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UNIFORMITY OF THE WC STARS IN THE LARGE MAGELLANIC CLOUD

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ABSTRACT

Uniformity of the WC stars in the LMC is investigated. It is a tenable hypothesis that $(b - v)_0$ is the same for all stars, and this enables estimates of absorption in the 30 Dor region where local irregularities are large. With absorption corrections based on $(b - v)_0 = -0.30$, we find that the flux in the C IV λ5808 line is the same for all the WC stars observed in the LMC; $\log f_\lambda$ (total, ergs cm^{-2} s^{-1}) $= -11.0 \pm 0.15$, corresponding to $\log f_\lambda$ (total, ergs s^{-1}) $= 36.5$ for $(m - M)_0 = 18.5$ mag. The scatter may be mostly observational, and the stars could be useful standard candles if WC4 stars in other galaxies are the same. The line flux ratio (λ5808/λ4650) $= -0.22 \pm 0.1$ dex and can be used to determine reddening.

Constant line flux suggests constant flux at the UV wavelengths responsible for C IV ionization. The large range of observed v magnitudes is probably a result of the presence of companions (either physically related or just unresolved).

The width of the λ5808 line is less than that of the λ4650 line in WC4 stars and greater in the WO stars. The width ratio correlates with line width; the combination of width and width ratio provides a simple diagnostic for the WO stars.

The use of Wolf-Rayet star emission-line fluxes for reddening and distance determination (if the method proves reliable) has a great advantage over other techniques. The method involves measuring fluxes that are 1–4 mag brighter than those in the continuum of a WR star and which are independent of contamination by the continuum of a companion (physically related or just unresolved); the broad lines stand out clearly even at low spectral resolution.

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

I. INTRODUCTION

WC stars in the LMC are a very uniform group. Smith (1968*b*) classified the 15 WC stars that were then known as WC5 and noted that the emission spectra are very similar; only the strength of the continuum seems to get stronger as one goes from the faintest to the brightest stars. Stars with a strong continuum were designated WC + OB. Prévot-Burnichon *et al.* (1981) examined the images of LMC WR stars on astrographic plates and found that all but one (Br 70) of the stars designated WC + OB have a "halo," indicating the presence of other unresolved stars. They suspect only three stars (Br 22, 68, and 94) of being true binaries.

Breysacher (1981) lists 19 WC stars; since then, Br 83 (Mk E) has been reclassified WC4–5 by Phillips (1982), and Morgan and Good (1985) have found four more WC stars. Torres, Conti, and Massey (1986; hereafter TCM86) found that the LMC WC stars display higher ionization than galactic WC stars and reclassified all but three as WC4 (Br 22 is WC6; Br 68 is WC5; Br 93 was classified WO4 by Barlow and Hummer 1982). TCM86 measured the equivalent widths (EWs) of the emission lines that are used for classification, but found disagreement for three stars between measurements made with photographic plates and with linear detectors. Emission lines in these stars can rise a factor of 40 above the continuum; until recently, there were no detectors capable of reliably measuring such a wide range of intensities.

In the Galaxy, line ratios within each subtype of WC stars were found (TCM86) to cover a wide range, analogous to the result found for WN stars by Conti, Leep, and Perry (1983). It is now a widely accepted generalization (which we challenge) that properties of WR stars cover a wide range, even within a subclass. Conti and Massey (1989; hereafter CM89) remeasured EWs for most WR stars in the Galaxy and LMC, using only linear detectors. In particular, they measured two of the three stars for which TCM86 had obtained disparate results and most of the strongest line stars for which equivalent widths are greater than 1000 Å. With the linear detectors at their disposal, both TCM86 and CM89 had to take two exposures, one for the peaks of the emission and one for the continuum.

We have also measured these stars (§ II) with a photon-counting spectrograph able to cover the necessary intensity range, and we find that the emission spectra are essentially identical both qualitatively and quantitatively. Constancy of the fluxes in the lines can be used to determine distances to stars in our own and other galaxies, if it can be shown that this property of the stars is the same in all galaxies.

We know that different galaxies have very different populations of subtypes (e.g., Smith 1988) and the LMC is an extreme example, with almost exclusively WC4 stars in the WC population. In the Galaxy, WC4 stars are rare; only five are listed by van der Hucht *et al.* (1988). However, studies to date have mostly concluded that stars in different galaxies with the same subclass are similar (e.g., Massey and Conti 1983; Massey, Conti, and Armandroff 1987). However, Smith and Willis (1983) noted that the He II λ4686 and λ1640 lines in WN stars and the O VI λ3811, 34 doublet in WC stars are stronger in the spectra of LMC stars than their galactic counterparts.

Arrangement of this paper is as follows: § II presents new spectroscopic data and collects existing spectroscopic and photometric data. Section IIIa assesses reddening for the WC stars and § III*d* derives unreddened line fluxes and continuum magnitudes and colors. Section IV discusses the significance and the uses of the constant line fluxes. Section V is a summary.

II. THE OBSERVATIONS

The new spectrophotometric observations were obtained with the 2D Frutti spectrograph of the 1 m Yale telescope of the Cerro Tololo Inter-American Observatory in 1988 March. The resolution is 4.3 Å. The detector head consists of a chain of image tubes fiberoptically coupled to a CCD chip, which is clocked at a rate of 15 MHz. The location of the detected photon events is determined to a fraction of a pixel by digital centroiding. The system is sensitive to photons in the wavelength range approximately 3500–7000 Å; this is determined by the camera optics and the S-20 photocathode used in the first intensification stage. The dynamic range of this detector is adequate for the strong lines in the WC stars. The only limitation is that for high fluxes the digital centroiding cannot distinguish between two or more partially overlapping photon events which occur within the same CCD readout cycle. The level at which this nonlinearity occurs was checked by observing several strong line stars with different amounts of neutral density filter inserted. We find that nonlinearity begins at $m_\lambda = 10.5$ or 11 mag at 4650 Å, but is still good at 10th magnitude at 5800 Å. Most of the stars in this program are faint enough that the flux in the strong lines is below that limit. When it is not, we have used neutral density filters.

The slit width was 2".7, chosen to minimize contamination when observing very faint stars (which was the main object of the observing program—to be reported elsewhere). The nights were photometric. However, the accuracy of our colors depends on the seeing and atmospheric dispersion being the same for the program star and the flux standard—not always a good assumption. On reduction, we discovered a slow sensitivity drift in the instrument. There were insufficient flux standard observations to correct star by star. We therefore chose to reduce all data with the mean flux calibration and apply small night corrections. The LMC WC stars were observed in immediate succession, in a total time interval of only 2 hr. The night correction was determined by requiring that the v (5160 Å) magnitude (numerically integrated over the half-width of the filter = 130 Å) match the filter values; the required night correction agrees well with the value derived from the nearest flux-standard observation. The scatter around the filter values is ± 0.07 mag in v, and the mean difference from the filter $b - v$ is -0.03 ± 0.04 mag. We note that there is, in principle, a difference in the zero point of the v-magnitudes and the $b - v$ color between the Oke (1964) standards on which the *ubv* system is based (Smith 1968*b*) and the more recent Hayes and Latham (1975; hereafter HL) calibration. The differences in the value for Vega are Oke-HL: $\delta v = 0.045$ mag, and $\delta(b - v) = +0.063$. However, Massey (1984) found no systematic shift [$\delta v = 0.01 \pm 0.04$ mag, and $\delta(b - v) = 0.01 \pm 0.06$] between spectrophotometric values based on the HL calibration and filter measures based on the Oke standards. We conclude that the difference in zero points disappeared in the errors between the Oke secondary standards and the primary standard, Vega, which was not observed directly in the WR filter system. We use a box function to represent the b and v filters. Massey (1984) and Torres-Dodgen and Massey (1988; hereafter TM88) use a Gaussian profile. The difference is probably not significant, and the advantage of the spectrophotometry is that it can define a specific wavelength interval in this manner.

Table 1 collects our own and other observations of magnitudes and emission-line contributions to v and $b - v$, location in nebulosity or a cluster, estimates of the interstellar reddening (the sources are detailed in the footnotes to the table), and dereddened filter-v magnitude for two extreme cases. Column (15) assumes $A_v = 3.3E_{B-V}$ (which follows from $R = A_V/E_{B-V} = 3.1$, $R' = A_v/E_{b-v} = 4.1$, $E_{B-V}/E_{b-v} = 1.21$, $E_{v-V}/E_{b-v} = 0.28$; Lundstrom and Stenholm 1980; Turner 1982); E_{B-V} is from available circumstantial evidence, and the uncertainties quoted reflect the range in the estimates. Column (16) assumes $A_v = 4.1E_{b-v}$, with E_{b-v} determined on the assumption that $(b - v)_0 = -0.30$ (which will be justified and discussed in § III*a*). The uncertainties quoted reflect the uncertainty in $b - v$; this is determined as the standard error of the mean color (s.d. of one observation, listed by Smith 1968*b* as a function of magnitude, divided by $\sqrt{n}$, where n is the number of observations). There are now available: *u'ubvv'* measures with filters (Smith 1968*b*); *ubvr* (called "synthetic" by TM88) magnitudes from spectrophotometry; and continuum (called "monochromatic" by TM88) magnitudes from spectrophotometry. Columns (5) and (6) are the difference between the continuum and synthetic values. In columns (2) and (3), we give the filter-measured v and $b - v$ magnitudes, when available. We note that spectrophotometric values of v given by TM88 are brighter by up to 0.24 mag (Br 8); Massey (1988, private communication) attributes the differences to background subtraction, in which case the smaller entrance slit of the spectrophotometric observations should yield more accurate data. However, "quality (1)" observations are only available for five of the WC stars, and, for ease and consistency, we use the filter values which exist for most of the stars.

Table 2 gives our new observations of line EWs, total and peak fluxes, and line widths for the seven strongest line WC4 stars in the LMC, two galactic WC4 stars and two galactic WO stars (we reclassify WR 30a as a WO4 + O4 star; § IV*e*). Table 2 also collects available data on all other WC4 and WO stars in the LMC and the Galaxy. Conversion of EWs to fluxes has been effected on the assumption that continuum magnitudes and colors given by TM88 or Massey (1984) have been derived from the same continuum assignment as the EWs of CM89. The relationship between flux per Å, EW, and continuum colors is (remembering that magnitudes are based on flux per Hz):

$$m(5808)_{\rm ctm} = v_{\rm ctm} - 0.78(v - r)_{\rm ctm} ;$$

$$m(4650)_{\rm ctm} = v_{\rm ctm} + 0.57(b - v)_{\rm ctm} ;$$

$$m_\lambda = m_v + 5 \log (\lambda/5556) ,$$

$$m_\lambda = \begin{cases} m_v + 0.10 & \text{at } \lambda = 5808 , \\ m_v - 0.39 & \text{at } \lambda = 4650 ; \end{cases}$$

$$-\log f_\lambda(\text{C IV } \lambda5808) = m_\lambda \times 0.4 + 8.47 - \log \text{EW} .$$

TABLE 1

MAGNITUDE AND COLOR DATA FOR THE MAGELLANIC CLOUD WC STARS

Br	WS	Spectrum (a)	v	$(b-v)$	ctm-"filter" δv	$\delta(b-v)$	n b,v (b)	ref	Nebula	LH#	Bt#	E_{B-V} LH	Brnt (c)	E_{b-v} (d)	v_o dereddening via E_{B-V}	E_{b-v}
7	3	WC4	15.10	−0.05 ± .05	···	···	4	1	DEM34	···	5	···	.09	.25 ± .05	14.80	14.08 ± .20
			15.02	−0.10	0.16	−0.02	−1	2	N11							
				−0.04	0.16	−0.03	1	3								
8	4	WC4	15.13	−0.11 ± .05	···	···	4	1	DEM36	8?	1	.11	.15-.28	.19 ± .05	14.47 ± .30	14.35 ± .20
			14.89	−0.13	0.23	−0.03	−1	2								
				−0.11	0.18	+0.10	1	3								
9	5	WC4+ O9.5II:	10.88	−0.22 ± .01	···	···	6	1	DEM34	9 N11	5	.10	.09	.08 ± .01	10.58 ± .02	10.55 ± .04
10	6	WC4 (f)	13.95	−0.10 : ±.03	···	···	2	1	DEM39	12	···	.21	(0.08)	.20 ± .03	13.26	13.13 ± .12
			13.89	−0.06	0.12	+0.12	−2	2	N91							
				−0.11	0.05	+0.04	1	3								
22	16	WC6+OB	12.02	−0.19	0.01	+0.04	−2	2	DEM134	42	B	···	.09-.13	.11 ± .06	11.66 ± .07	11.57 ± .25
			12.23	···	···	···	···	5	N120							
28	21	WC4+OB	12.92	−0.25 ± .015	···	···	4	1	N200	50	···	···	(0.08)	.07 ± .01	12.66	12.63 ± .06
			12.89	−0.26	0.06	-0.04	−1	2								
31	23	WC4+O9	11.50	−0.21 ± .02	···	···	1	1	N51	54	IV	.06*	.08-.13	.09 ± .02	11.15 ± .08	11.13 ± .08
			b=11.18	···	···	···	-2	2								
32	24	WC4+OB	12.51	−0.24 ± .02	···	···	2	1	N144	58	II	.04*	.15-.16	.07 ± .02	12.11 ± .13	12.22 ± .08
			12.39	−0.23	0.02	-0.02	−1	2								
43	31	WC4	14.36	−0.26 ± .04	···	···	3	1	···	···	III	···	.08-.17	.07 ± .04	13.95 ± .15	14.07 ± .16
			b=14.01	···	···	···	−2	2								
				−0.14	0.11	+0.02	1	3								
44	32	WC4+OB	13.42	−0.18 ± .02	···	···	2	1	N206	69	3?	.12	.18	.12 ± .02	12.92 ± .10	12.93 ± .08
50	35	WC4	14.09	−0.21 ± .04	···	···	3	1	N154	81	2	.25*	.18-.19	.09 ± .04	13.38 ± .12	13.72 ± .16
			14.03	−0.36	0.24	−0.15	−2	2								
				−0.18	0.06	−0.02	1	3								
62	36	WC4+OB (g)	14.1	+0.16	0.05	+0.02	1	3	N157	90?	2	.26*	.16-.23	.31 ± .15	13.4 ± .2	12.8 ± .6
			14.0	−0.14 :	−0.01	+0.30	−3	2								
			15.1	···	···	···	···	5								
67	40	WC4+OB	11.75	+0.02 ± .02	···	···	3	1	N157	···	2	···	.16-.23	.32 ± .02	11.11 ± .12	10.44 ± .08
68	39	WC5+OB	13.34	−0.25 ± .02	···	···	2	1	DEM261	96	2	.18*	.16-.23	.07 ± .02	12.70 ± .12	13.05 ± .08
70	41	WC4+OB?	14.0	···	···	···	···	5	DEM261	97	2	.18*	.16-.23	···	13.4 ± .1	···
74	42	WC4	15.58	+0.09 ± .05	···	···	4	1	N157	···	2	···	.16-.23	.39 ± .05	14.94 ± .12	13.98 ± .20
			15.41	+0.19	0.28	−0.12	−1	2								
				+0.11	0.12:	−0.12:	1	3								
83	···	WC4+OB	12.8	···	···	···	···	6	N157	100	2	.46	···	···	11.3	···
87	···	WC4+WN6	12.1	···	···	···	···	6	N157	100	2	.46	···	···	10.6	···
93	···	WO4	15.1	···	···	···	···	6	···	···	2?	···	.16-.23	···	15.0? ± .6[e)]	···
			16.1 var?	···	0.32	···	−3	2								
94	49	WC4+OB	13.41	−0.15 ± .02	···	···	2	1	N158	104	2	.23	.16-.23	.15 ± .02	12.77 ± .12	12.80 ± .08
MG1	···	WC4?+O	14.6	···	···	···	···	4	N105	31	B	.10*	.09-.13	···	14.2 ± .1	···
MG4	···	WC4?	18.9:	···	···	···	···	4	N157	99	2	.46	.16-.23	···	17.9 ± .5	···
MG5	···	WC4?	18.3	···	···	···	···	4	N157	100	2	.46	.16-.37	···	17.3 ± .5	···
MG6	···	WC4?+O6	13.3	···	···	···	···	4	N158	104	2	.23	.16-.23	···	12.7 ± .1	···

[a] Spectral types for the companions are as given by Breysacher 1986. Classes for the WC stars are from TCM86. Br 62 is called " + OB " because our observations include light from the nearby star, as do those of reference (2).

[b] For references (1) and (3), n is the number of independent observations. For reference (2), it is the quality factor -1 = good, -2 = uncertain, -3 = unphotometric.

[c] E_{B-V} values listed under "LH" are from Lucke 1974, except that the value for LH100, the central cluster in 30 Dor, is from Melnick 1983, and for LH99, following Morgan and Good 1985, the same value is adopted. An asterisk (*) denotes an interpolated value from surrounding clusters, as given by Lucke. Values listed under "Brnt" are based on Brunet 1975, except that, for region 2, we insert the values 16–23 from Fitzpatrick and Savage 1984 generally, and 16–37 for the region W and N of the center of the nebula. A minimum value of 0.08 as adopted.

[d] E_{b-v} assume that $(b-v)_0 = -0.30$, with a minimum value of 0.07.

[e] Br 93 uncertainty in v_0 includes uncertainty in v.

[f] Prévot-Burnichon *et al.* (1981) suggest that the photometry of Smith 1968*b* includes the brighter star to the east. However, the consistency of photometry and spectrophotometry suggests that the v measure is correct for the WC star alone.

[g] Breysacher 1986 also includes Br 62 as a single star. However, the spectrophotometric data is clearly contaminated by the nearby star, which reflects in the v_0 and EWs in Tables 1 and 2. The reddening is uncertain, resulting in large error bars.

REFERENCES.—(1) Smith 1968*b*. (2) Torres-Dodgen and Massey 1988. (3) Present observations. (4) Morgan and Good 1985. (5) Breysacher 1986, derived from V from WS64 with corrections. (6) V from Breysacher 1981 plus 0.77 (single), 0.26 (binary) from Breysacher 1986.

TABLE 2

LINE STRENGTHS FOR LMC AND GALACTIC WC4 AND WO STARS

Star	Spectrum	Ref	CIV 5801,12 logew	.... -log flux	....	....	CIII/IV 4650 logew	.... -log flux	....	....	CIII 5696 logew		OV 5590 logew	.... -log flux	....	....	CIV 5470 logew		HeII 5411 logew		HeII 4861 logew		CIV 4442 logew		HeII 4340 logew		OVI 3811,34 logew	
(a)			(A) (b)	total (c)	peak (d)	fwhm (A)	(A) (b)	total (c)	peak (d)	fwhm (A)	(A) (b)	-log f total (c)	(A) (b)	total (c)	peak (d)	fwhm (A)	(A) (b)	-log f total (c)	(A) (b)	-log f total (c)	(A) (b)	-log f total (c)	(A) (b)	-log f total (c)	(A) (b)	-log f total (c)	(A) (b)	-log f total (c)
Br 7	WC4	1	3.47 :	11.26	13.02	49	3.19	11.24	13.12	69	<.7	np	2.00	12.67	14.52	54:	1.77	12.89	1.78	12.83	1.63	12.83	1.49	12.89	1.52	12.86	1.86	12.42
...	....	2/3	3.26	11.34	...	58	2.86	11.50	...	70	1.51	...	1.73	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br 8	WC4	1	3.46 :	11.36	13.14	52	3.37	11.13	12.98	67	1.67	13.08	2.03	12.67	14.40	41	1.77	12.89	1.52	13.10	1.63	12.89	1.68	12.76	1.86	12.57	1.94	12.38
...	....	2/3	3.23	11.36	...	65	3.07	11.26	...	67	1.59	...	2.03	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	....	4	3.27	...	...	...	3.22	...	...	...	1.76	...	2.09	...	...	...	...	...	...	...	1.11	...	...	...	1.69	...	1.62	...
Br 9	WC4+O9.5II:	3	...	...	...	...	2.06 ?	...	...	74	0.60	...	1.00	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br10	WC4	1	3.29	10.86	12.76	73	3.13	10.74	12.70	87	1.53	12.59	1.69	12.40	14.21	58:	1.38	12.68	1.60	12.45	1.20	12.70	1.04	12.79	1.20	12.59	1.71	12.07
...	....	2/3	3.19	10.94	...	79	3.13	10.80	...	79	1.12	...	2.07	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br22	WC6+OB	2/3	2.29	11.10	...	74	2.25	10.84	...	78	1.59	...	1.07	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br28	WC4+OB	2/3	2.51	11.24	...	56	2.30	11.13	...	68	np	...	1.16	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br31	WC4+O9	2/3	2.06	...	...	...	1.70	...	...	76	np	...	1.37	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br32	WC4+OB	2/3	2.37	11.19	...	77	2.11	11.11	...	85	np	...	1.15	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br43	WC4	1	3.35 :	11.08	12.92	60	3.28	10.81	12.72	77	1.65	12.70	1.82	12.48	14.24	57	1.49	12.76	1.36	12.89	1.41	12.70	1.49	12.52	1.56	12.43	1.85	12.02
...	....	3	3.42	...	...	...	3.07	...	...	76	1.82	...	2.18	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	....	4	3.12	...	...	...	3.24	...	...	...	1.52	...	1.85	...	...	...	...	...	...	...	1.26	...	...	...	1.70	...	1.73	...
Br44	WC4+OB	3	2.81	...	...	...	.....	...	...	...	np	...	1.65	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br50	WC4	1	3.46 :	10.89	12.79	69	3.26	10.70	12.63	81	1.11	13.10	1.60	12.59	14.40	52	1.71	12.45	1.63	12.60	1.51	12.48	1.30	12.57	1.40	12.43	1.73	11.98
...	....	2/3	3.17	11.06	...	79	3.15	10.76	...	...	1.32	...	1.77	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
...	....	4	3.24	...	...	77	3.19	...	...	...	1.69	...	1.76	...	...	...	...	...	...	...	1.41	...	...	...	1.48	...	1.36	...
Br62	WC4+OB	1	2.94	11.29	13.23	77	2.63	11.38	13.35	85	<.7	np	1.26	12.92	14.81	82:	1.04	13.13	1.40	12.76	0.85	13.20	0.60	13.46	...	...	1.46	12.59
...	....	2/3	2.70	11.43	...	79	2.44	11.51	...	84	0.72 :	...	1.24:	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br67	WC4+OB	3	1.89	...	...	...	...	...	...	...	np	...	.....	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br68	WC5+OB	3	2.72	...	...	...	...	...	...	73	1.38	...	1.55	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br74	WC4	1	...	11.67	13.47	52	3.26	11.50	13.36	69	1.96	13.22	2.17	12.95	14.67	43	1.83	13.22	1.63	13.38	...	...	1.46	13.28	1.51	13.25	1.95	12.76
...	....	2/3	3.20	11.58	...	64	3.09	11.52	...	71	1.67	...	1.83	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br83	WC4+OB	6	...	...	...	...	1.84	...	...	80	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br93	WO4	2/3	3.49	v dbtfl	...	106	2.73	v dbtfl	...	102	np	...	2.32	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
Br94	WC4+OB	3	2.67	...	...	...	...	...	...	...	np	...	1.68	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
MG 1	WC4?	5	...	...	...	...	2.5	...	...	89	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
MG 5	WC4?	5	...	...	...	...	3.2	...	...	72	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
MG 6	WC4?	5	...	...	...	...	2.1	...	...	88	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
WR19	WC4	1	2.74	10.99	12.96	87	2.75	11.36	13.34	89	1.43	12.34	1.90	11.92	13.86	101	1.20	12.64	1.15	12.73	...	...	...	...	1.46	12.73	1.32	13.09
...	....	2	2.64	11.15	...	85	2.58	11.51	...	...	...	...	1.90	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
WR30a	WO4+O4 (e)	1	2.26	11.43	13.49	112	1.82	12.04	14.01	80	0.70	13.01	1.28	12.42	14.11	33	0.30	13.40	0.48	13.28	0.85	13.01	...	...	0.48	13.41	0.85	13.21
WR38	WC4	1	2.88	11.62	13.48	64	2.81	11.93	13.86	79	1.34	13.18	1.83	12.70	14.51	68	1.00	13.53	1.18	13.36	...	...	0.70	14.06	1.26	13.56	1.91	13.16
...	....	2	2.94	11.61	...	72	2.78	11.97	...	...	...	...	1.99	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
WR142	WO2	2	2.53	11.29:	...	135	2.60	11.60:	...	...	...	...	2.23	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
WR143	WC4 (f)	2	2.74	10.32	...	59	2.66	10.74	...	73	1.45	...	1.70	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
WR144	WC4	2/3	3.37	11.01	...	56	3.13	no b-v	...	68	1.70	...	2.25	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
WR146	WC4	2	2.60	no v-r	...	67	2.57	no b-v	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...
																			CIV,HeII 5430		OVI 5289		? 4500					
WR102	WO1	1	2.3:	12.15	14.33	152	2.52	12.03	14.06	94	...	np	2.17	12.22	14.44	157	...	...	1.00	13.38	1.79	12.64	1.53	13.09	...	...	3.24	11.52
...	....	2	2.08	12.17	...	127	2.45	no b-v	...	...	...	...	2.10	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...

[a] LMC stars are identified by their number in the catalog of Breysacher 1981 or Morgan and Good 1985; Galactic stars by their number in the 6th catalog (van der Hucht *et al.* 1981). Br 70 and 87 and MG 4 have no available line data.

[b] EWs from TCM86 are given when no value is available from CM89.

[c] Total fluxes are in units of ergs $cm^{-2}\,s^{-1}$.

[d] Peak fluxes are in units of ergs $cm^{-2}\,s^{-1}\,Å^{-1}$. They have the continuum subtracted and are the average over one half of the FWHM, which gives a well-defined value despite structure in the lines.

[e] WR 30a is reclassified WO4 + O4 on the basis of the strong O VI λ3811,34 lines, and of the λ4659/λ5808 flux and FWHM ratios (see § IV*e*).

[f] WR 143 is reclassified WC4 on the basis of the spectrum in the atlas of Torres and Massey 1987, which shows $\lambda5590 \gg \lambda5696$.

REFERENCES.—(1) Present paper. (2) EWs from CM89; continuum from TM88 or Massey 1984. (3) TCM86. (4) Smith and Willis 1983. (5) Estimates from spectra published by Morgan and Good 1985. (6) Moffat *et al.* 1987.

Note that we work in flux per Å which has a cleaner conceptual connection to EW. Continuum values corresponding to the EW measurements of TCM86 and Smith and Willis (1983) are not available.

In all, flux estimates are available for 10 LMC WC4 stars, three galactic WC4 stars, and two galactic WO stars. Out EWs for the LMC stars are consistently greater than those of CM89 and somewhat closer to the earlier values of TCM86. Our instrument has lower sensitivity in the red; our continua at 5800 Å have low signal-to-noise ratios and have clearly been underestimated. However, the differences for C III/IV λ4650 are unexplained. The fluxes agree better than the EWs, demonstrating that fluxes for strong lines are more accurate than EWs, especially when the level of the continuum is as poorly defined as in these strong-line WC stars. Br 62 is closely crowded to the east by an equally bright star. Our narrower slit excludes more of the light from this star and gives a higher EW than CM89. For the narrowest line stars (Br 7 and 8), our line widths for C IV λ5808 are significantly smaller than those of CM89, and our widths for λ4650 are somewhat larger than given by TCM86. The differences from CM89 are in the sense expected for the different resolutions (4 Å in this data, 15 Å for CM89), but the effect is rather larger than expected from a simple convolution of a Gaussian broadening profile.

III. RESULTS

Our spectra for six of the seven strong-line LMC stars and two of the galactic stars are shown in Figures 1*a* and 1*b*. The LMC spectra are all very similar. Only two things distinguish one star from another: the line widths, which vary from 50 to 80 Å for λ5808, and the presence, in about half the spectra, of a faint C III λ5696 line. The strong carbon lines, at 4650 and 5808 Å, rise 3–4 mag above the continuum in all the LMC stars observed except Br 62, which suffers contamination from a nearby star. Br 74 (not shown because our spectrum is noisy at the continuum level) is identical to Br 8. The galactic spectra are similar, but have some important differences which are discussed in § IV*e*.

a) $(b - v)_0$ *and Reddening*

Interstellar absorption is generally small in the LMC. However, many of the WR stars are in the 30 Dor region, where the absorption can reach $A_V = 1.5$ mag (Fitzpatrick and Savage 1984; Melnick 1983), and corrections for any given star are uncertain. To investigate the possibility that all the LMC WC stars have the same value of $(b - v)_0$, Figure 2 plots observed $b - v$ against E_{B-V} from nearby stars, as listed in Table 1. Points representing stars in the 30 Dor region are circled, and the number in Breysacher's (1981) catalog is given.

The solid line has the expected slope on the basis that $E_{B-V} = 1.21\ E_{b-v}$ (Turner 1982) and is set to pass through the best determined points. It yields $(b - v)_0 = -0.30$. The dashed line gives $(b - v)_0 = -0.35$, corresponding to $(B - V)_0 = -0.30$ (Turner 1982); it is hard to account for any point lying higher. The stars in the 30 Dor region account for five of the six stars that do not agree (within their uncertainties) with the solid line. Br 50 and 68 lie 25′ and 50′ SE of 30 Dor, and a lower E_{B-V} seems acceptable. The three 30 Dor region stars requiring higher reddening to fit the line are Br 62, 67, and 74, which all lie close together and just to the SW of the 30 Dor nebula. Br 62 is closely crowded by another star, and the observations are contaminated, yielding very different values for $b - v$ from the two spectrophotometric observations available. The reddenings indicated are $E_{b-v} = 0.30 \pm 0.15$, 0.32, and

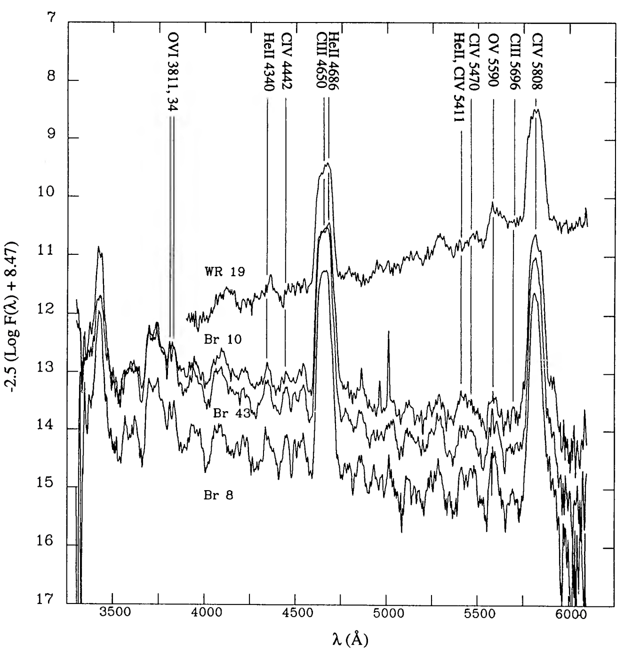

FIG. 1*a*

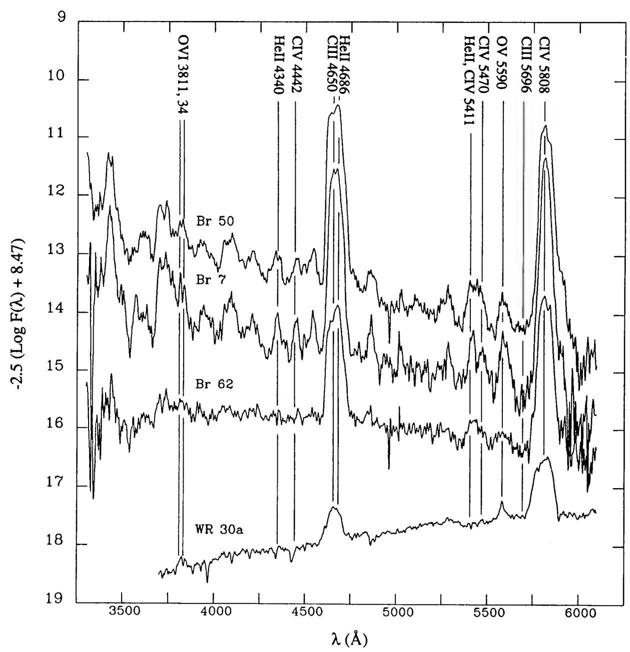

FIG. 1*b*

FIG. 1.—(*a*) Spectra of LMC WC4 stars showing weak C III λ5696 emission, plus the spectrum of the Galactic WC4 star, WR 19. Lines mentioned in the text are marked. Ordinate is $m_\lambda = -2.5\ (\log f_\lambda + 8.47)$; to avoid overlapping spectra, 2.5 mag has been subtracted from WR 19. The differences $m_v - m_\lambda$ are 0.16 mag at $v = 5160$ Å, and 0.57 mag at $b = 4270$ Å. (*b*) Spectra of LMC WC4 stars showing (almost) no C III λ5696 emission, plus the spectrum of the galactic WO star, WR 30a. Lines mentioned in the text are marked. Ordinate is $m_\lambda = -2.5(\log f_\lambda + 8.47)$; to avoid overlapping spectra, 2.0 mag has been added to Br 62, and 2.5 mag to WR 30a. The differences $m_v - m_\lambda$ are 0.16 mag at $v = 5160$ Å, and 0.57 mag at $b = 4270$ Å.

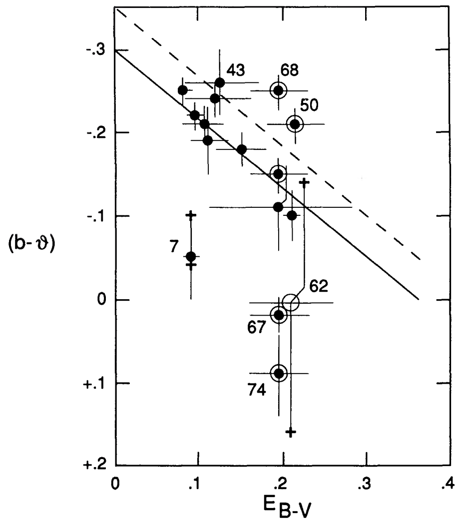

FIG. 2.—Plot of observed $b - v$ colors for LMC WC stars vs. E_{B-V} color excess from nearby stars (see Table 1). Dots are filter measurements, and crosses are spectrophotometric measurements (no zero point corrections applied). Stars in the 30 Dor region are circled. Stars discussed in the text are marked with their number in the catalog of Breysacher (1981). Error bars in $b - v$ are the standard error. Error bars on E_{B-V} reflect the range of values from different sources.

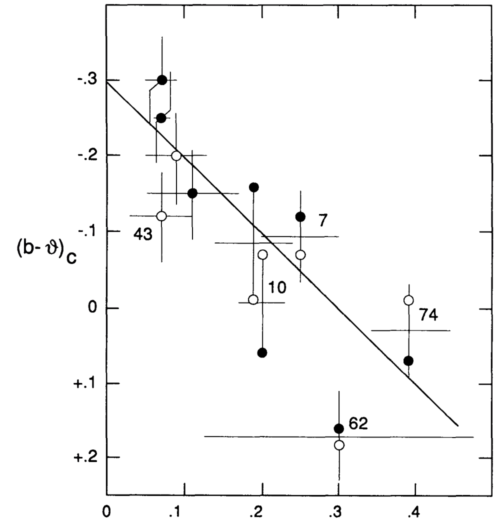

FIG. 3.—Plot of continuum $b - v$ colors as given by Torres-Dodgen and Massey (1988) (*filled dots*) and from spectrophotometry in this paper (*open circles*) vs. E_{b-v} color excess derived on the assumption that $(b - v)_0 = -0.30$. Error bars in $b - v$ are ± 0.06, generally sufficient to include the independent measurements. Error bars on E_{b-v} are the standard error of the $b - v$ measurements.

0.39, respectively. The WN stars Br 64, 65, 66, 69, 71, and 73 also lie in this region; of these, Br 64, 65, 66, and 69 have been observed by TM88 and have comparably large $b - v$. A belt of relatively large absorption is indicated.

The "non–30 Dor region" star which requires higher reddening to fit the line is Br 7. Its $b - v$ value is uncertain by ± 0.05 mag, which is not enough to explain the red color; two values of $b - v$ from spectrophotometry are marked by crosses and fall within the error bars for the filter photometry. It is not in an association, and E_{B-V} is the minimum foreground value; it is near Br 9, which is quite blue ($b - v = -0.22$). From this evidence, higher reddening seems unlikely, but deserves further investigation.

One could also consider the result of assuming that the *continuum* colors were all the same. The result would be similar. Figure 3 plots the continuum colors (as derived by TM88 and ourselves) versus E_{b-v}, assuming $(b - v)_0 = -0.30$. The error bars are ± 0.06 in $(b - v)_{\mathrm{ctm}}$, which is generally sufficient to include the two independent determinations (except for Br 50, where the TM point is off the graph and appears to be inordinately blue). Differences between the measured values are a result of both observational accuracy (± 0.04) and different choices of continuum [indicated by different values of $\delta(b - v)$ in Table 1]. The correlation is good and suggests $(b - v)_{\mathrm{ctm}} = -0.30$, conveniently equal to the filter value. All things considered, *the hypothesis that all LMC WC stars have the same* $(b - v)_0$ *appears to be viable*, although the reddening in the vicinity of Br 7 needs to be investigated. Fitzpatrick and Savage (1984) find high values of total to selective absorption in the region of 30 Dor. Our correction for absorption, using $R = 3.1$ and $R' = 4.1$ (Turner 1982), may underestimate the brightness of the stars in this region.

b) *Flux in the Lines*

Table 3 contains the dereddened total and peak fluxes for $\lambda 4650$ and $\lambda 5808$ and flux ratios of interest for the 10 LMC WC4 stars and five Galactic WC4 and WO stars for which flux data is available. These are derived on the assumption that $(b - v)_0 = -0.30$, and they use the ratios of δ log flux (or flux ratio) to E_{b-v} given in row 1. Over the visible wavelengths, the reddening is approximately linear in $1/\lambda$, although the slope changes in the blue. For wavelengths between b and r: $\delta \log (f_{\lambda_1}/f_{\lambda_2})/E_{b-v} = (1/\lambda_1 - 1/\lambda_2)$, with λ in microns. For wavelengths between u and b, the ratio is approximately 0.7 times the value given by this formula.

Figure 4 plots $\log f_0(\lambda 5808)$ versus v_0. Stars which are probably composite (see Breysacher 1986 and Prévot-Burnichon *et al.* 1981) are circled. Our new fluxes and those derived from CM89 + TM88 are plotted in different symbols to show the present observational uncertainty. *The flux is essentially constant over a range of 3 mag in* v_0, except for Br 10, which is a factor of 2 brighter.

Figure 5 plots the line ratio $\log f_0(\lambda 5808/\lambda 4650)$, which we call "$C_0$," versus v_0. The value is constant within the errors of

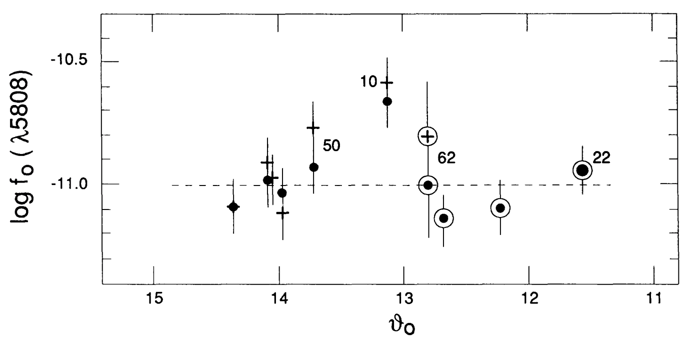

FIG. 4.—Plot of dereddened flux in the C IV $\lambda 5808$ line for WC stars in the LMC (Table 3) vs. the dereddened v magnitude. Dereddening has been effected using the E_{b-v}, derived on the assumption that $(b - v)_0 = -0.30$ (Table 1). Fluxes from spectra presented in this paper are plotted as crosses. Fluxes derived from EWs of CM89 and continuum magnitudes of TM88 are plotted as dots. Stars believed to be composite are circled. Star numbers are from the catalog of Breysacher (1981). Dereddening for Br 62 is uncertain; otherwise, error bars are ± 0.1 dex. The adopted mean value is shown by the dashed line.

TABLE 3

DEREDDENED FLUXES AND FLUX RATIOS

STAR	REFERENCE	E_{b-v} ($\pm$0.05)	$-\log f_0$ [TOTAL FLUXES; ergs cm^{-2} s^{-1}] λ5808 ($\pm$0.07)	λ4650 ($\pm$0.09)	C_0 ($\pm$0.02)	$-\log f_0$ (PEAK VALUES; ergs cm^{-2} s^{-1} Å^{-1}) λ5808 ($\pm$0.07)	λ4650 ($\pm$0.09)	C_0' ($\pm$0.02)	DEREDDENED FLUX RATIO $\lambda5808/\lambda5696$	$\lambda5808/\lambda5590$	$\lambda5590/\lambda5696$	$\lambda4650/\lambda5470$	$\lambda4650/\lambda5411$	$\lambda3830/\lambda5590$
$\delta[-\log f]/E_{b-v}$		1.00	1.42	1.85	0.43	1.42	1.85	0.43	0.03	0.07	−0.03	−0.32	−0.30	−0.74
Br 7	1	0.25	10.91	10.78	−0.13	12.67	12.66	−0.01	...	1.39	...	1.73	1.67	0.44
...	2	0.25	10.99	11.04	0.05	...	...	...	...	...	...	...	...	...
Br 8	1	0.19	11.09	10.78	−0.31	12.87	12.63	−0.24	1.71	1.30	0.42	1.82	2.03	0.43
...	2	0.19	11.09	10.91	−0.18	...	...	...	...	...	...	...	...	...
Br 10	1	0.20	10.58	10.37	−0.21	12.48	12.33	−0.15	1.72	1.53	0.20	2.00	1.77	0.48
...	2	0.20	10.66	10.43	−0.23	...	...	...	...	...	...	...	...	...
Br 22	2	0.11	10.94	10.64	−0.30	...	...	...	...	...	...	...	...	...
Br 28	2	0.07	11.14	11.00	−0.14	...	...	...	...	...	...	...	...	...
Br 32	2	0.07	11.09	10.98	−0.11	...	...	...	...	...	...	...	...	...
Br 43	1	0.07	10.98	10.68	−0.30	12.82	12.59	−0.23	1.62	1.40	0.22	1.97	2.10	0.51
Br 50	1	0.09	10.76	10.53	−0.23	12.66	12.46	−0.20	2.21	1.69	0.51	1.78	1.93	0.68
...	2	0.09	10.93	10.59	−0.34	...	...	...	...	...	...	...	...	...
Br 62	1	0.3	10.8	10.8	0.0	12.80	12.80	0.00	...	1.61	...	1.85	1.47	0.55
...	2	0.3	11.0	10.9	−0.1	...	...	...	...	...	...	...	...	...
Br 74	1	0.39	11.12	10.78	−0.34	12.92	12.64	−0.28	1.54	1.25	0.28	1.84	2.00	0.48
...	2	0.39	11.03	10.80	−0.23	...	...	...	...	...	...	...	...	...
WR 19	1	1.36	9.06	8.84	−0.22	11.03	10.82	−0.21	1.31	0.83	0.46	1.72	1.78	−0.16
...	2	1.36	9.23	8.99	−0.24	...	...	...	...	...	...	...	...	...
WR 30a	1	1.09	9.88	10.02	0.14	11.94	11.99	0.05	1.55	0.91	0.62	1.71	1.57	0.02
WR 38	1	1.23	9.87	9.65	−0.22	11.73	11.58	−0.15	1.52	0.99	0.52	1.99	1.80	0.45
...	2	1.23	9.70	9.53	−0.17	...	...	...	...	...	...	...	...	...
WR 142	2	1.63:	8.98:	8.58:	−0.4:	...	...	...	...	...	...	...	...	...
WR 143	2	1.51	8.18	7.95	−0.23	...	...	...	...	...	...	...	...	...
WR 102	1	1.07	10.63	10.05	−0.58	12.81	12.08	−0.73	...	0.00	...	...	...	1.49

REFERENCES.—(1) This paper; (2) EWs from CM89; continuum magnitudes from TM88 or Massey 1984.

TABLE 4

SUMMARY OF LINE PROPERTIES

DATA SOURCE	NUMBER OF STARS	$\log f_0$(λ5808, ergs cm^{-2} s^{-1}) Total	Peak (Å^{-1})	FWHM(Å)	$\log f_0$(λ4650, ergs cm^{-2} s^{-1}) Total	Peak (Å^{-1})	FWHM(Å)	$\log f_0$($\lambda5808/\lambda4650$) Total = C_0	Peak = C_0'	FWHM
This paper[a]	5	-10.97 ± 0.13	-12.79 ± 0.11	56 ± 7	-10.71 ± 0.10	-12.60 ± 0.07	73 ± 5	-0.26 ± 0.08	-0.19 ± 0.09	0.77 ± 0.0
CM88+TM88	6	-11.04 ± 0.08	...	...	-10.82 ± 0.16	...	...	-0.22 ± 0.08	...	...
Adopted (LMC)	...	-11.0 ± 0.15	...	...	-10.8 ± 0.2	...	...	-0.22 ± 0.10	...	...
At 1 kpc	...	−7.6	−9.4	...	−7.4	−9.2	...	...	...	...
log (total flux, ergs s^{-1})	...	36.5	...	...	36.7	...	...	...	...	...

[a] The stars included are Br 7, 8, 43, 50, 74. Br 10 deviates from the average by more than 2 σ and is excluded. The reddening correction for Br 62 is poorly known and it is also excluded.

[b] The stars included are Br 8, 22, 28, 32, 50, 74.

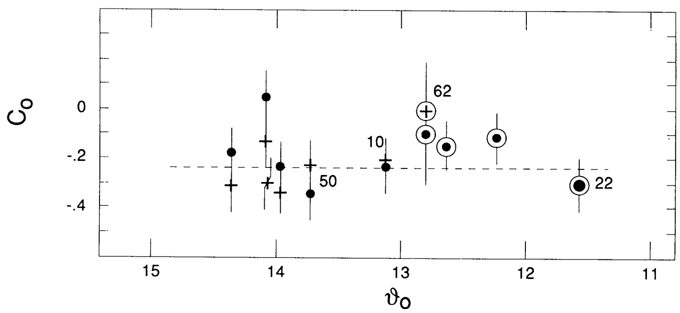

FIG. 5.—Plot of the dereddened flux ratio for the two strong carbon lines; $C_0 = \log f_0(\lambda5808/\lambda4650)$, in the spectra of WC stars in the LMC vs. the dereddened v magnitude. Symbols are the same as in Table 5. The adopted mean value is shown by the dashed line.

observation. Table 4 gives the mean and standard deviations of line quantities and their ratios. The two data sets, ours and CM89+TM88, are treated separately but are in good agreement. For the total flux, we adopt the mean, and for the ratio we adopt the value from the CM89 data which have a wider data base, including composite stars as well as single stars. To get total flux on a $\log f_0$ at a distance of 1 kpc, we assume a distance modulus for the LMC of 18.5 mag (Feast 1988).

The average peak fluxes are also given for our sample. These quantities could be useful for distance determinations, but the effect of line widths will need to be taken into account. Data to do this are not yet sufficient.

c) *Equivalent Width versus* v_0

To ascertain whether constant flux applies over the larger sample of stars for which EWs are available, Figure 6 plots log EW(λ5808) versus v_0 (E_{b-v} dereddened). The dashed line is

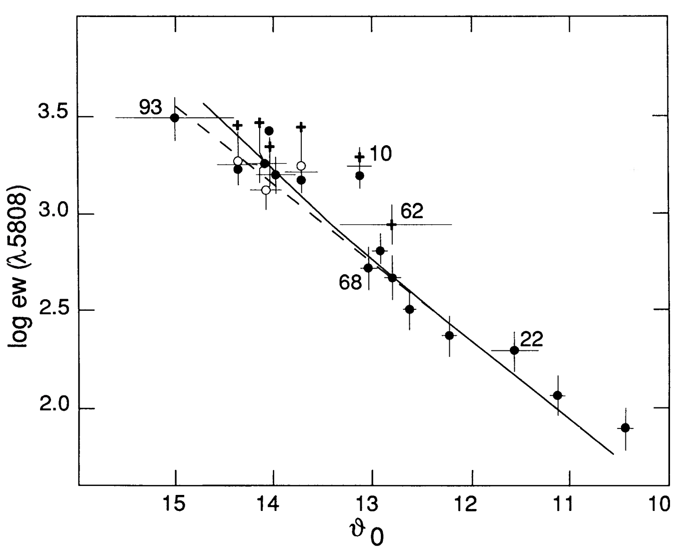

FIG. 6.—Plot of log equivalent width of the C IV λ5808 emission line in LMC WC stars vs. the dereddened v magnitude. Stars discussed in the text are identified by their number in the catalog of Breysacher (1981). Filled circles are EWs from Conti and Massey (1988), open circles from Smith and Willis (1983), and crosses from the present data. The latter are uncertain owing to low accuracy of the continuum. Error bars in log EW are ± 0.01 as estimated by the observers. Error bars on v_0 correspond to the standard error in $b-v$ (and hence E_{b-v}). Dashed line is the expected relation if the flux in the line is constant, and v_0 represents the continuum. Solid line allows for a contribution of emission in the filter, if this has constant flux and contributes 0.18 mag for the strong line stars.

the expected slope if the flux in the line is constant, and v_0 represents the continuum. The solid line allows for the presence of emission lines in the v band (on the assumption that these also have constant flux) and is set to pass through the average log EW = 3.23, $v_0 = 14.04$ mag, and $\delta v = 0.18$ mag for the strong line WC4 stars (Br 7, 8, 43, 50, 74). Error bars on the EWs are ± 0.1 dex, the estimated uncertainty from the observers. The agreement is good, indicating that the intrinsic flux, per star, in the C IV λ5808 line is a constant within the observational uncertainty, for all the stars except Br 10 (noted above). The spectrum of Br 10 is practically identical to that of Br 50, except that it has stronger C III λ5696 emission. It is of particular interest that Br 22 (WC6) and Br 68 (WC5) also fall on the line, indicating that the λ5808 flux is not sensitive to subclass over this limited range.

Br 93 is a WO4 star. Its visual magnitude is uncertain (Table 1); its λ5808 flux could be as strong as that of the WC4 stars or could be weaker. Its EW ratio for $\lambda5808/\lambda4650$ indicates that the flux ratio is certainly different.

A similar diagram for λ4650 shows the same slope but with greater scatter—both around the line and between observers. The estimates of EWs and v_0 for the faint stars found by Morgan and Good (1985) fall to the left of the line. They may be WO4 stars like Br 93, which has weaker λ4650 than the WC4 stars, or the reddening may have been underestimated. Two of the four lie in or near the 30 Dor nebula, where other WC stars (see § III*a*) indicate high absorption.

d) *Absolute Magnitudes and Intrinsic Colors*

Table 5 gives mean dereddened M_v and colors. For a distance modulus of the LMC of 18.5 mag (Feast 1988), the mean absolute v magnitude, $M_v = -4.5 \pm 0.2$, slightly brighter that the value derived by Breysacher (1986) and significantly brighter than the value (-3.0) adopted by van der Hucht *et al.* (1988) for the galactic WC4 stars. The $u'-b$, $u-b$, and $b-v'$ "filter" colors are significantly different for single and composite stars owing to the reduced effects of emission lines in the composite spectra. The $b-v$ and $v-r$ filter colors are little affected by emission and are the same for single and composite stars. We note that, in late-type WC stars (WC7–9), u is relatively emission-free, and for these stars $u'-v$ may be a good continuum indicator.

Continuum magnitudes and colors are brighter and bluer than the values derived by TM88 due to larger $(m-M)_0$ and reddening corrections. Continuum colors are essentially the same for single and composite stars.

Table 5 also gives the zero point difference (Oke) − (Hayes and Latham), and $m_\lambda - m_v$; the colors in m_λ, corresponding to the ordinates in Figure 1; and the slopes of the continuum flux $\delta \log f_\lambda/\delta\lambda$, which are the numbers required to convert from EW ratios to flux ratios. In m_v, the continuum is approximately linear in λ from u to r. In m_λ, it is linear from u to v, but the slope becomes flatter between v and r.

IV. DISCUSSION

a) *The "Single" WC4 Stars*

For all WC stars in the LMC (except Br 10), the flux in the strong carbon lines is the same within observational uncertainty, but the continuum flux ranges over 4 mag. For the five faint, strong-line stars (Br 7, 8, 43, 50, 74) all properties seem to be similar: the spectra (Fig. 1), the EWs (Table 2 and Fig. 6), the line fluxes (Table 3 and Fig. 4), the continuum magnitudes

TABLE 5

ABSOLUTE MAGNITUDES AND INTRINSIC COLORS FOR LMC WC4 STARS

QUANTITY	n	v	$u' - b$	$u - b$	$b - v$	$b - v'$	n	$v - r$[a]
				Filter Colors				
E/E_{b-v}[b]	...	4.1	0.93	0.69	1.00	1.29	...	0.68
Single[c] star mag	6	14.0 ± 0.2	−0.46 ± 0.15	−0.54 ± 0.12	−0.30	−0.03 ± 0.06	4	−0.27 ± 0.08
Composite star mag	9	...	−0.25 ± 0.04	−0.18 ± 0.06	−0.30	−0.35 ± 0.05	3	−0.28 ± 0.02
				Continuum Colors[a]				
Single star mag	4	14.1 ± 0.2	...	−0.17 ± 0.09	−0.30 ± 0.09	...	...	−0.23 ± 0.02
Composite star mag	3	...	...	−0.15 ± 0.03	−0.32 ± 0.02	...	...	−0.28 ± 0.05
Oke–Hayes and Latham	...	+0.045	...	−0.102	+0.063	...	...	+0.045
Zero point $m_\lambda - m_v$	...	−0.16	...	−0.34	−0.41	...	...	−0.32
m_λ colors	...	...	...	−0.51	−0.71	...	...	−0.55
$\delta \log f_\lambda$(ctm)/($\delta\lambda \times 10^{-3}$)	...	...	...	−0.33	−0.32	...	...	−0.26

[a] The $v - r$ and all continuum magnitudes are from TM88 and are dereddened with our E_{b-v} (Table 1). Continuum magnitudes and colors are available for five of the "single" stars (Br 7, 8, 10, 50, and 74) and four of the binaries (Br 28, 32, 22 and 31 with partial data). Br 50 is excluded from the continuum color averages because TM88's spectrophotometric values of $b - v$, both continuum and total, disagree seriously with our values and with those of Smith 1968*b*. The v value is included, however, because the star is significantly the brightest and its exclusion would create an illusion of difference due to different samples. Br 62 is also excluded because the reddening is very uncertain.

[b] Color excess ratios used for $u' - b$, $u - b$, $b - v$, $b - v'$ are from Smith 1968*b*, and for $v - r$ from Massey 1984.

[c] Stars with complete data in Smith 1968*b* are all six "single" stars Br 7, 8, 10, 43, 50, and 74; Br 10 is excluded for the M_v average, because it falls more than 2 σ above the mean. Spectrophotometry of TM88 gives mean $v \approx 0.1$ mag brighter, but the same mean $u - b$ and $b - v$.

and colors (Table 5). This is remarkable uniformity for stars that have become infamous for their irregularity. We take these values as the properties of a typical WC4 star.[1]

Figures 4 and 6 imply that values of v_0 brighter than 13.0 are a result of the inclusion of one or more OB stars in the measurement aperture. Prévot-Burnichon *et al.* (1981) find that *all* of the relevant stars in Figure 6 have "halos," indicating the presence of other unresolved stars. The flux measures indicate that *in each binary or group* (except perhaps Br 10), *there is one and only one WC4 star*. The double brightness of Br 10, in both line and continuum, suggests the possible presence of two WC4 stars.

b) Reddening Determinations

The flux ratio $\lambda5808/\lambda4650$ can be used to determine the reddening. For an intrinsic total flux ratio of $C_0 = -0.22$ dex and a peak flux ratio of -0.19 dex, the absorption at $\lambda5808$ is given by

$$\delta \log f_\lambda(5808, \text{ISabs'n}) = 3.32[\log f, \text{total}(4650/5808) + 0.22] ,$$

and very provisionally

$$\delta \log f_\lambda(5808, \text{ISabs'n}) = 3.32[\log f, \text{peak}(4650/5808) + 0.19] .$$

The variation of the flux ratio with spectral subclass will be determined in a later paper. Flux ratio determinations are accurate to perhaps 0.10 dex; the intrinsic range (which is as yet unknown) is smaller than this. Thus, determination of the reddening by this method is (at present) accurate to about 0.13 dex (σ). Absorption at $\lambda5808$ is then only known to 0.4 dex (1 mag). This is not very accurate, but can be improved by more accurate observations and improved calibration. The sensitivity of the line ratio to reddening is slightly greater than that of $B - V$.

[1] If we use the E_{B-V} corrections from nearby stars, we find that the EW of $\lambda5808$ is constant for the six faintest stars, but the v_0 covers a range of 1.5 mag, from $v_0 = 13.3$ to 14.9: Br 10 and 50 are brighter than the average, Br 43 falls on the average line, and Br 7, 8, and 74 are fainter than the average for their EW. If the spread is real, it is hard to understand the tight correlation of EW with v_0 among the composite stars.

c) Excitation of λ5808 and λ4650

Hillier (1988) finds that the C IV $\lambda5808$ line is produced principally by recombinations, but he is unable to reproduce its strength. Constancy of the line flux from one star to another suggests constancy of the UV flux available to ionize C IV, viz., at wavelengths shortward of 192 Å.

The $\lambda4650$ line is generally supposed to originate from the C III $3p^3P_0$–$3\ s\ ^3S$ transition and would be expected to decrease in early subtypes which display higher ionization. The classification ratio, C IV $\lambda5808$/C III $\lambda5696$, changes by a factor of 100 or more from WC4 to WC9; however, the C IV $\lambda5808$/C III $\lambda4650$ ratio changes by only a factor of 2. To account for the persistence of the $\lambda4650$ line to early spectral subtypes, CM89 suggest that either C IV contributes to the $\lambda4650$ emission or that the $\lambda4650/\lambda5696$ ratio is anomalous, like the N IV $\lambda3480/\lambda4057$ ratio in WN stars, to which it is isoelectronic. We now assess both possibilities and also the contribution by He II $\lambda4686$.

i) C III λ4650

Hillier (1988) noted that, in WN stars, the ratio N IV $\lambda3480/\lambda4057$ is markedly different in different stars. Both lines are produced by transitions between levels with $n = 3$, and both are produced by continuum fluorescence; however, $\lambda3480$ is a triplet, while $\lambda4057$ is a singlet. The greater population of the triplet levels means that the "traffic" through the $\lambda3480$ transition will be regulated to the number of continuum photons available, and the strength of the line is not sensitive to the number of N IV ions.

The isoelectronic transitions in C III are $\lambda4650$ (triplet) and $\lambda5696$ (singlet). By analogy, we expect the $\lambda4650$ line to be less sensitive than the $\lambda5696$ line to the number of C III ions, and to persist to early subtypes.

ii) C IV λ4658

Transitions in C IV that contribute to the $\lambda4650$ band are $6g$–$5f$ ($\lambda4658$) and $6f$–$5d$ ($\lambda4646$). We expect these to be mostly resulting from recombination and to become stronger in the early subtypes. The next strongest C IV line from these levels is the $6d$–$5p$ transition at 4442 Å, which is visible in most WC spectra. Hillier (1989) finds that the line is fluoresced, which accounts for its persistence but removes its usefulness as an indicator. C IV 10–7 at 5470 Å is, however, mostly due to recombination. Hummer and Storey (unpublished calculations) give effective recombination coefficients (α) for the transition for a range of T_e and N_e. The predicted line strengths are proportional to $Q = h\nu\alpha$. At $T_e = 30{,}000$ K and $\log N_e = 11$, the values of Q for $6g$–f, $6f$–$5d$ and 10–7 are 2.17 E−26, 7.49 E−27, and 1.02 E−27, respectively. We therefore expect a flux ratio of $\lambda 4658 + \lambda 4647$ to $\lambda 5470$ of 1.47 dex if there are no optical depth effects. Table 6 gives EWs for various subclasses from the (unpublished) atlas of WC profiles (Smith and Kuhi; henceforward the SK atlas). Table 7 gives the observed line ratios for LMC and galactic stars. Two conclusions follow:

1. The contribution of C IV to the $\lambda 4650$ emission could be as high as 30%–60% in WC4–5 stars.
2. The small ratio of $\lambda 4650/\lambda 5470$ (1.5–1.2 dex) in WC6–9 stars suggest that something else contributes to the $\lambda 5470$ line.

iii) He II $\lambda 4686$

In WC4 stars, the lines are so broad that He II $\lambda 4686$ is completely blended with $\lambda 4650$. In the other WC subclasses, the lines are partially resolved. Table 7 gives the flux ratios $\lambda 4650/\lambda 5411$ for the LMC WC4 stars and $\lambda 4686/\lambda 5411$ for the SK atlas WC5–8 stars. If the latter ratio applies in WC4 stars, then $\lambda 4686$ could account for 8% to 30% of the flux in the $\lambda 4650$–4686 blend.

In conclusion, a fluorescence mechanism for C III $\lambda 4650$ and contributions from C IV and He II seem sufficient to account for the persistence of the $\lambda 4650$ line to early spectral subtypes. The net effect is that the flux ratio of $\lambda 5808$ to $\lambda 4650$ is very insensitive to subclass.

d) *Widths of $\lambda 5808$ and $\lambda 4650$*

There is a significant difference in line width between $\lambda 5808$ and $\lambda 4650$, which becomes greater for narrow-line WC4 stars and is shown in Figure 7. The ratio for the WC4 stars ranges from about 0.7 to 1.0. The double peak in the $\lambda 4650$ profile in the LMC spectra strongly suggests that the contribution of He II $\lambda 4686$ is responsible. The impression is reinforced by looking at the collage of WC spectra of different subclasses given in the atlas of Torres and Massey (1987; henceforward referred to as the TM atlas). In the WO stars, the He II and C III contributions appear to drop out, leaving only the C IV 6–5 recombination, which is weaker and narrower than the $\lambda 5808$ line.

Whatever the reason for the change in line width, the consequence is that peak and total fluxes need to be calibrated explicitly if these are to be accurate for distance determinations.

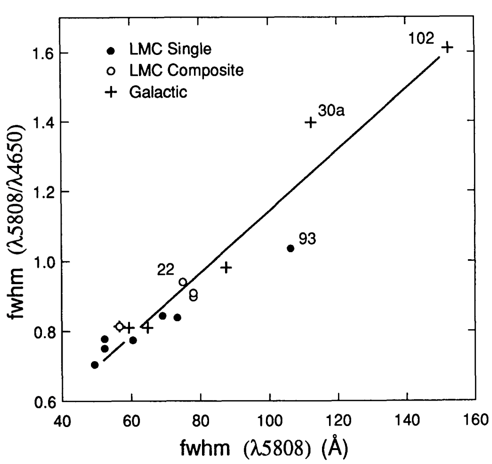

FIG. 7.—Plot of the ratio FWHM of the $\lambda 5808$ and $\lambda 4650$ emission line in the spectra of LMC and Galactic WC4 and WO stars vs. the FWHM of $\lambda 5808$. The WO stars, Br 93, WR 30a, and WR 102, all have ratios greater than 1; WR 30a has a composite spectrum. LMC stars believed to be composite are shown as open circles.

e) *Galactic WC4 Stars*

If the properties of WC4 stars in other galaxies are the same as those in the LMC, we may determine distances from the line fluxes alone. This would be invaluable for faint crowded galactic and extragalactic stars.

Figure 1*a* includes the spectrum of WR 19, which is fairly typical of the galactic WC4 stars. The EWs of the two strong carbon lines are clearly smaller than for the LMC stars, but EWs of the weak lines, which are mostly due to oxygen lines, are similar; i.e., the ratio of the C/O lines is different. Taking C IV $\lambda 5808$/O V $\lambda 5590$ as an indicator, the EW (or flux) ratio is 1.0 ± 0.1 dex for the four WC4 stars in Table 2 and 1.4 ± 0.1 dex for the six strong-line WC4 stars in the LMC, a significant difference of 0.4 dex.

The LMC stars display higher ionization. This manifests itself in the C IV $\lambda 5808$/C III $\lambda 5696$ ratio which was the basis on which TCM88 reclassified the LMC stars to WC4.[2] The higher ionization also manifests itself in the oxygen lines. Smith and Willis (1983) noted that O VI $\lambda 3811,34$ is stronger in the three LMC stars observed by them than in galactic WC5 stars. Our O VI EWs for the galactic WC4 stars are uncertain, but the LMC stars appear to be stronger in this line.

It is not clear whether the C/O difference results from ionization or abundance. However, it clearly raises the question of whether the carbon fluxes are the same in the two galaxies. Since no galactic WC4 star has an independent distance determination, we are unable to resolve the matter at this time.

As for the LMC stars, the EWs of C IV $\lambda 5808$ in the galactic stars cover a significant range. If the intrinsic line fluxes are the same in all stars, then most of the galactic stars have companions which contribute to their continua. WR 19 and 143 would require companions 0.8 mag brighter than the WR star.[3] They show no signs of absorption spectra, but neither do most of the LMC stars which we believe (Prévot-Burnichon *et al.* 1981) to be multiple systems.

Table 8 applies both the line flux and M_v, $b - v$ method to the six galactic WC4 and WO stars with available flux data. In the line flux method, we assume that the carbon line fluxes equal the value for the LMC stars. In the continuum method, we must make an assumption about whether the stars are "single" or multiple. For the present purpose, we assume they are single and have $M_v = -4.5$ and $(b - v)_0 = -0.30$. The distances are then larger than derived by van der Hucht *et al.* (1988) (with $M_v = -3.0$) but smaller than derived from the line fluxes. The last column gives the difference in magnitude

[2] For the LMC WC4 stars, the EW ratio is 1.5 to 2.1 dex. For the galactic stars, it ranges from 1.3 to 1.7. The highest $\lambda 5808/\lambda 4650$ ratio is for WR 144 which, of the galactic WC4 stars, is the most similar to the LMC stars.

[3] Smith (1968*a*) classified both stars as "+OB" on the grounds of weak emission lines (WR 19) and photometric parameters (WR 143).

TABLE 6

log (Equivalent Width) and Line Widths from Unpublished Smith and Kuhi Atlas

WR Number	HD Number	Spectrum	λ5808 log (EW)	λ5808 FWHM	λ5696 log (EW)	λ5696 FWHM	λ5590 log (EW)	λ5590 FWHM	λ5411 log (EW)	λ4686 log (EW)	λ4686 FWHM	λ4650 log (EW)	λ4650 FWHM	λ4442 log (EW)	λ5470 log (EW)	log (EW Ratios) λ4686/λ5411	log (EW Ratios) λ4650/λ5470	FWHM Ratios λ5808/λ5696	FWHM Ratios λ5590/λ5696
111.......	165763	WC5	2.87	45	1.88	61	1.82	53	1.39	2.10:	...	3.02	53	1.54	1.59	0.71	1.43	0.74	0.87
4.......	16523	WC5	2.91	44	1.76	68	1.66	55	1.07	1.99:	...	3.00	53	1.58	1.52	0.92	1.48	0.65	0.81
137.......	192641	WC6	2.10	36	1.93	53	0.95	37	0.82	1.69	33	2.31	33	1.02	0.98	0.87	1.33	0.68	0.70
135.......	192103	WC7	2.31	28	2.65	38	1.00	31	1.37	2.05	24	2.61	24	1.44	1.33	0.68	1.28	0.74	0.82
103.......	164270	WC9	2.12	32	2.57	20	0.91	12	1.07	1.47	23	2.11	16	1.02	1.10	0.4	1.01	1.60	0.60

Note.—All EW and FWHM are in Å.

TABLE 7

Some Line Ratios in WC Stars

Line Ratio	Subclasses	log EW	log (ctm flux)	log (line flux)
λ4650/C IV λ5470	WC4	...	0.24[b]	2.0 − 1.7[c]
λ4650/C IV λ5470	WC5–9	1.5 − 1.0[a]	...	1.7 − 1.2[d]
λ4650/He II λ5411	WC4	...	0.22[b]	2.1 − 1.5
He II λ4686/He II λ5411	WC5–8	0.8 ± 0.1[a]	...	1.0 ± 0.1[d]

[a] From Table 6.
[b] From $\delta \log f_\lambda(\mathrm{ctm})/\Delta\lambda$ values in Table 5.
[c] From Table 3.
[d] Continuum flux ratio assumed to be the same as for WC4.

TABLE 8

DISTANCES OF GALACTIC WC4 STARS

WR	SPECTRUM	v	$b-v$	$v-r$	REF	n	$-\log f(\lambda5808)$ Total	$-\log f(\lambda5808)$ Peak	$C=\log f$ ($\lambda5808/\lambda4650$) Total	$C=\log f$ ($\lambda5808/\lambda4650$) Peak	C−Co[a] Total	C−Co[a] Peak	E_{b-v}[b] Total	E_{b-v}[b] Peak	E_{b-v}[b] $b-v$	M_v	d(kpc)[c] CONTINUUM	D(kpc)[d] LINE FLUX Total	D(kpc)[d] LINE FLUX Peak	log EW $\lambda5808$ (Å)	Δm[e] WR−COMPANION
19......	WC4	13.75	1.04	0.85	1	1	10.99	12.96	0.36	0.38	0.58	0.57	1.35	1.33	1.34	−4.5	3.48	4.81	6.08	2.73	0.84
		13.75	1.06	0.72	2	−1	11.15	...	0.35	...	0.57	...	1.33	...	1.36	−4.5	2.43	6.01	...	2.64	1.15
38.....	WC4	15.4	0.93	0.67	1	1	11.62	13.48	0.31	0.38	0.53	0.57	1.23	1.33	1.23	−4.5	9.36	12.03	11.06	2.88	0.23
		15.4	0.84	0.55	2	−3	11.61	...	0.36	...	0.58	...	1.35	...	1.14	−4.5	11.10	9.82	...	2.94	−0.06
143.....	WC4	11.95	1.21	0.78	3	2	10.32	...	0.42	...	0.64	...	1.49	...	1.51	−4.5	1.13	1.77	...	2.74	0.80
30a.....	WO4+O4	13.33	0.79	0.56	1	6	11.43	13.49	0.61	0.52	0.83	0.71	1.93	1.65	1.09	−6.0	9.38	...	...	...	...
102.....	WO1	15.10	0.77	0.38	1	1	12.15	14.33	−0.12	−0.27	0.10	−0.08	0.23	−0.19	1.07	−2.8	5.04	...	...	...	...
		14.77	...	0.57	3	1	12.17	...	...	...	...	...	...	...	...	...	...	...	...	...	...
142.....	WO2	13.82	1.39	0.88	3	1	11.29	...	0.31	...	0.53	...	1.23	...	1.69	−2.9	0.87	...	...	...	...

NOTE.—Data for WR 144 and WR 146 are incomplete, and fluxes cannot be determined from available data.

[a] C−Co = log [f, total ($\lambda5808/\lambda4650$)] + 0.22, or = log [f, peak ($\lambda5808/\lambda4650$)] + 0.19.

[b] $E_{b-v} = 2.33(\mathrm{C}-\mathrm{Co})$, or $= (b-v) + 0.30$.

[c] d is derived in the usual manner from v, M_v, and $A_v = 4.1\,E_{b-v}$.

[d] $\log D(\mathrm{kpc}) = 0.5\,[-\log f(\mathrm{tot}, \lambda5808) - 3.32\,(\mathrm{C}-\mathrm{Co}) - 7.6]$, or $= 0.5\,[-\log f(\mathrm{peak}, \lambda5808) - 3.32\,(\mathrm{C}-\mathrm{Co}) - 9.4]$.

[e] Assumes that the single star has log EW($\lambda5808$) = 3.23.

REFERENCES.—(1) Present data; n = number of independent observations. (2) TM88; $-n$ = quality factor; fluxes from EWs of CM89. (3) Massey 1984; n = number of observations; fluxes from EWs of CM89.

between the WR stars and the O star companion needed to bring EWs, fluxes, and distances into agreements.

Table 8 also includes reddening and distance estimates using *peak* fluxes. The WO stars immediately distinguish themselves by producing dramatic disagreement between the two methods. This comes about because the WO stars have a FWHM ratio of $\lambda5808/\lambda4650$ greater than one (Fig. 7). The line-flux ratio derived for WC4 stars is certainly not valid for WO stars; should one mistake a WO star for a WC4 star, the disagreement between the two reddening estimates is a clear warning.

We have reclassified WR 30a as WO4 + O4 (see WC4 + O4 in van der Hucht *et al.* 1988). The $\lambda4650$ line has a normal width for a WC4 star (FWHM = 80 Å), but the $\lambda5808$ line is much stronger and broader (FWHM = 112 Å. O VI $\lambda3811{,}34$ (the original defining feature designated by Barlow and Hummer 1982) is stronger than the surrounding blend of lines, but not as strong as in other WO stars shown in the TM atlas. Except for the ratio of the line widths, this spectrum is easily mistaken for a WC4, but use of the flux calibrations for WC4 would result in extreme errors (as Table 8 shows).

f) Other Galaxies

It will be of great interest to compare line fluxes for WC4 stars in other galaxies. A number of these have been observed spectroscopically (e.g., Massey and Conti 1983; Massey, Conti, and Armandroff 1987; Moffat and Shara 1983, 1987; summary by d'Odorico and Rosa 1982), but, unfortunately, accurate fluxes are not available. d'Odorico and Rosa (1982) give flux estimates for the $\lambda5808$ feature (normalized to the distance of the LMC) in Mk E (Br 83) in the LMC, a WN + WC spectrum in NGC 604 (in M33), the WO star in IC 1613, and a WN + WC spectrum in NGC 5128. The flux from Mk E and from the WO star in IC 1613 are lower, with $\log f \approx -12$. However, the NGC 604 and NGC 5128 spectra have $\log f(tot, \lambda5808) \approx -11$ as found for the LMC stars. For WC stars in M31, Moffat and Shara (1983) give relative intensity plots for five WC5–6 stars. These yield a line flux ratio of (-0.36 ± 0.09) dex and $\log f(tot, \lambda5808) \approx -14.7 \pm 0.1$. The ratio agrees with the value for the same classes in the Galaxy (Smith, Shara, and Moffat 1989) and indicates that all stars are unreddened. The flux is a factor of 25 lower than for the LMC stars.

For stars classified WCE in M33, Massey and Conti (1983) give EWs which correspond to a range of $\log f(tot, \lambda5808)$ from the LMC value (MC 2) to about 6 times fainter (MC 19). Direct flux measures with well-determined calibrations are needed.

WC4 and 5 spectra are conspicuous and easy to identify, even for very faint stars, because C IV $\lambda5808$ is very strong, with a peak flux 15 to 100 times higher than any other line in its vicinity. The main potential confusion is with WO stars. These may be distinguished by the characteristics:

1. Strong lines of one or more of the oxygen ions: O VI $\lambda3811$, $\lambda3834$, O V $\lambda5590$, or O IV $\lambda3480$;
2. Line width of C IV $\lambda5808$ greater than 90 Å;
3. Line width of C IV $\lambda5808$ greater than that of $\lambda4650$;
4. Log EW ($\lambda5808/\lambda4650$) outside the normal range for WC4 stars (0.0–0.4).

Criterion 1 was the original defining feature of the WO stars (Barlow and Hummer 1982). However, the O VI and O IV lines are often outside the observed wavelength range; criteria 2, 3, and 4 appear to be universal properties of the class and are easier to apply in practice.

V. SUMMARY

The main results of this paper are the following:

1. It is a tenable hypothesis that $(b - v)_0$ is the same for all observed LMC WC stars.
2. The flux in the C IV $\lambda5808$ line is 3×10^{36} ergs s^{-1} and is constant within observational errors for all but one of the 10 WC4 stars with available flux data.
3. The flux ratio $\lambda5808/\lambda4650$ is (-0.22 ± 0.10) dex and is also constant within the errors.
4. The WC5 star, Br 68, and the WC6 star, Br 22, have the same $\lambda5808$ line flux as the WC4 stars, but the WO4 star, Br 93, appears to be somewhat weaker in $\lambda5808$ than the WC4 stars.
5. Stars believed to be single have an absolute v magnitude $M_v = -4.5 \pm 0.2$ for $(m - M)_0 = 18.5$. Stars brighter than $v_0 = 13$ mag appear to be binaries or unresolved groups of stars.
6. Constancy of the $\lambda5808$ flux implies constant UV flux shortward of 192 Å. Constancy of the $\lambda4650$ flux appears to be a fortuitous accident resulting from the blend of lines in the emission feature.
7. There is a tight correlation between the ratio of line widths ($\lambda5808/\lambda4650$) and the width itself; the correlation is shared by galactic and LMC stars. WO stars have $\lambda5808$ line width greater than 90 Å and a line width ratio grater than one.
8. We reclassify WR 143 as WC4 and WR 30a as WO4 + O4, leaving the number of galactic WC4 stars at five and increasing the number of galactic WO stars to three.
9. The C/O line ratios are systematically higher in the galactic WC4 stars than in the LMC stars.
10. Scant flux measurements of WC stars in M31 and M33 indicate that the C IV $\lambda5808$ flux may be less than for the WC4 stars in the LMC.

The emission lines of WC4–6 stars are conspicuous in external galaxies and may be useful as standard candles. With the advent of linear area detectors, it is very easy to measure the flux in an emission line. For strong lines, the flux measures can be much more accurate than the EWs, because the latter require good signal-to-noise ratio in the continuum. Since the continuum in distant stars is almost always contaminated by the light of unresolved stars, the accuracy of absolute magnitudes and colors are likely to be low.

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