hydrogen; see Paper I) in WN stars.

WR 144 has C IV and O V line strengths similar to Br 93 (=San 2) in the LMC. Perhaps WR 144 is also a WO 4, but our spectra do not extend far enough into the blue to study the O VI emission at 3820 Å; the star is heavily reddened. Alternatively, from Figure 8 one might rather conclude that both WR 144 *and* Br 93 are on the normal high-excitation extension of the WC sequence since their O V is not anomalous. We could identify them as new WC 3 types.

Tables 3 and 4 also contain the FWHM measures of C IV λ5808. In Massey, Conti, and Armandroff (1987) these data are plotted with respect to the [log] EW measures of the same lines. It was shown there that the single WC types fit a well-known relationship between the line width and strength, with the weakest lined stars, the WCL types, having the narrowest features, and the strongest lined objects, the WCE types, having broader lines. The binary and composite systems have generally weaker lines for the same line width, and many of them fell outside the relationship for the normal stars. Massey *et al.* used these data to address the issue of potential binary or composite objects among the stars identified in some Local Group galaxies. The line strengths and widths of the WC stars form a continuum of values, from the strongest, broadest lined types, to the weakest narrowest features. For the WC class, the line widths can be used to confirm the subclass, whereas in the WN types they cannot.

V. THE WN/WC STARS

We have collected in Table 5 a list of the eight WN stars from Tables 1 and 2 that have anomalous C IV line strengths as indicated in Figure 5. Three of these, WR 8, WR 98, and WR 145, have already been classified as being of composite type WN + WC in the W-R catalog (van der Hucht *et al.* 1981). Among the others, WR 26, WR 58, and Br 29 were footnoted in Paper I as having very strong C IV; Br 29 had been identified as having very strong C IV from the resonance line at 1548, 1550 Å by Garmany and Conti (1982). The anomalous C IV strengths of WR 153 and Br 72 are indicated here for the first time.

Are the spectra of these objects composite, that is arising from two stars, or do they represent an intermediate composition case in a single star in which both carbon and nitrogen lines are strong? Although we cannot definitively answer this question for all entries of Table 5, there are clues that suggest that in nearly each case we are dealing with an emission-line spectrum from only one star. To start with, two of the objects (WR 145 and WR 153) are known binaries. The former star is a single-lined system (Pesch, Hiltner, and Brandt 1960) with a period of about 21 days, but with an ill-defined orbit. Massey (quoted in Conti 1982) has pointed out that from data he has collected the nitrogen and carbon lines move in phase, thus the emission spectrum arises from one star. Curiously, there has not been a recent analysis of the system.

WR 153 (GP Cep) is a quadruple system, composed of an O and WN 6 star in mutual orbit of 6.7 days, and another two (presumably both type O) stars in an orbit of 3.5 days (Massey 1981). The two pairs may also orbit each other in a longer period. Massey did not have spectroscopic data available in the yellow red region for GP Cep, but the WN emission lines clearly follow a 6.7 day orbital period. An *IUE* spectrum shows that C IV λ1548, 50 is strong (Hutchings and Massey 1983). A relatively easy future observational project would be to study

TABLE 5

WN/WC and WC/WN Stars

Catalog	Name	Catalog Spectrum	Line Widths 4686 Å	Line Widths 5806 Å	Revised Spectrum
WR 8	HD 62910	WN 6 + WC 4	28	32	WC 4/WN 6
WR 26	MS 1	WN 5	61	63	WCE/WN 5
WR 58	MR 51	WN 4	36	39	WN 4/WCE
WR 98	HDE 318016	WN 7 + WC 7	24	22	WC 7/WN 6
WR 145	MR 111	WN + WC	28	36	WN 3/WCE
WR 153	GP Cep	WN 6 + 0	31	34	WN 6/WCE + O
Br 29	HDE 269485	WN 3p	43	54	WN 3/WCE
Br 72	HDE 269891	B1 I + WN 3	53	82	WCE + WN + B1I

the velocity variations of the C iv feature in GP Cep (it is the brightest object of Table 5!): are they related to the already identified WN star, or rather to one of the other ones? The result of this investigation would help our understanding of whether or not we are, indeed, dealing with the spectrum of a single WN/C object, or two stars in the case of WR 153.

Niemela (1982) has rather extensively studied WR 8 for potential radial velocity variations. There seems to be a periodicity in the velocity of the violet displaced He i λ3889 absorption feature with a period of some 85 days but only marginal evidence for any velocity variations of the N iv λ4058 or C iv λ4441 lines in this object. We suspect the absence of any convincing periodic variation in the emission lines means the star is single; the absorption feature is formed well out in the wind, and its variations may not have anything to do with a putative companion. Willis and Stickland (1986) have suggested that the WC and WN lines found in the UV are in fact formed in the same stellar wind, and based upon this assumption Stickland and Willis (1982) derive a C/N ratio intermediate between that of WC and WN stars. Clearly this star will repay continued observation.

Not much is known about the possibility of radial velocity variations in any of the other stars of Table 5. There is thus so far no direct evidence that the WN and WC emission-line spectra come from two separate stars. What of the individual spectra themselves?

In Table 5 we have included the line widths of the He ii λ4686 and C iv λ5806 features. With the exception of Br 72, the widths are surprisingly similar! We closely inspected the "WN" and "WC" classification lines in each spectrum, and in the last column of Table 5 give our new spectral types, separated by a solidus (/). There is some loss of information in those cases in which the blend at 4650 Å had contributions from both N iii and C iii ions, but it was possible to assign the leading subclass to either the WN or WC case, depending on the overall appearance of the emission-line spectrum; the stronger one appears first in our classification. Only one star, WR 98, shows evidence for an appreciably strong C iii λ5696 line, and its WC classification is formally WC 7. All the WC subtypes are of the WCE group. No WN subclass is as late as WN 7; in other words, in none of them is N iii λ4640 relatively strong.

A detailed inspection of the entries of Table 5 indicates that the line widths of the carbon lines are relatively narrow for the WCE subtype in WR 8, WR 58, WR 145, and WR 153. The narrow line widths of WR 8 are particularly striking: the WC type is formally WC 4 as the O v line at 5592 Å is present, while C iii λ5696 is weaker. The line width of single WC 4 stars is more typically 50–70 Å (Paper III and Tables 3 and 4), yet only some 30 Å for WR 8. In these four stars the line widths are consistent with the WN subtypes but narrow for the WC class, thus suggesting that we are dealing with an anomalous spectrum and not two separate stars. In WR 26 the line widths are relatively broad, but are similar for both the WN and WC emission lines. In WR 98 and Br 29 the line widths are similar and consistent with both WN and WC subclasses. In Br 72, the WC line is considerably broader than the He ii λ4686 feature; in addition, an absorption line spectrum due to an O-type star is seen. The different line widths suggest that in this one case we are probably dealing with a composite spectrum in which three stars are present; this is certainly possible, given the potential for spatially unresolved stars in the LMC to be on the slit together. One is reminded of the composite nature of R140 which was eventually resolved into separate WN and WC stars by Phillips (1982).

We have previously plotted in Figures 1–8 the lines strengths appropriate for normal WN and WC stars and discussed "normal" behavior. Let us now review the data for the WN/WC objects, first as WN types. In Figure 1 the He ii spectra of the WN/WC objects is found to behave normally. In Figures 2 and 3, WR 58 and Br 29 have N v and WR 153 has normal N iii strengths, respectively, appropriate for their WN subtype. In Figure 4*a*, WR 8 and Br 29 have normal N iv, but the feature is weak in WR 26. Unfortunately N v is blended with a strong λ4650 emission in this star (and a spectrograph of this region was not available in Paper I). Lundstrom and Stenholm (1984*a*) note the presence and roughly equal strength of N iii, N iv λ4057, and N v in this object. In Figure 4*b* the N iv line of WR 153 appears normal. For the WN comparisons we find the WN/WC spectra to appear more or less normal, with the possible exception of WR 26.

For the WC comparisons we examine Figures 6, 7, and 8. In only two objects, WR 8 and WR 98, is C iii λ5696 present with our data; the formal WC subtype is WC 4 for the former star and WC 7 for the latter, and both are WCE by our definition given above. The weakness or absence of λ5696 in the other stars indicates they must be of very early WC type, although as we have noted above in Table 5 for several of these objects this "early" a formal classification is inconsistent with the relatively narrow line strengths. In four WN/WC objects, λ4650 is present as indicated by Figure 7 and is found for WR 8 and WR 98 to be of roughly normal line strength. The λ4650 feature is a little weak in WR 26 and WR 145 given the strength of C iv λ5808; the absence of this feature in the other WN/WC stars is very curious since C iv λ5808 is strong in all of them and as we have already shown, a strong λ4650 contribution is present even in the earliest WCE single stars. Perhaps here we are beginning to see some evidence that the carbon features in the WN/WC stars do not always behave in a consistent manner. Only WR 8 has a measurable O v feature, and as shown in Figure 8 its strength appears normal for the WC subtype.

We believe these data taken together in fact strongly suggest we are dealing with the emission-line spectrum of a single star in seven of the eight stars of Table 5; Br 72 is probably composite (Moffat and Seggewiss 1986 have suggested a composite type for Br 72 based upon these considerations). Radial velocity studies of all stars would probably help to settle the matter; if any are binaries, this has to show up in periodic velocity variations with the WN and WC features moving out of phase. So far all the evidence in this direction is negative. If the seven stars are indeed objects in which the emission-line spectrum is coming from a single star, then we are seeing a "transition" in chemical composition between a purely WN phase, in which the products of core H-burning are enhanced, and an advanced WC phase, in which we see the products of core He-burning. This has important implications for the evolution and structure of W-R stars.

VI. EMISSION-LINE FLUXES

We can discuss the emission-line strengths with our spectrophotometric data, not only in terms of the equivalent widths as we have done above, but also in terms of the line fluxes, in units of energy flux (ergs $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$) within the line, without normalization to the continuum. The equivalent widths have the advantage of being expressed in units of the continuum; thus, one can compare lines of different ions at various wavelengths and ignore the effects of differential reddening and the different apparent brightnesses of W-R stars upon the measurements. We have already shown in the previous eight figures that in nearly all cases the lines of various ions in W-R stars are strong or weak together, with the exception of changes in the ionization balance with spectral subtype. On the other hand, the line fluxes have the advantage of being a more physical quantity and an examination of their values with other stellar properties may prove useful. After all, the stellar continuum flux at 4686 Å has nothing whatsoever to do with the production of He III and the subsequent recombination that forms He II λ4686. In addition, it is possible for two stars at the same distance to have intrinsically identical emission-line fluxes but radically different equivalent widths if their stellar luminosity or continuous energy distribution differs.

To utilize this, we do need a sample of stars, all of which are at similar distances with similar reddenings, and here the W-R stars in the LMC serve us well. We chose for this experiment to look at the line fluxes of the WN stars in the LMC for the He II λ4686, N IV λ3480, and 4608/4640:N V/N III. Their emission features were recorded from the unnormalized spectra. These are given in Table 6, along with the absolute visual magnitudes (M_v) derived by Torres-Dodgen and Massey (1988) from their "line-free" photometry (for the stars in their Table VI only). Note that the line fluxes of N IV λ3480 are only slightly weaker than λ4686, due to increased stellar brightness toward the UV.

In Figure 9 we show the relation between the [log] EW of He II λ4686 and the M_v of the LMC WN stars, and we have separated the single stars from the binary or composite ones. For the single WNE stars there is a range of ~0.7 dex in the [log] EWs and ~3 mag in the brightness, but no apparent

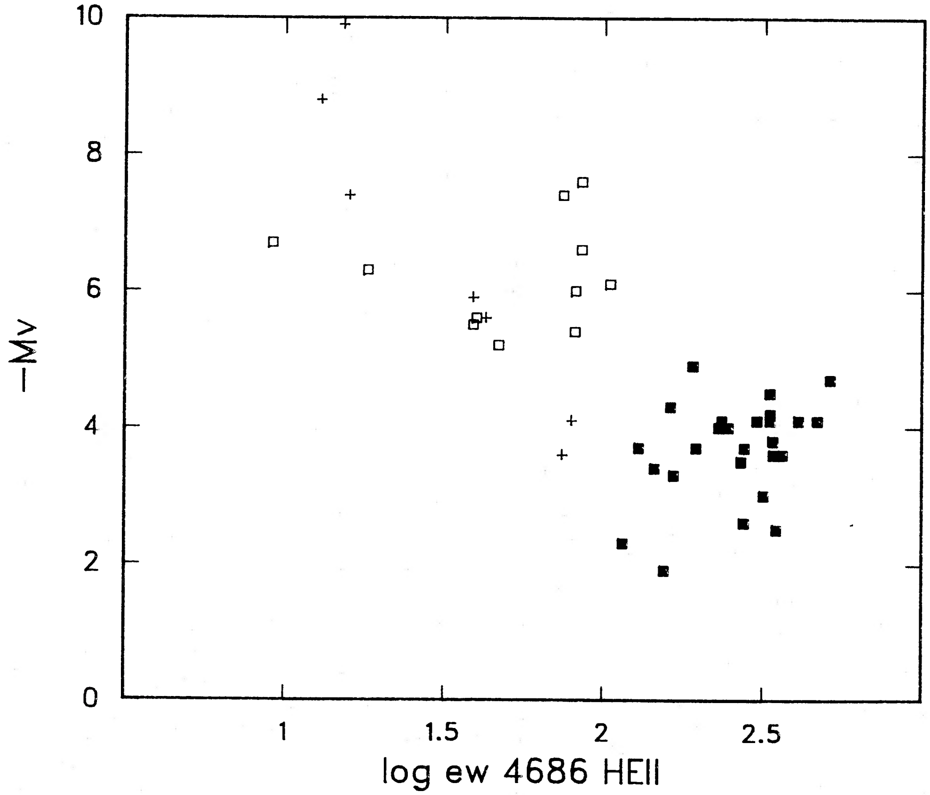

FIG. 9.—Equivalent width (log) of He II λ4686 and the M_v for WN stars in the LMC (*filled squares*, WNE; *open squares*, WNL). Stars that are binaries or composite are indicated by a " + " sign.

TABLE 6

FLUXES (log) FOR LMC WN STARS[a]

Br	Name	Spectral Type	m_v	4686 Å	3480 Å	N III/V
1	-70 1	WN 3	15.9	2.83	1.89	2.11
3	WS1	WN 3–4	14.8	3.25	2.98	2.57
4	AB15	WN 2	17.1	2.17	1.25	...
12	HDE268847	WN 4	14.8	3.41	3.12	2.65
13	HD33133	WN 8	12.7	3.52	2.98	3.17
14	HDE269015	WN 4	14.4	3.17	3.07	2.49
15	-70 64	WN 4	14.8	2.96	2.85	2.24
16	HD34187	WN 2.5	13.8	3.47	3.08	2.55
18	HDE269227	WN 9	12.1	2.81	...	2.93
19	WS13	WN 4	14.6	3.42	3.16	2.75
20	WS14	WN 4	14.3	3.19	3.07	2.55
21	HDE269333	B1 Ia + WN 3	11.2	3.44	3.15	2.63
23	WS17	WN 3	14.6	3.20	2.89	2.49
24	WS18	WN 7	13.4	3.32	2.76	2.77
25	AB16	WN 3	15.5	2.89	2.60	2.21
26	HD36063	WN 7	12.7	3.71	3.19	2.82
27	WS20	WN 3	14.9	3.04	2.85	2.40
29	HDE269485	WN 3p	14.8	3.28	3.07	2.48
33	AB1	WN 3 + abs	14.8	2.67	2.40	1.72
34	HDE269546	B3 I + WN 3	9.9	3.80	3.22	...
35	HDE269549	WN 4	14.8	3.23	3.07	2.38
36	WS27	WN 8	13.5	2.96	2.40	...
37	WS28	WN 3 + abs	14.1	3.15	2.91	2.35
38	AB2	WN 4	15.4	2.72	2.39	1.95
40	HDE269264	WN 4	14.9	3.22	3.01	2.50
42	WS30	WN 3	15.4	3.03	2.69	2.13
46	HDE269692	WN 3	14.7	3.17	3.01	2.46
47		WN 8	13.8	2.30	...	...
48	HDE269748	WN 4 + abs	13.3	3.12	2.85	2.57
51	-66 156	WN 3	15.0	2.74	2.66	2.21
52	FD47	WN 4 + abs	14.9	2.77	2.49	1.90
56		WN 6	...	2.83	2.40	1.65
57		WN 7	14.0	2.85	2.06	2.41
58		WN 5–6	13.9	1.97	1.85	...
64	BE381	WN 9	13.5	2.69	...	2.65
69	AB9	WN 4	16.6	2.09	1.90	1.50
80	R135	WN 7	13.2	3.64	2.61	2.99
85	HDE269908	WN 3–4p	15.0	3.33	2.80	2.40
88	R146	WN 4.5 + abs	13.0	3.11	2.86	...
89	HD38282	WN 6	11.1	4.19	...	3.43
90	HDE269928	WN 6	12.2	3.72	2.72	3.02
92	HD38344	WN 6	13.1	3.43	2.62	2.45
99	WS51	WN 4	14.9	3.23	2.87	2.42
100	HDE270149	WN 4	14.6	3.39	3.09	2.64

[a] Units for flux are 10^{-15} ergs cm^{-2} s^{-1}.

correlation between these parameters. Similarly, among the single WNL stars there is a range of 1.0 dex in the [log] EW, 3 mag in brightness, and no correlation between these values. However, the WNE stars have generally stronger λ4686 than the WNL objects. In some of the binary WN stars, the continuum light is dominated by the companion supergiant star, so we would not expect any correlation.

In Figure 10, we show the relation between the [log] flux of λ4686 (in units of 10^{-15} ergs cm^{-2} s^{-1}) and M_v. Here there is a correlation in flux with M_v for the WNE stars; most of the WNL stars might fit a similar but vertically displaced relation. We see that among stars of similar subtype, the brighter have more flux in He II λ4686 because they are brighter in M_v. This relationship is not apparent from Figure 9 where the [log] EWs are plotted, since this measure of the line strength normalizes to the continuum, but the two figures are directly related through their visual magnitudes. The reddening and extinction in the WN stars of the LMC is similar, although not identical, from star to star. The M_v values were corrected for A_v, while the values of the λ4686 flux have not been as the differences in $E(b - v)$ were small.

We have made plots of the λ3480 flux versus the M_v for the stars of Table 6. As expected from the results of Figures 4*a*, 4*b*, and 10, there is good correlation of line flux and magnitude for the WNE stars but a poorer one for the WNL stars. Likewise, plots of the λ3480 flux versus the N V λ4606 or N III λ4640 flux appear similar to those of Figures 2*a* and 2*b*. It should be noted that this is true because we are intercomparing only stars in the LMC, in which the distances and reddening are similar. It has not escaped our attention that inverting this finding and plotting fluxes of He II λ4686 and N IV λ3480 for highly reddened WN stars such as are found in our Galaxy (e.g. Table 1) might

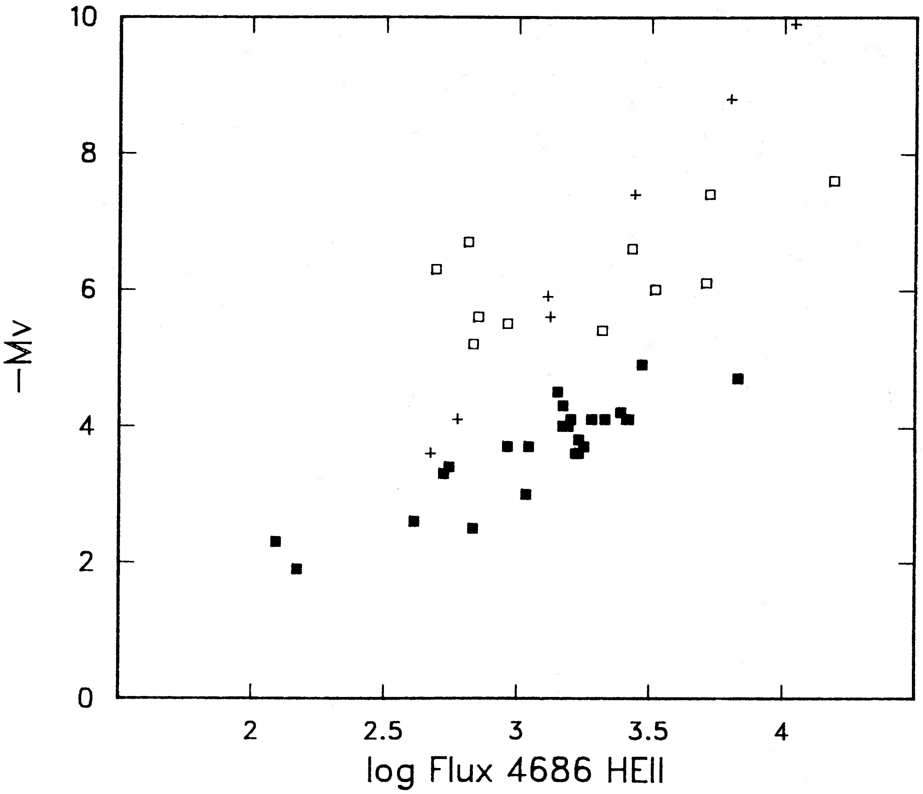

FIG. 10.—Fluxes (log) of He II λ4686 and the M_v for WN stars in the LMC (*filled squares*, WNE; *open squares*, WNL). Stars that are binaries or composite are indicated by a " + " sign.

enable one to estimate the reddening from line emission intensities independent of any modeling of the stellar continua. Furthermore, flux measurements of the He II λ1640 line, compared with the He II λ4686 line, should provide direct information on the interstellar UV extinction problem for W-R stars. These topics will be considered in a future paper.

VII. THE DISTRIBUTION OF SUBTYPES

Hidayat, Supelli, and van der Hucht (1982) and others have called attention to the predominance of the WC 9 stars toward the central regions of our Galaxy. A detailed reinvestigation of the distances of W-R stars in our Galaxy has recently been completed by Conti and Vacca (1988) using the revised "line-free" photometry of individual stars (Massey 1984; Torres-Dodgen and Massey 1988), an improved calibration of the M_v–spectral type relation, and newly adopted values for the intrinsic colors, following Torres-Dodgen and Massey. By segregating the WN and WC subtypes as described above, Conti and Vacca find that the WCL stars are found only in the spiral arms nearer the Galactic center; the WNL stars seem to be more concentrated toward the center but are also found beyond the solar circle. The WCE and WNE stars show no strong dependence on galactocentric distance. They also confirm that the WN/WC ratio depends on the galactocentric distance, there being relatively fewer WC stars toward the anticenter, analogous to what is found for M33 (Massey and Conti 1983*c*).

Perhaps this Galactic longitude correlation is only due to small number statistics and by itself might not mean anything. Yet we do have the curious and well-known fact that WCL stars in the LMC are absent (Table 4). WNL are found in the LMC but are fewer in numbers than the WNE, unlike our Galaxy near the Sun where the numbers are similar (Table 1). Table 2 has 36 WNE and 13 WNL (the more complete list of LMC WN stars in the catalog of Breysacher 1981 implies numbers of 54 and 18, respectively). Curiously, most of the WNL stars are in or near the 30 Dor complex (11 WNL). The line strengths of the W-R subtypes that are found in the LMC are *very similar* to those of our Galaxy, as may be noted from Figures 1–8.

The SMC contains no WCL or WNL stars, although it does contain a population of O-type stars (Garmany, Conti, and Massey 1987). There are six WNE and one WCE, the latter more properly classified as a WO subtype. We have also noted the general absence of WCL stars in other galaxies of the Local Group (Massey, Conti, and Armandroff 1987), yet some WNL stars are found there. In fact, aside from the directions toward the Galactic center, WCL stars have not been detected elsewhere, a fact we and others have been hard pressed to explain. The absence of WCL stars in both the LMC and M31 would appear to suggest metal abundance does not play an exclusive role since the composition of M31 is solar or higher; the presence or absence of very massive stars in M31 is not really known for certain, either, although there is a hint of a possible anomaly in the color magnitude diagrams of several associations as given by Massey, Armandroff, and Conti (1986). Very few stars are found there with inferred masses larger than 40 solar masses, but in the absence of additional confirmation, we frankly do not feel the photometry we have done can by itself compel us to this conclusion; further spectroscopy of the bluest stars may help settle the issue. Let us just say here that possibly only the most massive progenitors with metal abundances of solar or greater produce WCL stars. Further studies of populations of O and W-R stars in various environments are needed.

We are greatly indebted to Ana Torres-Dodgen for keeping us closely posted on progress in the photometry. She and Werner Schmutz have made much appreciated comments on the text. We are indebted to D. J. Hillier for the explanation of the N IV and C III triplet/singlet behavior, and to A. F. J. Moffat for some comments on the text. P. S. C. appreciates continued support from the National Science Foundation, most recently under grant AST85-80728. We wish to thank the staff of the NOAO for their help in acquisition of the data, extending over many observing runs in both hemispheres.

REFERENCES

Barlow, M. J., and Hummer, D. G. 1982, in *IAU Symposium 99, Wolf-Rayet Stars: Observations, Physis, Evolution*, ed. C. de Loore and A. J. Willis (Dordrecht: Reidel), p. 387.
Beals, C. S., and Plaskett, H. H. 1935, *Trans. IAU*, **5**, 184.
Breysacher, J. 1981, *Astr. Ap.*, **43**, 203.
———. 1986, *Astr. Ap.*, **160**, 185.
Conti, P. S. 1982, in *IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolution*, ed. C. W. H. de Loore and A. J. Willis (Dordrecht: Reidel), p. 3.
Conti, P. S., Garmany, C. D., de Loore, C., and Vanbeveren, D. 1983, *Ap. J.*, **274**, 302.
Conti, P. S., Leep, E. M., and Perry, D. N. 1983, *Ap. J.*, **268**, 228 (Paper I).
Conti, P. S., and Vacca, W. 1988, *A.J.*, submitted.
Garmany, C. D., and Conti, P. S. 1982, in *IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolution*, ed. C. W. H. de Loore and A. J. Willis (Dordrecht: Reidel), p. 105.
Garmany, C. D., Conti, P. S., and Massey, P. 1987, *A.J.*, **93**, 1070.
Hidayat, B., Supelli, K. A., and van Der Hucht, K. A. 1982, in *IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolution*, ed. C. W. H. de Loore and A. J. Willis (Dordrecht: Reidel), p. 105.
Hillier, D. J. 1988, *Ap. J.*, **327**, 822.
Hiltner, W. A., and Schild, R. E. 1966, *Ap. J.*, **143**, 770.
Hutchings, J. B., and Massey, P. 1983, *Pub. A.S.P.*, **95**, 151.
Lundstrom, I., and Stenholm, B. 1984*a*, *Astr. Ap. Suppl.*, **56**, 73.
———. 1984*b*, *Astr. Ap. Suppl.*, **58**, 163.
Massey, P. 1981, *Ap. J.*, **244**, 157.
———. 1984, *Ap. J.*, **281**, 789.
Massey, P., Armandroff, T., and Conti, P. S. 1986, *A.J.*, **92**, 1303.
Massey, P., and Conti, P. S. 1980, *Ap. J.*, **242**, 638.
Massey, P., and Conti, P. S. 1981, *Ap. J.*, **244**, 173.
———. 1983*a*, *Ap. J.*, **264**, 126.
———. 1983*b*, *Pub. A.S.P.*, **95**, 440.
———. 1983*c*, *Ap. J.*, **273**, 576.
———. 1984, *Ap. J.*, **281**, 789.
Massey, P., Conti, P. S., and Armandroff, T. E. 1987, *A.J.*, **94**, 1538.
Moffat, A. F. J., and Seggewiss, W. 1986, *Ap. J.*, **309**, 714.
Niemela, V. S. 1982, in *IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolution*, ed. C. W. H. de Loore and A. J. Willis (Dordrecht: Reidel), p. 299.
Pesch, P., Hiltner, W. A., and Brandt, J. C. 1960, *Ap. J.*, **132**, 513.
Phillips, M. M. 1982, *M.N.R.A.S.*, **198**, 1053.
Prevot-Burnichon, M.-L., Prevot, L., Reveirot, E., Rousseau, J., and Martin, N. 1981, *Astr. Ap.*, **103**, 83.
Smith, L. J., and Willis, A. J. 1982, *M.N.R.A.S.*, **201**, 451.
Stickland, D. J., and Willis, A. J. 1982, in *IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolution*, ed. C. W. H. de Loore and A. J. Willis (Dordrecht: Reidel), p. 491.
Torres, A. V. 1988, *Ap. J.*, **325**, 759.
Torres, A. V., Conti, P. S., and Massey, P. 1986, *Ap. J.*, **300**, 309 (Paper III).
Torres, A. V., and Massey, P. 1987, *Ap. J. Suppl.*, **65**, 459.
Torres-Dodgen, A. V., and Massey, P. 1988, preprint.
Van Beveren, D., and Conti, P. S. 1980, *Astr. Ap.*, **88**, 239.
van der Hucht, K. A., Conti, P. S., Lundstrom, I., and Stenholm, B. 1981, *Space Sci. Rev.*, **28**, 227.
Willis, A. J. 1982, *M.N.R.A.S.*, **198**, 897.
Willis, A. J., and Stickland, D. J. 1986, in *New Insights in Astrophysics: 8 Years of UV Astronomy with IUE* (ESA-SP-263), p. 339.

PETER S. CONTI: Joint Institute for Laboratory Astrophysics, Box 440 University of Colorado, Boulder, CO 80309-0440

PHILIP MASSEY: Kitt Peak National Observatory, National Optical Astronomy Observatories, P.O. Box 26732, Tucson, AZ 85726