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ABSOLUTE MAGNITUDES AND INTRINSIC COLOURS OF WOLF-RAYET STARS

*Lindsey F. Smith**

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Summary

Results of five-colour narrow band photoelectric observations are given for forty-three Wolf-Rayet (WR) stars in the Magellanic Clouds and for seventy-seven WR stars in the Galaxy. Photometric classification criteria are established and most WR stars in the Magellanic Clouds are classified. Absolute magnitudes are found to be correlated with spectral subclass; among the WN stars, those in the lowest excitation subclasses are the most luminous.

It is found that the WR stars in the Large Magellanic Cloud are very similar to stars of the same spectral subclass in the Galaxy. However, subclasses WC6, WC 7, WC 8 and WC 9 are completely absent from the Magellanic Clouds, and WN 6 stars are rare.

The relationship between absolute magnitude and spectral appearance of the WC 5 + OB stars and the WN 4 + OB stars is consistent with the hypothesis that these are binary systems in which WR stars, similar to single stars of the same type, are associated with O or B stars.

1. *Introduction.* In the Galaxy, determinations of absolute magnitudes are severely hampered by lack of knowledge of distances, and by the irregularity of interstellar absorption. Graham (1965), using distances of galactic clusters determined by Hβ photometry, derived absolute magnitudes for six WR stars; resulting values of M_V range from $-5{\cdot}2$ mag. to $-7{\cdot}1$ mag. Rublev (1963) obtains a range of M_V from $-4{\cdot}5$ mag. to $-7{\cdot}0$ mag. for WR stars in Cygnus and he noted that binary WR stars are more luminous than single WR stars. Earlier attempts by Roman (1951), Andrillat (1958) and Onderlicka (1958) were based on poor assumptions regarding the distances of the stars or the amount of interstellar absorption and gave rather lower luminosities. Clearly, errors in determining the absolute magnitudes of galactic WR stars are sufficient to mask any differences between the mean absolute magnitudes of the various subclasses.

The most reliable absolute magnitudes come from observations of WR stars in the Large Magellanic Cloud. Westerlund & Smith (1964) find, from photographic photometry, a range of absolute magnitude from $-3{\cdot}6$ mag. to $-9{\cdot}3$ mag. (for $m-M = 18{\cdot}8$ mag.). They also demonstrate that the absolute magnitude of the stars depends on the degree of multiplicity and, among WN stars, upon the membership or non-membership of the 30 Doradus complex or other associations. Up until the present time, few of the WR stars in the Magellanic Clouds have been assigned to subclasses. Thus, it has not been possible to determine the dependence of absolute magnitude on subclass.

The present paper presents the results of five-colour narrow band photoelectric photometry of WR stars in the Magellanic Clouds and in the southern Milky Way

* Present address: Department of Astronomy, University of California, Los Angeles.

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(Section 2). Westerlund (1966) has given results of narrow band photometry of most northern WR stars. The present programme was planned in conjunction with Westerlund's programme and uses a similar photometric system. The two studies provide nearly complete coverage of known WR stars in both hemispheres.

The use of narrow band interference filters is dictated by the strength and width of the emission bands in WR spectra. These have a significant effect on the observed magnitudes in any of the conventional broad band systems and the size of this effect is difficult to determine (e.g. Pyper 1966). The use of interference filters makes it possible to select regions of the spectrum containing virtually no emission lines, or single selected emission lines for measurement. A photo-electric scanner can also provide these data but, for faint stars, the filter technique is simpler and more efficient. The present programme requires observations of stars as faint as fifteenth magnitude. It is found that filters with a pass band of about 100 Å are sufficiently narrow to avoid serious contribution from emission lines but wide enough to allow reasonably accurate measurement of a fifteenth magnitude star with a 40-in. telescope.

Consistent spectral classification of galactic WR stars has been given in a previous paper (Smith 1968, henceforward referred to as Paper I). In this paper classifications are given, on the same system, for nearly all WR stars in the Magellanic Clouds. These are assigned from consideration of slit spectrograms or of photometric criteria (Sections 3.2 and 3.4). Thence it is possible to determine a mean absolute magnitude for each subclass represented in the Magellanic Clouds (Section 3.3). In Section 3.5 it is established that the WR stars in the Large Magellanic Cloud are similar to those in the Galaxy. Section 3.6 concerns the determination of mean absolute magnitudes for subclasses that are not represented in the Magellanic Clouds. Conclusions regarding the absolute magnitudes of single WR stars are given in Section 3.8 and Table XV. Conclusions regarding the absolute magnitudes and nature of binary WR stars are presented in Section 3.7.

In a later paper the distribution of WR stars in the Galaxy and in the Magellanic Clouds will be considered.

2. *Observations*

2.1 *The photoelectric equipment, the filter system.* Photoelectric observations have been made with a set of five narrow band interference filters. Three of these were chosen to have transmission bands which avoid, as far as possible, the emission lines in the spectra of WN stars. The transmission bands of the other two filters include the emission lines, N IV λ3480 and He II λ5412, respectively, and provide spectral classification parameters. The transmission curves of the filters were obtained on a Beckman ratio recording spectrophotometer in April 1964, before the observing programme was started and in April 1966, after the programme was complete; no changes were observed. Information regarding the manufacturers and the transmission properties of the filters are given in Table I. Table II gives the emission lines occurring between half peak transmission points of each filter. Particularly strong lines are marked with an asterisk, weak lines with '†'. '‡' indicates that the wavelength listed is that of the approximate centre of a multiplet. The table is compiled from the tables of lines in WR spectra given by H. J. Smith (1955, henceforward referred to as HJS).

Most of the observations were made at the Cassegrain focus of the 40-in. reflector at Siding Spring Observatory, supplemented by a few nights at the

TABLE I

Transmission properties of the filters

Name, Maker	Central wavelength (Å)	$1/\lambda$ (μ^{-1})	Peak transmission (%)	Width at half peak transmission (Å)	Width at 10% of peak transmission (Å)
u′ Schott	3500	2·86	43	80	210
u Schott	3650	2·74	39	100	280
b Spectrolab	4270	2·34	60	70	170
v Spectrolab	5160	1·94	50	130	180
v′ Schott	5500	1·82	64	230	410

TABLE II

Emission lines occurring between half peak transmission points

Filter	WN	WC
u′	N IV λ3481‡	{O II λ3471†, O V λ3501†}
u		{C III λ3609, C IV λ3689, O VI λ3622}
		C II λ4267
b, *v*		{C II λ5145‡, O V λ5114†, O VI λ5112†}
v′	He II λ5412*	{C IV λ5411*, C IV λ5471*, O V λ5597*, O VI λ5410, He II λ5412*}

* Denotes a very strong line.

† Denotes a comparatively weak line in all classes.

‡ Denotes the central wavelength of a multiplet band.

Cassegrain focus of the 50-in. reflector at Mount Stromlo Observatory. A dry ice refrigerated 1P21 photomultiplier was used for all observations.

2.2 *Determination of zero points and reduction of observations.* In the present photometric system, all filters have band widths of less than 250 Å. Hence, λ_{eff} for each filter is well defined and effectively independent of the colour of the star and of the spectral response of the detector. Thus, to define the standard system it is necessary only to define the zero point in each colour. These have been chosen to give the best average agreement with a selection of spectrophotometric standards established by Oke (1964) and Code (1960). Because the *u*-filter (λ_{eff} = 3650 Å) includes the Balmer discontinuity in its redward ring, the expected values for magnitudes at this wavelength were determined by numerical integration of the product of the energy distribution of the star and the transmission of the filter.

Kuhi (1966) has shown that WR spectra show no Balmer discontinuity. Hence, the measured value of u for these stars will represent the continuum at $\lambda 3650$.

Since all Oke and Code standards are near the equator, secondary standards were chosen from the photometric sequences of Wesselink (1963) near the Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC), and from the list of Morris (1961) along the galactic plane.

TABLE III

Photoelectric standards

Star	Sp	v	$(u'-b)$	$(u-b)$	$(b-v)$	$(v-v')$
ξ^2 Cet	B9 III	4·25	+1·11	—	−0·15	−0·17
ν Ori	B0 V	4·51	−0·20	−0·08	−0·30	−0·12
η Hya	B3 V	4·19	+0·22	+0·26	−0·26	−0·10
θ Crt	B9	4·61	+1·04	+0·87	−0·17	−0·07
θ Vir	A0	4·31	+1·31	+1·04	−0·11	−0·06
109 Vir	A0 V	3·67	+1·23	+1·00	−0·11	−0·03
58 Aql	A0	5·63	+1·32	+1·07	−0·03	−0·01
HD 3719	A0	6·89	+1·34	+1·11	−0·03	−0·04
25938	A0	6·58	+1·31	+1·09	−0·05	−0·05
52812	B3 V	6·87	+0·18	+0·22	−0·24	−0·10
63308	B3 V	6·51	+0·29	+0·30	−0·20	−0·10
72350	B5 IV	6·27	+0·52	+0·46	−0·13	−0·03
86659	B4 IV	6·14	+0·40	+0·40	−0·19	−0·08
116226	B7 IV	6·35	+0·64	+0·52	−0·16	−0·06
125721	B3 V	6·03	−0·02	+0·05	−0·18	−0·08
158186	B3 IV	7·01	+0·01	+0·07	−0·07	−0·02
170978	B3 IV	6·81	+0·52	+0·48	−0·07	−0·03
180183	B3 IV	6·74	+0·18	+0·23	−0·23	−0·08

Six nights on the 40-in. reflector were used for establishing the zero points and for measuring the secondary standards. Extinction coefficients were determined from observations of the same star at different zenith angles. Table III gives the adopted values of the magnitudes and colours of the primary and secondary standards. Differences between the observed values for the colours of the primary standards and those derived from the work of Oke and Code are generally of the order of $\pm 0{\cdot}02$ mag. For $(u-b)$, only, the deviations are of the order of $\pm 0{\cdot}04$ mag. implying that some inconsistencies occur in the Oke and Code magnitudes near the Balmer discontinuity.

Observations of the programme stars were reduced by direct comparison with a nearby standard which was always measured within an hour, usually within half an hour, of the observation of the programme star. A correction for differential extinction was applied. In this way, the derived magnitudes and colours are independent of slow changes of extinction with time and direction.

2.3 *Accuracy of the photometry and detection of variables.* The standard errors of the mean values of the magnitudes and colours have been estimated from the range of values obtained on different nights. For the standard stars, the standard error in each of v, $(u'-b)$, $(u-b)$ and $(v-v')$ is 0·015 mag.; the standard error in $(b-v)$ is 0·007 mag. For programme stars, the standard deviation of a single observation is given in Table IV for successive magnitude intervals. The standard error (S.E.) of each of the mean magnitudes and colours (Tables VI and VII) is given by: S.E. = S.D./$\sqrt{n}$, where n is the number of observations and is generally about 3. The number of observations quoted in the last column of Tables VI and VII is the number of observations of the colour (b–v); most other colours have been measured more often than this.

TABLE IV

Standard deviation of a single observation

b	b	u'–u	u–b	b–v	b–v'
<9	0·02	0·01	0·02	0·01	0·01
9–12	0·04	0·02	0·02	0·02	0·02
12–14	0·06	0·03	0·04	0·03	0·04
14–15	0·13	0·11	0·12	0·07	0·06
>15	0·20	0·20	0·18	0·10	0·12

If the range of observed magnitudes exceeded four times the expected standard deviation, the star is marked variable (v) in Tables VI and VII; there are four stars in this category. If the range lay between 3 and 4 standard deviations then the star is marked possibly variable (v?); there are seven stars in this category.

The present filter system is similar to that used by Westerlund (1966). Zero points were established by Westerlund in the same way, i.e. by observing spectrophotometric standards chosen from the lists of Oke (1964) and Code (1960). The differences in the central wavelengths in the two systems are small and we assume that the systems differ only in zero point. The bandwidths of Westerlund's filters are, in general, slightly smaller than the author's. The two programmes have three primary standards (58 Aql, ξ^2 Cet, ν Ori) and five WR stars (HD 165688, HD 168206, HD 165763, MR 87, HD 50896) in common. Table V gives the mean differences in the magnitudes and in the colours between the two systems in the sense (present system – Westerlund's system). Two of the WR stars, MR 87 and HD 50896 were observed by Westerlund only once; and these stars are not used in the comparison. Neither are values of (u–b) for the late type primary standards (58 Aql, ξ^2 Cet) used because the u-filter includes the Balmer discontinuity in its redward wing and the observed value is unduly sensitive to the transmission characteristics of the filter. The overall standard deviations are of the order of 0·05 mag. which, considering the complexity of the spectra and the differences in the filter bandwidths, is regarded as satisfactory.

TABLE V

Comparison between the present system and Westerlund's system

	δv	$\delta(u$–$b)$	$\delta(b$–$v)$
Mean difference	$+0^{m}\cdot07$	$+0^{m}\cdot01$	$+0^{m}\cdot01$
Standard deviation	±0·06	±0·03	±0·03

2.4 *Results*. In the LMC, 41 WR stars have been observed, including stars from all spectral subtypes, magnitude ranges and types of location, as defined by Westerlund & Smith (1964; henceforward referred to as WdS). Only two WR stars are

TABLE VI

Photometry of WR stars in the Magellanic Clouds

Star		b	u′–b	u–b	b–v	b–v′	n
			WR stars in the LMC				
WS	1	14·82	−0·71	−0·08	−0·25	−0·06	2
	2	13·95	−0·54	−0·07	−0·15	+0·17	2
	3	15·05	−0·42	−0·60	−0·05	+0·30	4
	4	15·02	−0·30	−0·47	−0·11	+0·23	4
	5 v?	10·66	−0·08	−0·03	−0·22	−0·32	6
	6	13·85	−0·21	−0·37	−0·10:	+0·14	2
	8	12·63	−0·26	−0·16	−0·10	−0·11	3
	9	14·30	−0·47	−0·10	−0·09	−0·05	2
	10	13·70	−0·39	−0·05	−0·06	+0·04	3
	11	12·95	−0·31	−0·12	−0·16	−0·22	3
	12	12·16	−0·15	−0·05	+0·07	+0·10	4
	13	14·66	−0·79	−0·14	−0·08	+0·23	3
	14	14·60	−0·53	+0·03	−0·11	+0·16	4
	15	11·17	−0·05		−0·14	−0·20	1
	18	13·27	−0·34	−0·20	−0·13	−0·10	4
	19	12·55	−0·35	−0·21	−0·17	−0·17	5
	21	12·67	−0·20	−0·18	−0·25	−0·25	4
	22	14·72	−0·52	−0·08	−0·08	+0·13	4
	23	11·29	−0·19		−0·21	−0·26	1
	24	12·27	−0·20	−0·15	−0·24	−0·30	2
	25	14·89	−0·58	−0·09:	−0·11	+0·05:	2
	26	9·82	+0·04	+0·04	−0·09	−0·15	4
	27	13·28	−0·22	−0·20	−0·19	−0·24	3
	28	13·97	−0·40	−0·08	−0·21	−0·21	4
	30	15·25	−0·60	−0·09	−0·10	+0·05	3
	31	14·10	−0·28	−0·50	−0·26	+0·07	3
	32	13·24	−0·15	−0·17	−0·18	−0·17	2
	34	14·67	−0·64	−0·19	−0·07	+0·08	4
	35	13·88	−0·14	−0·39	−0·21	+0·18	3
	39	13·09	−0·12	−0·15	−0·25	−0·18	2
	40	11·77	+0·10	+0·08	+0·02	+0·03	3
	42	15·67	−0·28	−0·11	+0·09	+0·42	4
	43	11·54	+0·08	+0·07	+0·03	+0·02	5
	45	12·93	−0·31	−0·14	−0·06		2
	46	11·04	−0·20	−0·13	−0·11	−0·12	4
	47	12·19	−0·04	+0·02	+0·03	+0·09	2
	48	13·13	−0·08	+0·13	+0·07		2
	49	13·26	−0·16	−0·12	−0·15	−0·10	2
	50	13·22	−0·30	−0·07	−0·13	−0·13	3
	53	14·59	−0·67	−0·09	−0·04	+0·14	2
R	136	9·47	+0·07	+0·09	+0·03	+0·02	2
			WR stars in the SMC				
SMC 1* v?		11·53	−0·29	−0·14	−0·22	−0·28	5
SMC 2†		12·81	−0·30	−0·19	−0·24	−0·25	4

* HD 5980.
† $1^h 29^m{\cdot}9$, $-73° 33'$ (1975).

TABLE VII

Photometry of galactic WR stars

Star	Sp	*b*	*u′–b*	*u–b*	*b–v*	*b–v′*	*n*
MR 6 v	WN5	6·87	−0·74	−0·16	−0·07	+0·12	10
7	WN5	12·07	−0·40	+0·13	+0·33	+0·64	5
9	WN6−C7	10·99	−0·04	+0·09	+0·43	+0·65	4
10	WC6+O7 : I	11·80	+0·57	+0·39	+0·76	+1·08	4
11	WN4·5	11·26	+0·18	+0·25	+0·18	+0·25	4
12	WC8+O7	1·42	−0·20	−0·12	−0·32	−0·36	1
13	(WN6)	11·54	+0·26	+0·28	+0·48	+0·68	2
15	WC6 : (+OB)	14·65	+0·77	+0·50	+0·82	+1·43	4
16 v?	WC6	9·57	+0·75	+0·20	+0·15	+0·51	5
17	WC6	12·48	+0·97	+0·59	+0·75	+1·39	4
19	WN8	8·68	+0·13	+0·12	+0·25	+0·36	5
20	WC7(+OB)	11·15	−0·05	−0·13	+0·04	+0·35	5
21	WN5	11·74	−0·24	+0·28	+0·54	+0·99	3
LS 3	WC5+OB	14·80	+0·83	+0·79	+0·95	+1·44	2
MR 23	WN4−C+OB	10·10	+0·18	+0·23	+0·30	+0·41	5
25	WN7	6·47	−0·04	+0·01	+0·03	+0·06	3
26	WC6	9·75	+0·29	+0·08	+0·04	+0·39	3
28	WN7	6·43	−0·16	−0·06	−0·06	−0·08	3
29	WN7+O7	8·46	+0·16	+0·17	+0·29	+0·37	3
LS 4	WC6+OB	15·76	+0·94	+0·70	+1·03	+1·61	3
MR 30	WC6+OB	13·00	+0·30	+0·17	+0·27	+0·48	4
31	WN4+BOn::	10·97	+0·15	+0·24	+0·28	+0·40	3
32	WN8+OB	11·51	+0·57	+0·50	+0·63	+0·82	4
33	WC5	12·54	+0·21	−0·01	+0·20	+0·55	4
34 v	WN8	7·96	−0·02	+0·01	+0·11	+0·21	20
LS 7	WC6:+OB:	14·9	+1·2			+0·8	1
MR 36	WC7+BOV:	8·19	+0·10	+0·05	−0·06	+0·01	3
39	WN4	13·33	−0·22	+0·11	+0·37	+0·55	4
40 v?	WN3	10·96	−0·17	−0·08	0·00	+0·05	3
42	WN6	11·81	+0·45	+0·42	+0·72	+0·97	3
43	WC6+O9·5I	5·58	−0·11	−0·05	−0·11	−0·14	1
44	(WC6)	13·03	+0·71	+0·47	+0·54	+0·91	2
46	WC5	10·13	+0·07	−0·17	+0·15	+0·56	3
47	WC7	11·22	+0·63	+0·38	+0·16	+0·41	3
48	WN4	13·45	+0·02	+0·22	+0·46	+0·65	4
LS 8	WC6	14·23	+0·47	+0·26	+0·26	+0·60	3
MR 49 v?	WN6−C	11·27	+0·10	+0·15	+0·40	+0·63	4
50	WC7	9·93	+0·18	+0·01	−0·18	+0·03	3
51	WN5	13·50	−0·42	+0·06	+0·42	+0·74	2
52	WC7	14·19	+1·26	+0·82	+0·94	+1·58	2
LS 9	(WC9:)	14·37	+1·28	+0·69	+0·69		1
MR 53	WN6	12·84	−0·17	+0·05	+0·28	+0·47	3
54	WN8	12·44	+0·60	+0·48	+0·73	+1·00	3
55	WN6	12·95	+0·36	+0·44	+0·74	+1·07	3
56	WC9	9·57	+0·48	+0·34	+0·14	+0·13	4
57	WC9+OB	11·06	+0·92	+0·73	+0·91	+1·21	3
LS 10	WR:	15·04	+1·2	+2·3	+0·47		1
MR 58	WN6	10·28	−0·29	−0·08	+0·06	+0·16	3
60	WN6	12·05	+0·09	+0·29	+0·63	+1·06	2
62	WC9+OB	13·76	+1·64	+1·29	+0·60	+0·96	2
64	WN7	6·82	+0·07	+0·09	+0·21	+0·32	3
65	WC7+O5−8	6·96	+0·18	+0·12	+0·01	+0·15	3
66	(WC9)	13·89	+1·50	+1·01	+1·14	+1·48	2
LS 11	WN7	13·23	+0·55	+0·42	+0·81	+1·07	1

TABLE VII (*continued*)

Star	Sp	b	u′–b	u–b	b–v	b–v′	n
MR 67	(WN6)	13·44	+0·19	+0·30	+0·65	+0·89	1
LS 12	WN6	14·73	+0·72	+0·68	+1·18	+1·64	2
LS 13	(WC9):	16·4	+1·2	+0·9	+1·3		1
MR 68	WC7+BOV	10·17	+0·65	+0·47	+0·44	+0·74	3
69	WC7	7·33	+0·23	+0·03	−0·12	+0·18	4
70	WN8+OB	12·87	+1·22	+0·87	+1·23	+1·71	2
71	WC9	10·66	+0·42	+0·30	+0·06	+0·06	1
72	WC6(+OB)	12·61	+1·19	+0·85	+1·15	+1·72	1
73	(WN6)	13·01	+0·23	+0·38	+0·74	+1·10	2
74	(WN5)::	15·59	+0·67	+1·1	+1·49		1
75	OB+WN	11·83	+0·61	+0·51	+0·68	+0·96	1
76	WC7−N6	13·59	+1·12	+0·69	+1·08	+1·57	1
77	WN6	14·61	+0·76	+0·55	+1·17	+1·72	2
79 v	WC9	9·04	+0·60	+0·40	+0·03	−0·05	4
80 v?	(WC9)	14·85	+1·69	+1·1	+1·31	+1·77	2
82	WC9	13·08	+1·35	+0·98	+0·72	+0·91	2
LS 14	OB+WN	10·84	+0·65	+0·49	+0·68	+0·91	1
MR 83	WN6	10·94	+0·08	+0·33	+0·71	+1·18	3
84 v?	WC5	8·18	−0·07	−0·27	−0·07	+0·24	4
85	WC8+BO:	9·90	+0·57	+0·41	+0·47	+0·69	3
86	WC5	13·82	+0·84	+0·40	+0·90	+1·44	2
87 v	WN6	13·40	+0·84	+0·69	+1·14	+1·52	4
LS 15	WC9	13·33	+1·24			+0·93	—
			Of stars				
HD 91421*		9·03	+0·17	+0·19	+0·02	+0·01	1
148937		7·02	+0·17	+0·17	+0·20	+0·26	3
151804		5·21	−0·02	+0·03	−0·01	−0·02	4
152408		5·92	+0·05	+0·07	+0·07	+0·13	3
163758†		7·29	−0·06	0·00	−0·04	−0·07	3

* HD 91421 = MR 24. Possible Of spectrum variable (see Paper I).
† HD 163758 = MR 78.

known in the SMC and were included in the programme. The results are given in Table VI which contains in successive columns:

1. For WR stars in the LMC, the numbers assigned by WdS, designated WS, or those assigned by Feast, Thackeray & Wesselink (1960), designated R. The two WR stars in the SMC are assigned numbers SMC 1 and SMC 2 and are identified in footnotes to the table.

2–6. Magnitudes and colour indices as defined in Table I and Sections 2.1 and 2.2.

7. Number of nights on which the colour (*b–v*) was observed.

In the Galaxy, 77 of the 84 stars south of declination −10° have been observed. The programme also included four Of stars and one possible Of star. The results are given in Table VII which contains in successive columns:

1. For WR stars, the MR (Roberts 1962) or LS (Paper I) number; for the Of stars, the HD number.
2. Spectral types as given and defined in Paper I.
3–7. Magnitudes and colour indices.
8. Number of nights on which the colour (*b–v*) was observed.

3. *Absolute magnitudes and intrinsic colours*

3.1 *Reddening lines.* It has been suggested (e.g. Johnson 1965; Wampler 1961) that the shape of the reddening curve is different in different regions of the Galaxy. This means that both the slope of the reddening lines in the two colour diagrams and the ratio of total to selective absorption vary and must be determined for each

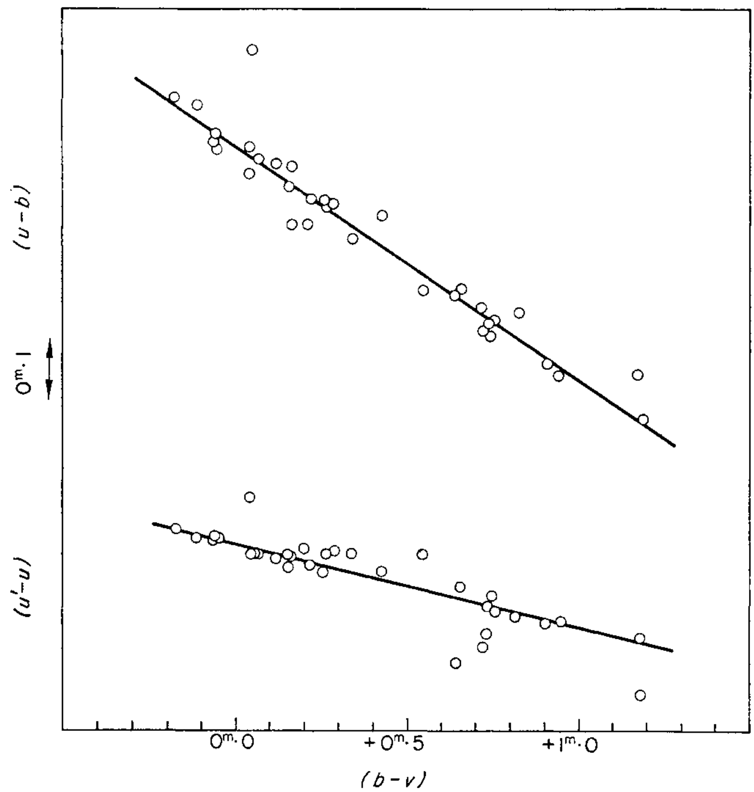


FIG. 1. *The reddening lines.*

region. In the present programme, this is impracticable. Fortunately, the predicted slopes of the reddening lines do not vary a great deal, so that the assumption of uniformity introduces little error and we shall adopt the observed slopes. For the sake of consistency with the majority of previous work, I assume

$$R = A_V/E_{B-V} = 3{\cdot}0,$$

in the *UBV* system and derive the corresponding ratio, R', in the present system.

Because the intrinsic colours of the stars in the various subclasses are not necessarily the same, the reddening lines will be parallel but will have different zero points. The slopes of the reddening lines have been determined from the two colour

TABLE VIII

Slopes of reddening lines

	$\frac{E_{u'-u}}{E_{b-v}}$	$\frac{E_{u-b}}{E_{b-v}}$	$\frac{E_{v-v'}}{E_{b-v}}$	$\frac{A_v}{E_{b-v}}$	$\frac{A_V}{E_{B-V}}$	$\frac{E_{B-V}}{E_{b-v}}$
Observed	0·24	0·69				
Johnson, Perseus	0·22	0·69	0·29	4·0	3·0	1·20

TABLE IX

Classification parameters for galactic stars

Star	Δ	ξ	φ
	WN3		
MR 40	−0·08	+0·09	+0·05
	WN4		
39	−0·14	+0·42	+0·07
48	−0·10	+0·31	+0·06
	WN4·5		
11	+0·13	+0·11	+0·02
	WN5		
6	−0·11	+0·56	+0·21
7	−0·10	+0·61	+0·21
21	−0·09	+0·65	+0·29
51	−0·23	+0·58	+0·20
	WN6		
13*	−0·05	+0·14	+0·06
42	−0·08	+0·14	+0·04
53	−0·14	+0·29	+0·11
55	−0·07	+0·26	+0·12
58	−0·12	+0·22	+0·08
60	−0·15	+0·35	+0·25
67*	−0·15	+0·27	+0·05
LS 12	−0·14	+0·24:	+0·12
MR 73*	−0·13	+0·33	+0·15
77	−0·25	+0·07:	+0·21
83	−0·16	+0·42	+0·26
87	−0·10	+0·12	+0·05
	WN7		
25	−0·01	+0·06	+0·02
28	−0·02	+0·09	0·00
64	−0·05	+0·07	+0·05
LS 11	−0·14	+0·06	+0·30
	WN8		
MR 19	−0·05	+0·05	+0·04
34	−0·07	+0·06	+0·07
54	−0·02	+0·06	+0·06
	WC5		
33	−0·15	−0·17	+0·29
46	−0·27	−0·20	+0·37
84	−0·22	−0·22	+0·33
86	−0·22	−0·22	+0·28
	WC6		
16	+0·10	−0·21	+0·32
17	+0·07	−0·20	+0·42
26	+0·05	−0·20	+0·33
44*	+0·09	−0·11	+0·21
LS 8	+0·08	−0·15	+0·26
	WC7		
MR 47	+0·27	−0·21	+0·20
50	+0·13	−0·21	+0·26
52	+0·17	−0·21	+0·37
69	+0·11	−0·23	+0·33

Star	Δ	ξ	φ
	WC9		
56	+0·24	−0·11	−0·05
66*	+0·22	−0·22	+0·01
71	+0·26	−0·11	−0·02
79	+0·38	−0·19	−0·09
80*	+0·2	−0·3	+0·08
82	+0·48	−0·20	−0·02
	WN4+OB		
31	+0·05	+0·16	+0·04
	WN7+OB		
29	−0·03	+0·08	−0·01
	WN8+OB		
MR 32	+0·07	+0·08	+0·01
70	+0·02	−0·06	+0·12
	WC5+OB		
LS 3	+0·13	+0·19	+0·22
	WC6+OB		
MR 10	−0·13	0·00	+0·10
LS 4	−0·01	+0·01	+0·28
MR 30	−0·02	−0·07	+0·13
43	+0·03	+0·03	0·00
72*	+0·06	−0·06	+0·24
	WC7+OB		
MR 20*	−0·16	−0·07	+0·30
36	+0·09	−0·06	+0·09
65	+0·11	−0·06	+0·14
68	+0·17	−0·07	+0·17
	WC8+OB		
12	+0·10	0·00	+0·05
85	+0·09	−0·05	+0·08
	WC9+OB		
57	+0·10	+0·03	+0·04
62	+0·88	−0·21	+0·19
	OB+WN		
75	+0·04	+0·06	+0·08
LS 14	+0·02	0·00	+0·03
	WN−C		
MR 9	−0·21	+0·24	+0·10
23	+0·02	+0·12	+0·02
49	−0·13	+0·15	+0·11
76	−0·05	−0·17	+0·18
	Class Doubtful		
MR 15	−0·07	−0·07	+0·37
LS 9	+0·21	−0·42	
LS 10	+2·0	+1·2	
LS 13	+0·7	−0·2	
MR 74	+0·1	+0·8	

TABLE IX (*continued*)

Star	Δ	ξ	φ	Star	Δ	ξ	φ
	Of				Standards (*continued*)		
HD 91421	+0·18	+0·02	−0·02	HD 3719	+1·13	−0·24	−0·03
148937	+0·03	+0·05	0·00	25938	+1·12	−0·23	−0·04
151804	+0·04	+0·05	−0·01	52812	+0·39	−0·02	−0·03
152408	+0·02	+0·04	+0·04	63308	+0·44	−0·04	−0·04
163758	+0·03	+0·05	−0·02	72350	+0·55	−0·09	+0·01
	Standards			86659	+0·53	−0·05	−0·02
ξ^2 Cet			−0·03	116226	+0·63	−0·16	−0·01
ν Ori	+0·13	+0·05	−0·03	125721	+0·17	+0·03	−0·03
η Hya	+0·44	−0·02	−0·02	158186	+0·12	+0·04	0·00
θ Crt	+0·99	−0·21	−0·02	170978	+0·53	−0·06	−0·01
θ Vir	+1·12	−0·30	−0·03	180183	+0·39	−0·01	−0·01
109 Vir	+1·08	−0·26	0·00				
58 Aql	+1·09	−0·26	0·00				

* Classification from ξ, Δ diagram.

diagrams, with $(b-v)$ as abscissa, for each subclass. Only stars classified by the author, (Paper I) or by HJS were used; stars believed to be binaries were excluded. The diagrams for all subclasses were superposed with vertical shifts to obtain the best fit between subclasses. This procedure was used because there are only a few stars in each subclass, so that the slope is not well defined by one subclass alone. The resulting diagrams are shown in Fig. 1 with the mean lines drawn in by eye estimate. The slopes of these lines are given in Table VIII and are close to those predicted by Johnson's reddening curve for the Perseus region. This curve also yields the ratio $R = 3{\cdot}0$, which is assumed here. Therefore, this curve has been used to obtain the values, $R' = 4{\cdot}0$, $E_{B-V}/E_{b-v} = 1{\cdot}20$ and $E_{v-v'}/E_{b-v} = 0{\cdot}29$.

3.2 *Photometric classification parameters.* Using the slopes of the reddening lines determined above, we may define three reddening-independent parameters:

$$\xi = -(u'-u)+0{\cdot}24\,(b-v)$$
$$\Delta = (u-b)-0{\cdot}69\,(b-v)$$
$$\phi = (b-v')-1{\cdot}29\,(b-v).$$

Tables IX and X give the values of these parameters for stars in the Galaxy and in the Magellanic Clouds, respectively, arranged according to spectral type. The stars are identified by the designations used in Tables VI and VII.

The expected variations with spectral subclass of ξ, Δ and ϕ are shown schematically in Fig. 2.

The principal emission lines affecting each filter were given in Table II. With reference to that table, it is seen that, for WN stars, ξ measures the strength of the N IV λ3480 line. It is large and positive when the line is strong and approximately zero when the line is absent. From the definition of the WN subclasses (Paper I, Table I), it is expected that ξ will be approximately zero for WN 8 stars, will increase through WN 7 and WN 6 to a maximum at WN 5 and WN 4, and decrease through WN 3. This means that a given value of ξ does not always correspond to a unique subclass.

For WC stars, NIV λ3480 is absent and ξ is dominated by the effect of carbon and oxygen lines in the *u*-filter. Consequently, for this group, ξ will be negative and approximately constant over all subclasses.

TABLE X

Classification parameters for stars in the Magellanic Clouds

Star	Δ	ξ	φ
	WN3		
WS 9	−0·04	+0·35	+0·07
28	+0·06	+0·27	+0·06
	WN4		
1*	+0·09	+0·57	+0·26
14	+0·11	+0·53	+0·30
22*	−0·02	+0·42	+0·23
25*	−0·01:	+0·46:	+0·19
30*	−0·02	+0·49	+0·18
	WN5		
13*	−0·08	+0·63	+0·33
53*	−0·06	+0·57	+0·19
	WN7		
18	−0·11	+0·11	+0·07
19	−0·09	+0·10	+0·05
46	−0·05	+0·04	+0·02
47	0·00	+0·07	+0·05
	WN8		
8	−0·09	+0·08	+0·02
12	−0·10	+0·12	+0·01
27	−0·07	−0·03	0·00
	WC5		
3*	−0·57	−0·19	+0·36
4	−0·39	−0·20	+0·37
6	−0·30	−0·18	+0·27
31	−0·32	−0·28	+0·41
35	−0·25	−0·30	+0·45

Star	Δ	ξ	φ
	WN4+OB		
11	−0·01	+0·15	−0·01
45	−0·10	+0·16	
50	+0·02	+0·20	+0·04
	WN6:+OB		
48	+0·08	+0·23	
	WC5+OB		
WS 5	+0·12	0·00	−0·04
21	−0·01	−0·04	+0·07
23			+0·01
24	+0·02	−0·01	+0·01
32	−0·05	−0·06	+0·06
39	+0·02	−0·09	+0·14
40	+0·07	−0·02	0·00
49	−0·02	0·00	+0·09
SMC 2	−0·02	+0·05	+0·06
	OB+WN		
WS 15			−0·02
26	+0·10	−0·02	−0·03
43	+0·05	0·00	−0·02
R 136	+0·07	+0·03	−0·02
SMC 1	+0·01	+0·10	0·00
	Class Doubtful		
WS 34	−0·14	+0·43	+0·17
42†	−0·17	+0·19:	+0·30
	WNpec		
2	+0·03	+0·43	+0·36
10	−0·01	+0·33	+0·12

* Classification determined from the ξ, Δ and v_0, ξ diagrams.

† WS 42 is the faintest WR star known in the Magellanic Clouds; ξ has not been determined with sufficient accuracy to classify it.

The presence of a companion will lessen the strength of the emission lines above the continuum and ξ will be numerically less than for a single star of the same WR type.

Δ measures the non-linearity, in $1/\lambda$, of the continuum in the region *u*, *b*, *v*. Thus, if a Balmer discontinuity is present, Δ is positive and approximately equal to the value of the discontinuity. (This may be seen in the values of Δ for the standard stars in Table IX.) Kuhi (1966) has shown that WR spectra display virtually no Balmer discontinuity. However, the binary stars display an increase in the slope of the energy distribution for $1/\lambda$ between 2·3 and 1·8. The *v*-filter of the present system is centred at $1/\lambda = 1{\cdot}94$. Thus, for WN stars, Δ will be most positive if the star is a binary.

For WC stars, Δ is dominated by the effect of C II λ4267 in the *b*-filter, and will decrease from WC 9 to WC 5.

Fig. 3 gives the graph of Δ vs ξ for WR stars in the Galaxy. Different symbols are used for each subclass; unclassified stars are represented by asterisks. With very few exceptions, the single stars in different subclasses are separated from each other and from the binaries. The divisions are marked by dashed lines. WN 7 and WN 8 stars are not separated and the separation of the WR stars among the binaries is poor: the dotted line provides approximate separation between WN and WC binaries. Stars in the very high excitation classes, WN 4 and WN 3, are scattered over the WN 6, 7 and 8 regions of the diagram, as expected (see Fig. 2).

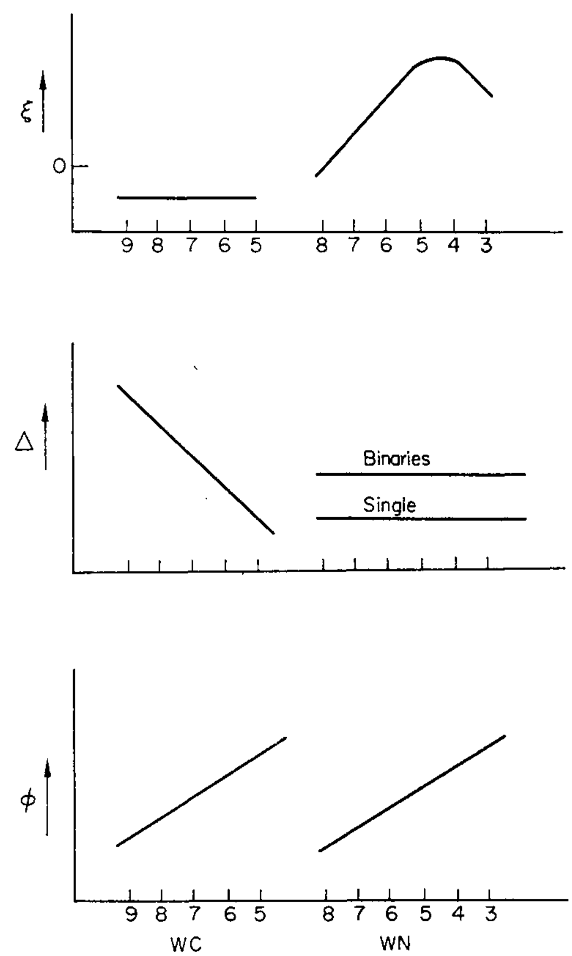


FIG. 2. *Schematic diagrams of the expected variation of the classification parameters with subclass.*

Most of the stars which do not conform to these divisions are of intermediate spectral types; e.g. MR 76, an intermediate class WC 7–N 6 star, is found in the WC 5 region. The positions of some other stars indicate that a revision of their classifications is required; e.g. MR 20, classified as WC 7 by HJS, is assumed from its position in the diagram to be a binary.

Thus, the diagram provides confirmation of the general consistency of the spectral classification, revises the classification of some stars, and determines a classification for those stars for which spectra are not available. Stars which have been classified from this diagram are marked with an asterisk in Table IX and the classifications are given in brackets, (), in Table VII and in the catalogue of Paper I.

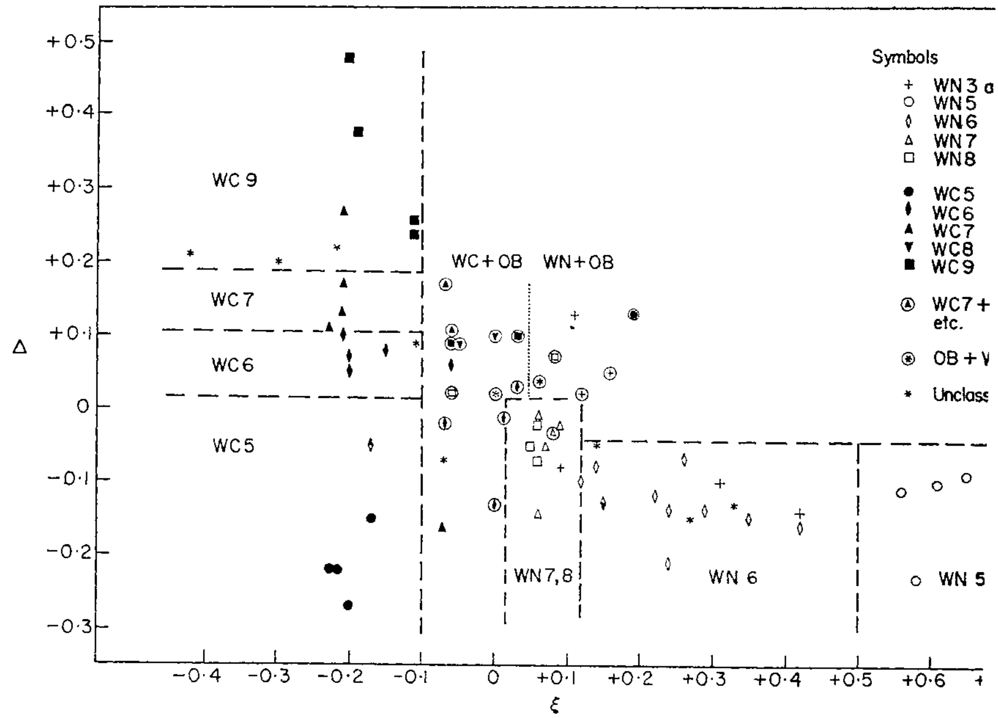


FIG. 3. *The graph of Δ vs ξ for galactic WR stars.*

The Of stars have not been plotted in Fig. 3. They fall close to the do dividing the WN+OB stars from the WC+OB stars. Their consistently values of Δ indicate the presence of a Balmer discontinuity or of a continuou distribution similar to that of the binary WR stars. Thus, there is a si difference between the continuous energy distribution of the Of stars and th WN7 and WN8 stars to which they show superficial spectral similarity.

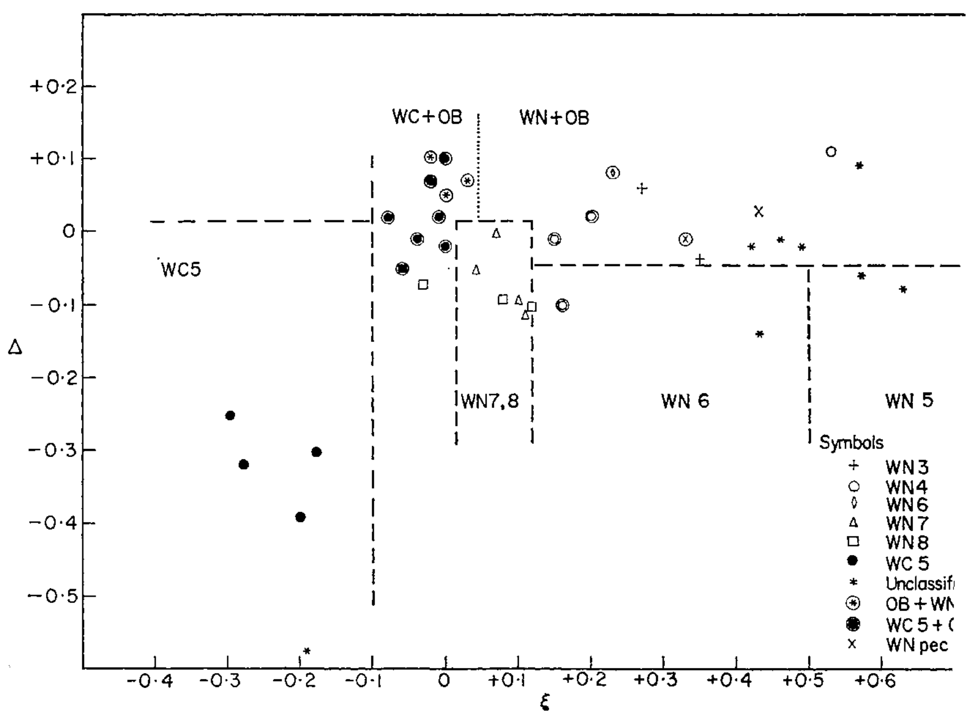


FIG. 4. *The graph of Δ vs ξ for WR stars in the LMC.*

Fig. 4 shows the graph of Δ vs ξ for the WR stars in the LMC. Of the stars that have been classified from slit spectrograms, the WC 5, WN 7 and WN 8 stars and the binaries occupy the same regions as in Fig. 3 and approximately similar numbers of stars are found in corresponding regions. WS 3, the only star of previously unknown type in this part of the diagram, is classified as WC 5 from its position in the diagram.

Stars of classes WC 6, 7, 8 and 9 are notably absent from the LMC.

Consider now, the WN 3–6 region of the diagram. We find two stars in the WN 5 region; this is not significantly fewer than the number of stars (four) found in the corresponding region of Fig. 3, and we may assume with reasonable confidence that these stars are WN 5 stars. Unfortunately, both are very faint and confirmation from slit spectrograms is not available.

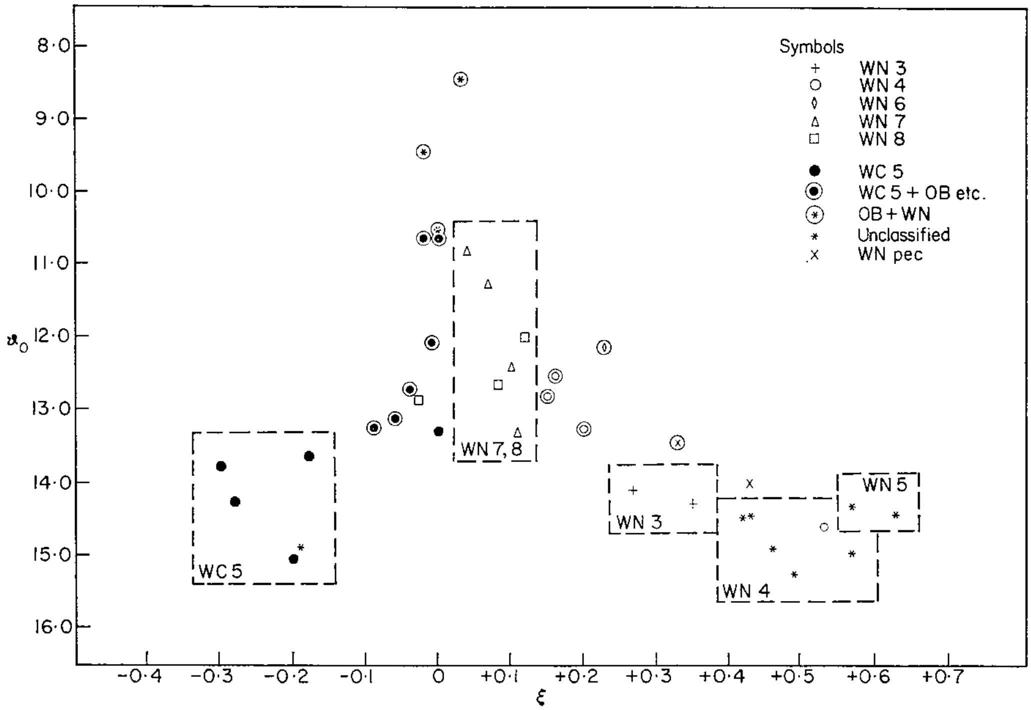


FIG. 5. *The graph of v_0 vs ξ for WR stars in the LMC.*

We find eight stars with $\xi > 0{\cdot}3$, but with values of Δ that are greater than the values found for galactic WN 5 and WN 6 stars; this is a region of the diagram that is unpopulated in Fig. 3. Slit spectrograms are available for the three brightest stars of this group and they are classified WN 4 + OB, WN pec* and WN 3. The remaining five stars lie very close together in a graph of ξ vs v_0 (see the following section). This graph is shown in Fig. 5, and the group in question is enclosed in dashed lines. A spectrum is available of only one of these stars, WS 14. It is classified WN 4 and closely resembles the spectra of the two galactic stars of this class. The small range of ξ and of v_0 implies that all five stars have the same spectral class, and we assign them all to class WN 4.

* This star is WS 2. The spectrum shows the He II λ4686 line strong and approximately 80 Å wide; this is broader than observed for any other WN star. Other emission lines are probably also present, but are not distinguished clearly on the rather over-exposed plate available. WS 10 appears to be rather similar, although this spectrum has the appearance of that of a binary.

The sixth star in the WN 4 region of Fig. 5 is WS 34; in Fig. 4 this star lies in the WN 6 region, below the group of WN 4 stars. In this region we expect to find stars of class WN 3, WN 4 and WN 6. Thus, although this is probably a WN 4 star, no definite classification is possible from the present data.

We find no certain examples, in the LMC, of class WN 6. WS 48 appears to be a binary and may have a WN 6 star as the WR component (see Plate 2); the single available spectrogram is not of sufficiently good quality for reliable classification. Feast, Thackeray & Wesselink (1960) assign the star R 140 to class WN 6; we have no further information on this spectrum.

For WN stars, ϕ measures the strength of the He II λ5412 line, which tends to increase from WN 8 to WN 5 (see Fig. 2). For WC stars, ϕ measures the strength of the He II λ5412, C IV λ5469 and O V λ5592 lines, all of which increase from WC 9 to WC 5. If ϕ is plotted against ξ a separation into subclasses is obtained much as in the plot of Δ vs ξ. The diagrams are useful for confirmation of the classifications derived from the ξ, Δ diagrams but do not add any further information and are not reproduced here.

3.3 *Absolute magnitudes and intrinsic colours for Wolf-Rayet stars in the LMC.* Absolute magnitudes and intrinsic colours can be determined with good accuracy in the LMC—the distance is effectively constant for all objects, the distance modulus is known to within $\pm 0{\cdot}2$ mag., and the uncertainties resulting from interstellar absorption are minimal.

Reddening in the LMC has been studied by Feast, Thackeray & Wesselink (1960, henceforward referred to as FTW), by Bok, Bok & Basinski (1962) and by Westerlund (1961). In this paper, I adopt a value of $E_{B-V} = 0{\cdot}04$ mag., as found by Bok *et al.* for NGC 1955, as an estimate of the foreground absorption. This is lower than the value, $E_{B-V} = 0{\cdot}07$ mag., found by FTW. However, the low absorption found by Bok *et al.* and even lower values found by Westerlund for some associations, indicate that FTW may have made an overestimate. I adopt, however, FTW's value, $E_{B-V} = 0{\cdot}06$ mag., for the mean excess of the reddening suffered by stars in nebulosity over that suffered by stars not in nebulosity.

Three WR stars, WS 24, WS 26 and WS 27, are in the clusters NGC 1962–5–6–70 and NGC 1984, for which Westerlund finds reddening values of $E_{B-V} = 0{\cdot}13$ and 0·2 mag., respectively; these values have been adopted for the relevant WR stars. Exception to the average reddening is also made in the region of the 30 Doradus Nebula, where it is known that the absorption is high and irregular (e.g. Faulkner 1964). The reddening for stars in this nebula has been derived on the assumption that they have an intrinsic value of $(b–v)$ equal to the mean value for other stars of the same spectral type. Values of E_{b-v} derived in this way are enclosed in brackets, (), in Table XI. Table XI lists the colours and magnitudes, corrected for reddening, and the absolute magnitudes derived on the assumption that the distance modulus of the LMC is given by $v_0 – M_v = 18{\cdot}7$ mag. (see e.g. Bok 1966). The table is divided according to spectral type.

3.4 *Classification of WR stars in the Magellanic Clouds.* In Section 3.2 we found, among the Magellanic Cloud stars observed, no stars in the subclasses WC 6, 7, 8 and 9 and few stars in the class WN 6. However, not all WR stars in the LMC were observed photometrically. It is important to verify that none of the omitted stars fall in one of these subclasses. Thus, it is appropriate, at this time, to gather all the

TABLE XI

Intrinsic colours and absolute magnitudes of WR stars in the LMC

Star	E_{b-v}	v_0	$(u'-b)_0$	$(u-b)_0$	$(b-v)_0$	$(b-v')_0$	M_v
			WN 3				
WS 9	0·03	14·27	−0·50	−0·12	−0·12	−0·09	−4·4
28	0·03	14·06	−0·43	−0·10	−0·24	−0·25	−4·6
			WN 4				
1	0·03	14·95	−0·74	−0·10	−0·28	−0·10	−3·8
14	0·03	14·59	−0·56	+0·01	−0·14	+0·12	−4·1
22	0·08	14·48	−0·59	−0·13	−0·16	+0·03	−4·2
25	0·03	14·88	−0·61	−0·11:	−0·14	+0·01:	−3·8
30	0·03	15·23	−0·63	−0·11	−0·13	+0·01	−3·5
			WN 5				
13	0·08	14·42	−0·86	−0·19	−0·16	+0·13	−4·3
53	0·08	14·31	−0·74	−0·14	−0·12	+0·04	−4·4
			WN 7				
18	0·03	13·28	−0·37	−0·22	−0·16	−0·14	−5·4
19	0·08	12·40	−0·42	−0·26	−0·25	−0·27	−6·3
46	(0·09)	10·79	−0·28	−0·19	−0·20	−0·24	−7·9
47	(0·23)	11·24	−0·25	−0·14	−0·20	−0·21	−7·5
			WN 8				
8	0·03	12·61	−0·29	−0·18	−0·13	−0·15	−6·1
12	0·03	11·97	−0·18	−0·07	+0·04	+0·06	−6·7
27	0·16	12·83	−0·36	−0·30	−0·35	−0·44	−5·9
			WC 5				
WS 3	0·08	14·78	−0·49	−0·65	−0·13	+0·20	−3·9
4	0·03	15·01	−0·33	−0·49	−0·14	+0·19	−3·7
6	0·08	13·63:	−0·28	−0·42	−0·18:	+0·04	−5·1
31	0·03	14·24	−0·31	−0·52	−0·29	+0·03	−4·5
35	0·08	13·77	−0·21	−0·44	−0·29	+0·08	−4·9
			WN 4+OB				
11	0·08	12·79	−0·38	−0·17	−0·24	−0·32	−5·9
45	(0·12)	12·51	−0·41	−0·22	−0·18		−6·7
50	0·03	13·23	−0·33	−0·09	−0·16	−0·17	−5·5
			WN 6:+OB				
48	(0·24)	12·10	−0·30	−0·03	−0·17		−6·6
			WC 5+OB				
5	0·08	10·56	−0·15	−0·08	−0·30	−0·42	−8·1
21	0·08	12·60	−0·27	−0·23	−0·33	−0·35	−6·1
23	0·03	11·38	−0·22		−0·24	−0·30	−7·3
24	0·11	12·07	−0·29	−0·22	−0·35	−0·44	−6·6
32	0·08	13·10	−0·22	−0·22	−0·26	−0·27	−5·6
39	0·03	13·22	−0·15	−0·17	−0·28	−0·22	−5·5
40	(0·28)	10·63	−0·16	−0·12	−0·26	−0·33	−8·1
49	0·03	13·29	−0·19	−0·14	−0·18	−0·14	−5·4
			OB+WN				
15	0·08	10·99	−0·12		−0·22	−0·30	−7·7
26	0·11	9·47	−0·05	−0·03	−0·20	−0·29	−9·2
43	(0·24)	10·55	−0·14	−0·09	−0·21	−0·29	−8·2
R 136	(0·24)	8·48	−0·15	−0·07	−0·21	−0·29	−10·2
			WN pec				
WS 2	0·03	13·98	−0·57	−0·09	−0·18	+0·13	−4·7
10	0·08	13·44	−0·46	−0·10	−0·14	−0·06	−5·3

TABLE XII

Spectral types of WR stars in the Magellanic Clouds

Star	HD(E)	*V*	Spectral type WS	R	Present	Location
WS 1		15·07	N		(WN 4)	F
2	32109	14·10	(N)		WN p	F
3	32125	15·10	C		(WC 5)	N 11 F
4	32257	15·13	(C)		WC 5	A
5	32228	10·88	W+O	WC 6+O 8:	WC 5+OB	N 11 A
6	32402	13·95	C		WC 5	N 91 A
7	268847	(14·36)	N			N16A F
8	33133	12·73	N		WN 8	F
9	269015	14·39	N		WN 3	F
10	34187	13·76	(N)		WN p+OB?	N105 A
11	34632	13·11	W+O		WN 4+OB	N 30 A
12		12·09	W+O		WN 8	A
13	34783	14·74	N		(WN 5)	N113 F
14		14·71	(N)		WN 4	F
15	269333	11·31	W+O	W+B1:I	OB+WN	N119 A
16		(11·97)	W+O	WC 6:	WC 5+OB	N120 A
17		(14·95)	N			F
18		13·40	N		WN 7	A
19	36063	12·72	N		WN 7	N198 F
20		(14·97)	N			F
21	36156	12·92	C		WC 5+OB	N200 F
22	269485	14·80	N		(WN 4)	N138 F
23	36402	11·50	W+O		WC 5+OB	N 51 A
24	36521	12·51	(N)		WC 5+OB	N144 A
25	269549	15·00	(N)		(WN 4)	F
26	269546	9·91	W+O	B3Ip+W?	OB+WN	N144 A
27		13·47	(N)		WN 8	A
28		14·18	N		WN 3	F
29	269624	(14·80)	(N)			F
30		15·35	(N)		(WN 4)	F
31	37026	14·36	(C)		WC 5	F
32	37248	13·42	C		WC 5+OB	N206 A
33		(14·36)	N			F
34	269692	14·74	N	W	(WN)	N 57 F
35	37680	14·09	C		WC 5	N154 A
36	269818	(14·3)				N157 A
37		(14·50)	N			F
38	269828	(11·6)	W+O		OB+WN	N157 A
39	38030	13·34	(N)		WC 5+OB	A
40	38029	11·75	W+O		WC 5+OB	N157 A
41		(13·55)	(C)		WC 5+OB	A
42	269888	15·58	N			N157 F
43	269891	11·51	W+O	BO:+W?	OB+WN	N157 D
44	269908	(14·72)	(N)			N158 F
45	269926	12·99	N	WN 5	WN 4+OB	N157 D
46	38282	11·15	N	WN 7	WN 7	N157 D
47	269928	12·16	N	WN 6−7	WN 7	N157 D
48	38344	13·06	N	WN 5+	WN 6:+OB	N157 D
49	38448	13·41	N		WC 5+OB	N158 A
50	38472	13·35	(N)		WN 4+OB	N158 A
51		(14·28)	N			N 74 A
52		(14·67)	N			F
53	270149	14·63	N		(WN 5)	N 74 A

TABLE XII (*continued*)

Star	HD(E)	V	WS	Spectral type R	Present	Location
R 134		(12·36)		WN 7		N157 D
R 135		(13·15)		WN 7		N157 D
R 136	38268	9·44		WN+O	OB+WN	N157 D
R 139		(11·87)		WN 7:+O:	WN 7:+OB	N157 D
R 140		(11·82)		WN 6		N157 D
SMC 1	5980	11·75		Wp	OB+WN	N 66 A
SMC 2		13·05			WC 5+OB	A

available information regarding the classification of the WR stars in the Magellanic Clouds.

Table XII contains all available spectroscopic data, and gives in successive columns:

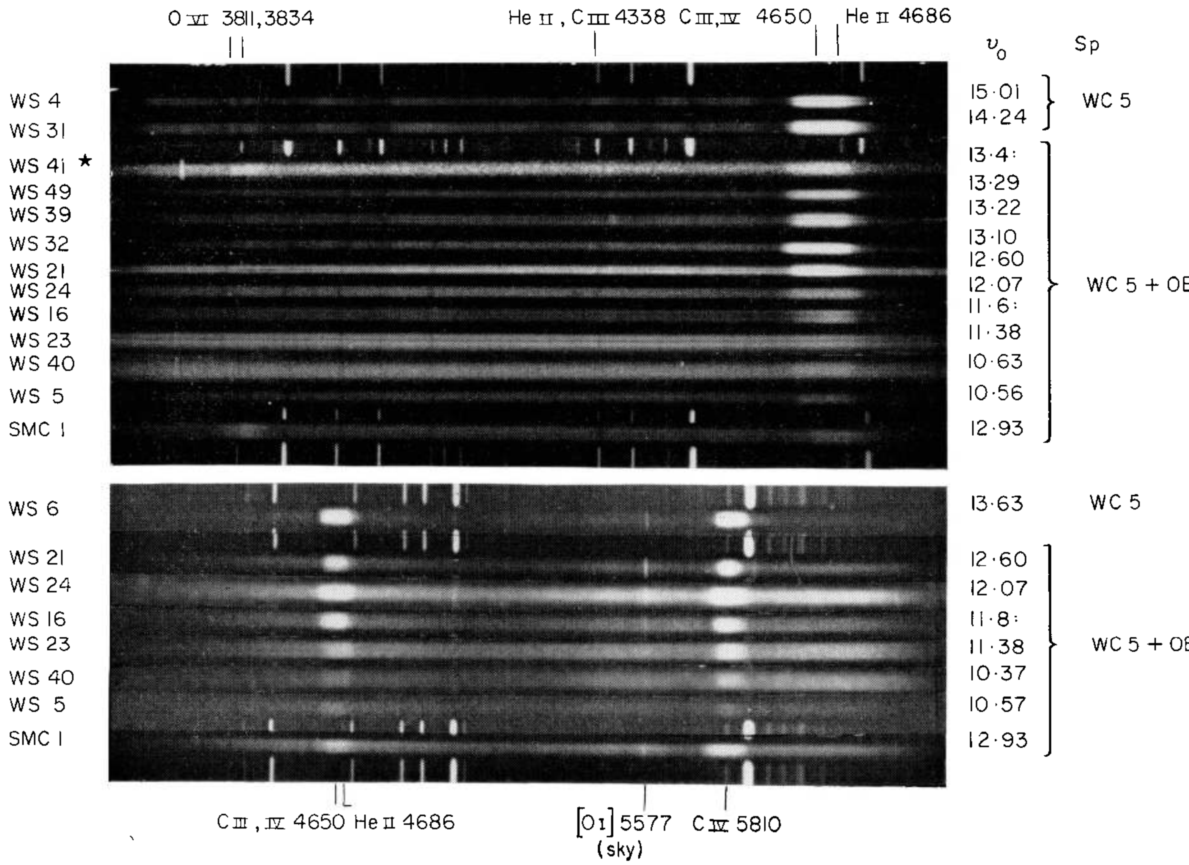
1. Designation, as in Table VI.
2. HD or HDE number.
3. v-magnitude as defined in Section 2.1 and 2.2. When a v-magnitude is not available, this column contains the V magnitude given by WdS enclosed in brackets, ().
4. Spectral class as given by WdS. These were determined from objective prism spectra, extended to the fainter objects by B, V, R photographic photometry. The photometrically derived classes are given in brackets, ().
5. Spectral class as given by FTW.
6. Spectral class determined in the present programme, either from slit spectrograms or from photometric criteria. The classification system is defined in Paper I. Classes derived from photometric criteria are given in brackets, ().
7. Location of the star, taken from WdS; association with nebulosity is indicated by the number (N) of the nebula in the catalogue of Henize (1956); 'D' indicates a member of the 30 Doradus complex, 'A' a member of an association and 'F' indicates that the object is apparently a field star.

The classifications assigned by FTW are consistent with those assigned from slit spectrograms obtained in the present programme. Because of the differences between the classification system defined by Beals (1938) (used by FTW) and the system defined in Paper I (used here), stars classified WC 6 by FTW are classified WC 5 by the author. Other classifications rarely differ by more than half a subclass.

WdS assigned only the sequence classification, WC or WN. The only contradictions found between their classifications and the present ones arise amongst the WC5+OB stars, some of which WdS classified as WN from photometric criteria. No contradictions are found in the classification of single stars.

Absence of WC6–9 stars. Slit spectrograms have been obtained of all stars classified WC by WdS except WS 3. All are classified as WC 5 or WC 5+OB. WS 3 was classified WC5 from photometric criteria in Section 3.2.

All WC5+OB stars are brighter than $v = 13.5$ mag. The only two stars classified WN by WdS from photometric criteria and unverified in this study are WS 29 and WS 44 with $V = 14{\cdot}80$ and $14{\cdot}72$ mag., respectively. The v-filter in the present system has an effective wavelength close to that of V in the Johnson Morgan system. For early-type stars we introduce an error of less than 0·1 mag. by assuming that $V = v$. For WR stars, the emission lines can contribute as much as 0·5 mag. to

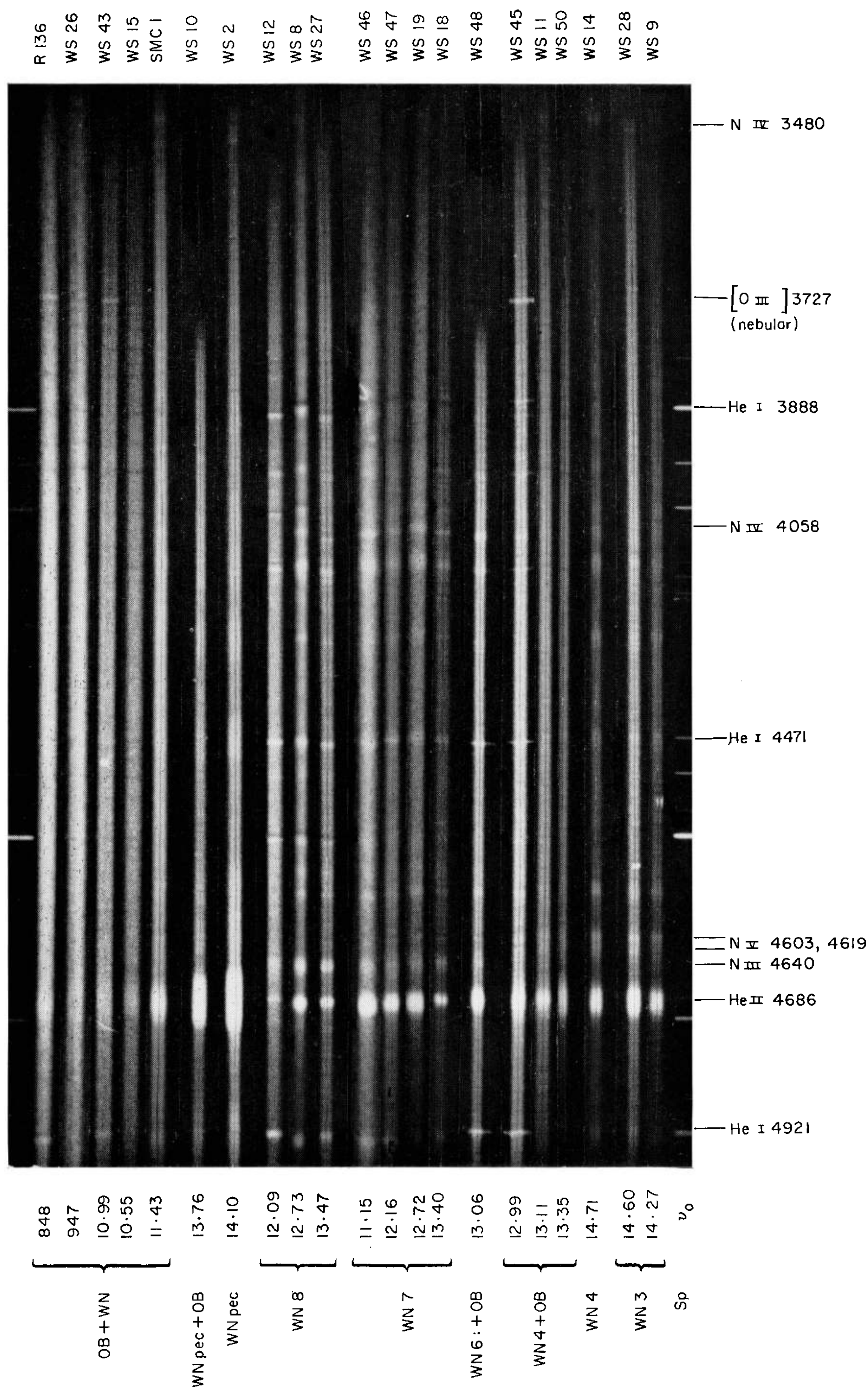


Spectra of WC stars in the Magellanic Clouds. The comparison spectrum is helium. Spectra in the upper half of the plate show the region from 3700 Å *to* 4900 Å. *Spectra in the lower half of the plate show the region from* 4400 Å *to* 5900 Å. *The spectra are arranged in order of increasing luminosity within each spectral class. SMC* 1 *is held separate from the LMC stars because the strength of the* O VI 3811, 3834 *lines makes it unique.*

★ The coarse grain of the spectrum of WS 41 results from the 080-01 emulsion.

[*Facing page* 428

PLATE 2



Spectra of WN stars in the Magellanic Clouds. The comparison spectrum is helium. The region from 3400 Å to 4900 Å is shown.

the brightness, in the sense that v will be fainter than V. Thus, it is clear that the luminosities of WS 29 and WS 44 are well below those of the binary WC stars and they cannot, therefore, be members of that class. The WdS classification, WN, is then correct.

For only one star, WS 26, we have no classification information. This star is a member of a close triplet and is difficult to observe. It is considered unlikely that this star alone belongs to one of the 'absent' classes.

It is possible that the stars of classes WC 6–9 lie fainter than the limiting magnitude of the WdS survey. WdS gave reasons for believing that the cut-off in the WR population at $V \approx 15$ mag. is real and that no WR stars exist below that limit in the LMC. If this is indeed the case, we conclude that WC 6–9 stars are entirely absent from the Magellanic Clouds.

Rarity of WN6 stars. Table XII gives subclasses for all WR stars except WS 36, discussed above, and eleven faint WN stars. All of the latter are fainter than $V = 14.2$ mag. It will be shown that galactic WN 6 stars have $M_v \approx -5.8$ mag., corresponding to $v_0 \approx 12.9$ mag. in the LMC. The mean unreddened magnitudes of WN 7 and WN 8 stars in the LMC are 11·9 and 12·5 mag., respectively (Table XI). Thus, we may be confident that the eleven faint WN stars are not members of classes WN 6, 7 or 8. Thus, the LMC contains only three possible examples of WN 6 stars (WS 36, WS 48 and R 140), significantly fewer than found in the Galaxy.

3.5 *Comparison of WR stars in the LMC and the Galaxy.* It is important to determine whether or not the WR stars in the LMC are significantly different from those in the Galaxy. Four avenues of comparison are available: spectral appearance, reddening-independent parameters, absolute magnitude estimates and distribution amongst the subclasses. We shall consider each of these in turn.

Spectral appearance. Amongst those subclasses that are well represented in the LMC, no radical differences in spectral appearance have been noticed. However, many of the stars are very faint and it was possible to obtain only very narrow spectra. Clearly, this comparison should be made in more detail when further data becomes available. As many as possible of the spectra are reproduced in Plates 1 and 2 for comparison with the spectra of galactic WR stars given in Paper I and also with those given by Hiltner & Schild (1966). All spectra shown were obtained with the Nebular spectrograph at the Newtonian focus of the 74-in. reflector at Mount Stromlo Observatory. The spectrograph is similar to the prime focus spectrograph of the 200-in. reflector at Palomar Observatory (described by Bowen (1952)). Spectra of the blue region were obtained with the 400 line grating in the second order and the $f/1 \cdot 2$ camera at a dispersion of 140 Å/mm. Spectra of the visual region, shown in Plate 1, were obtained with the 400 line grating in the first order and the $f/1 \cdot 2$ camera at a dispersion of 280 Å/mm. For the very narrow spectra, two prints are mounted side by side to increase the visibility of the lines. The emulsions used are Eastman Kodak IIa-D, IIa-O (baked for 48 h at 50°C) and an experimental emulsion, 080-01.

Reddening-independent parameters. It has been pointed out in Section 3.2 that, in the ξ, Δ diagrams (Figs 3 and 4) and in the ξ, ϕ diagrams, the regions occupied by the stars in the various subclasses are the same for the two galaxies. This implies that the mean line strengths are the same for stars in the same subclass in the two galaxies.

TABLE XIII

Absolute magnitudes of some galactic WR stars
(by distance moduli by Graham)

MR	HD	Spectral type	$(b-v)_0$	E_{b-v}	A_v	A_V	v_0	V_0-M_V	M_v
25	92740	WN 7	−0·20	0·23	0·92	1·4	5·52	12·2	−6·7
28	93131	WN 7	−0·20	0·14	0·56	1·4	5·93	12·2	−6·3
29	93162	WN 7+O 7	−0·20	0·49	1·96	1·4	6·21	12·2	−6·0
64	151932	WN 7	−0·20	0·41	1·64	1·7	4·97	11·3	−6·3
65	152270	WC 7+O 5−8	−0·26	0·27	1·08	1·5	5·87	11·3	−5·4
12	68273	WC 8+O 7					1·74	8·3	−6·6

Absolute magnitude estimates. The absolute magnitudes of WR stars in the LMC have been derived in Section 3.3. In the Galaxy, some WR stars appear to be associated with groups of O and B stars which are sufficiently close to the sun to allow good distance determinations. Graham (1965), using Hβ and *UBV* photometry, has determined distance moduli for O and B stars associated with six WR stars. By making some reasonable assumptions regarding the intrinsic colours of the galactic WR stars, we may determine the reddening; this is preferable to the use of a mean value for the area because absorption is very uneven in the regions concerned. The successive columns of Table XIII contain:

1, 2. MR and HD numbers of the WR star.
3. Spectral classification.
4. Assumed intrinsic colour, $(b-v)_0$.
5. Colour excess, E_{b-v}.
6. v absorption, $A_v = 4E_{b-v}$.
7. Mean visual absorption, A_V, in the *UBV* system, as given by Graham.
8. v magnitude corrected for absorption, $v_0 = v-A_v$.
9. Distance modulus, V_0-M_V, derived by Graham.
10. Derived absolute magnitude, M_v.

For the WN 7 stars and for the binary WN 7+O 7 star I have assumed that $(b-v)_0 = -0·20$ mag., the value found for the LMC stars in the class WN 7. For WC and WC+OB stars I have adopted the mean values of $(b-v)_0$ found for WC 5 and WC 5+OB stars, respectively, in the LMC. γ^2 Velorum is assumed to be unreddened.

The table includes three WN 7 stars. The derived values of M_v range from −6·3 to −6·7 mag. This is a smaller range than is found in the LMC (−5·4 to −7·9 mag).

The table also includes one binary WN 7+O 7 star, with a derived value of $M_v = -6·0$ mag. If we assume that the companion is of luminosity class V, and take M_v(O7V) = −5·2 mag. (Schmidt-Kaler 1965), we find M_v(WR) = −5·3 mag. This is near the lower limit of the range of luminosities in the LMC. It is possible that there are no stars in the Galaxy which are comparable to the extremely luminous pair of WN 7 stars in the 30 Doradus nebula, or that the latter are binaries. The other stars in Table XIII have no counterpart in the LMC and are discussed in the next section.

Distribution amongst the subclasses. It was established in the previous section that the subclasses WC 6, 7, 8 and 9 are well represented in the Galaxy, but are entirely absent from the LMC, and that stars of class WN 6 appear to be rather less common in the LMC than in the Galaxy.

Conclusions. We conclude that WR stars in the LMC are similar to those in the same subclasses in the Galaxy. The absence of WC 6–9 stars and the rarity of WN 6 stars in the LMC is remarkable. However, I do not believe that this invalidates the assumption that stars in the other subclasses are similar; more reasons for this view will be given in a later paper.

3.6 *Absolute magnitudes of galactic WR stars.* Classes WC 6, 7, 8 and 9 are not represented in the LMC and no definite examples of class WN 6 are known. Thus, we must determine the absolute magnitudes of stars in these subclasses from observations in the Galaxy. Absolute magnitudes for two stars in these subclasses were derived in the previous section. Further information can be obtained if we assume that any two WR stars which are seen 'near' each other in the sky and which have 'approximately equal' colour excesses are at the same distance. This hypothesis depends upon two observations. Firstly, that several clusters are known which contain two or more WR stars. Secondly, WR stars are sufficiently rare that the probability of chance coincidence in the surface distribution is not very high. Thus, it is likely that the pairs chosen in the above manner will be real.

If we take limits for 'near' and 'approximately equal' to be 1°·0 and within 0·20 mag., respectively, we have four pairs of stars in which one is of a class whose luminosity is known from observations on the LMC. These are listed in Table XIV.

Table XIV

Absolute magnitudes of some galactic WR stars
(by comparison of close pairs of stars)

Pair No.	MR Nos	Assumption made	WN 6	WN 6+ BO:I	WC 7+ O 5−8	WC 7	WC 8 +O 7
1	12	$V_0 - M_V = 8{\cdot}3$					−6·6
2	54, 55	$M_v(\text{WN 8}) = -6{\cdot}2$	−5·8				
3	64, 65	$V_0 - M_V = 11{\cdot}3$			−5·4		
4	86, 87	$M_v(\text{WC 5}) = -4{\cdot}4$	−5·9				
5	115, 116	$M_v(\text{WN 3}) = -4{\cdot}5$		−6·8			
6	47, 49	$M_v(\text{WN 6} - \text{C}) = -5{\cdot}8$				−4·8	

To determine the reddening, some assumptions must be made regarding the intrinsic colours of the stars. I assume that the WN 6 stars, both single and double, have $(b\text{–}v)_0 = -0{\cdot}17$ mag., the mean value of all the subclasses of WN stars in the LMC; since the range of intrinsic colour over these subclasses is only 0·06 mag., this figure is unlikely to be in error by more than 0·03 mag.

I assume that WC 6 and WC 7 stars have $(b\text{–}v)_0 = -0{\cdot}21$ mag., and that binaries in these classes have $(b\text{–}v)_0 = -0{\cdot}26$ mag., the values found for WC 5 and WC 5+OB stars, respectively; however, it is noted that the effect of emission lines makes these values somewhat uncertain.

−0·32 mag., the value of $(b\text{–}v)$ for γ^2 Vel, is taken as an estimate of $(b\text{–}v)_0$ for WC 8 and WC 9 stars; this value is also somewhat uncertain.

Some of the stars are binaries; the absolute magnitudes of the O and B stars given by Schmidt-Kaler (1965) are used to correct for the contribution of the companion to the total luminosity.

The results are given in Table XIV, which contains in successive columns:

1. A reference number.
2. MR numbers for the WR stars.

3. The assumption made in the derivation of the absolute magnitude.

4–8. The resulting absolute magnitudes listed according to the spectral sub-class.

Single WN 6 stars occur in two 'pairs' of WR stars and their derived values of M_v differ by less than 0·1 mag.; we adopt M_v(WN 6) = −5·8 mag. Also, a binary WN 6+BO : I star occurs in pair 5. Taking M_v(BO I) = −6·2 mag., we find M_v(WN 6) = −5·9 mag., in good agreement with the adopted value. In the LMC, there are two possible WN 6 stars: WS 48 is classified as WN 6+OB in the present study, and has $v_0 \approx 12{\cdot}1$ mag.; hence $M_v \approx -6{\cdot}6$ mag. in reasonable agreement with $M_v = -5{\cdot}8$ for a single star. FTW classify the star R 140 in the 30 Doradus nebula as WN 6; they give $V = 11{\cdot}8$ mag. (*UBV* system), yielding $M_V < -6{\cdot}9$ mag. This is considerably more luminous than found above. It may be that this star is also a binary.

The class WC 7 is represented in Table XIV by MR 65 in pair 3, with $M_v = -5{\cdot}4$ mag. This star is a binary; the companion is classified as O5–8 by HJS. Stars of spectral types O 5V and O 8V have $M_v = -5{\cdot}6$ and −5·0 mag., respectively. The classification O 5 is obviously incompatible with the total luminosity derived above. Further, the spectrum shows the WR emission spectrum standing strongly above the continuum, so that the WR star cannot be much fainter than the companion. If we take the class of the companion as O 8V, we find M_v(WC 7) = −4·1. Pair 5 provides the only other evidence available. WR 49 is a WN6 star with somewhat enhanced carbon lines (HJS). If we assume that it has $M_v = -5{\cdot}8$ mag., as derived for normal WN 6 stars, we find $M_v = -4{\cdot}8$ mag. for the WC 7 star, MR 47. The mean of these values for the absolute magnitude of WC 7 stars is −4·4 mag. This is equal to the value derived for WC 5 stars, which makes it seem reasonable.

The class WC 6 is not represented in Table XIV. We would expect these stars to have a mean absolute magnitude intermediate between that for WC 5 and WC 7 stars and, accordingly, we adopt M_v(WC 6) = −4·4 mag.

The class WC 8 is represented by the star MR 12 (γ^2 Vel) in pair 1, with $M_v = -6{\cdot}6$ mag. The classification, O 7, for the companion is from HJS. Taking M_v(O 7V) = −5·2 mag. yields M_v(WC 8) = −6·2 mag.

The class WC 9 is not represented in the table. In spectral appearance it is most like the class WC 8 and we adopt the same mean absolute magnitude as for that class.

So far, we have made no use of the absolute magnitudes derived by Rublev (1963), since he considers that little confidence can be placed in his individual values. Comparing the values derived above with those in Rublev's Table VI to which he assigns the greatest weight, we find fair agreement for WN 6 stars, but disagreement for WC 9 stars (called WC 8 by Rublev), which Rublev finds to be rather less luminous than estimated above.

3.7 *Nature of the WR binaries*. In the classification of the spectra of WR stars, the criteria defined in Paper I have been used. In particular, a star is classified as a binary, WR+OB, whenever the emission lines stand less strongly above the continuum than they do in the spectrum of a single star of the same WR subclass. Data presented in this paper provides evidence that this is a realistic classification, and shows, simultaneously, that the companions of the WR stars of a given subclass may have a wide range of luminosities.

The situation is illustrated most clearly by Plate 1; this shows spectra of WC 5 stars arranged in order of increasing luminosity. As the total luminosity increases, the contrast between the emission lines and the continuum decreases, while the detectable emission features remain qualitatively the same. This is exactly what would be observed if a WC 5 star, similar to the stars classified as single, were combined with O and B stars of varying luminosities. All the stars classified as binaries are more luminous than the stars classified as single. The binaries range between one and four magnitudes brighter than the mean of the single stars. Thus, if the WC 5 stars in the binaries have $M_v = -4\cdot4$ mag., the absolute magnitudes of the O and B star companions must be between $-4\cdot7$ and $-8\cdot0$ mag. It is likely that the brightest objects contain more than two stars; this is known to be the case, for example, for WS 5 (WdS).

As the relative strengths of the emission lines decrease, the classification parameters, in particular ξ, tend to zero. Thus, the progression of increasing luminosity with decreasing line strength is also demonstrated in Fig. 5.

A similar situation exists among the WN 4 stars. In Plate 2 the WN 4+OB stars are arranged in order of increasing luminosity and again show progressively weaker lines. In Fig. 5 it is seen that the increase in luminosity is accompanied by the approach of ξ to zero.

3.8 *Conclusions.* The derived mean absolute magnitudes and intrinsic colours of WR stars are summarized in Table XV. Standard deviations are given when available from observations in the LMC. The values are well determined except for those for WC 8 and WC 9 stars. The latter are based on the absolute magnitude of γ^2 Velorum and are rather uncertain.

TABLE XV

Adopted mean absolute magnitudes and intrinsic colours of WR stars

Class	$\overline{M}_v$	S.D.	$\overline{(b-v)_0}$	S.D.
WN 3	−4·5	±0·1	−0·18	±0·06
WN 4	−3·9	±0·3	−0·17	±0·06
WN 5	−4·3	±0·1	−0·14	±0·02
WN 6	−5·8		−0·17	
WN 7	−6·8	±1·0	−0·20	±0·05
WN 8	−6·2	±0·4	−0·15	±0·16
WC 5	−4·4	±0·6	−0·21	±0·07
WC 6	−4·4		−0·21	
WC 7	−4·4		−0·21	
WC 8	−6·2		−0·32	
WC 9	−6·2		−0·32	
WN 4+OB			−0·19	±0·03
OB+WN			−0·21	±0·01
WC 5+OB			−0·26	±0·05

It is noteworthy that the lowest excitation spectra are associated with the most luminous stars. Assuming that there is some correlation between the effective temperature of the stars and the degree of ionization indicated by the dominant lines in their spectra, it follows that the WN 7 and WN 8 stars have much larger radii than do the WN 3, 4 and 5 stars. The same may be true among the WC stars, but the uncertainty in the absolute magnitudes derived for WC 8 and WC 9 stars makes this assertion premature.

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Mount Stromlo and Siding Spring Observatories,
Research School of Physical Sciences,
The Australian National University.
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