Mon. Not. R. astr. Soc. (1968) **141**, 317–327.

THE DISTRIBUTION OF WOLF-RAYET STARS IN THE GALAXY

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(Communicated by Dr L. H. Aller)

(Received 1968 April 18)

Summary

The distances of galactic Wolf-Rayet stars are derived and their distribution on the galactic plane is shown. It is found that the various subclasses show differing degrees of concentration towards the galactic centre. All WC 9 stars appear to be located within 7 kpc of the galactic centre; WN 6 and WC 7 stars show a concentration to the area within 9 kpc of the galactic centre; other subclasses are concentrated to the area outside 9 kpc of the galactic centre. Since the three subclasses that show concentration to the area within 9 kpc of the galactic centre are missing from, or rare in, the Large Magellanic Cloud we conclude that the stellar population in the Large Magellanic Cloud is very similar to that in the solar neighbourhood but quite unlike that in the inner regions of the Galaxy. Previous rate of star formation is suggested to be the controlling factor.

The overall pattern of the Wolf-Rayet distribution suggests spiral arms with inclinations of 3–5°, in qualitative agreement with the theory of a spiral pattern arising from density waves suggested by Lin & Shu (1964, 1966, 1967) and Lin (1967a, b).

The Wolf-Rayet stars are strongly concentrated to the inner edges of the H I and OB spiral features in Cygnus and Carina. Consistency with the density wave model is possible if star formation occurs mainly on the inner edges of spiral arms and if the Wolf-Rayet stars are exceedingly young objects.

1. *Introduction.* Wolf-Rayet (WR) stars are known to be extremely luminous Population I stars (see e.g. Roberts (1962), Westerlund & Smith (1964), Reddish (1967)) and thus we expect them to be powerful spiral tracers. However, until recently, consistent spectral classification, accurate photometry and values for the absolute magnitudes and intrinsic colours of the stars were not available. Spectral classifications have now been provided for nearly all known WR stars by Hiltner & Schild (1966) and by Smith (1968a, b; henceforward referred to as Paper I and Paper II respectively). Narrow band photometric colours have been provided by Westerlund (1966) and by Smith (Paper II). Absolute magnitudes and intrinsic colours were established in Paper II. We are, therefore, for the first time, in a position to examine the detailed distribution of these objects.

2. *The galactic distribution.* Table I gives the mean values and standard deviations of the absolute magnitudes and intrinsic colours of the WR stars, as derived in Paper II. The photometric system used is fully defined in Paper II. b and v have $1/\lambda_{\text{eff}} = 2{\cdot}34$ and $1{\cdot}94$ respectively; these values are close to those of B and V in the Johnson-Morgan system. The pass bands of b and v were chosen so as to avoid, as far as possible, emission lines occurring in the spectra of WN stars.

v and $(b–v)$ are taken from Paper II for the southern WR stars and from Westerlund (1966) for the northern ones. In accordance with the differences in zero

TABLE I

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

points between the systems, determined in Paper II, 0·07 mag has been added to Westerlund's *v*-values and 0·01 mag to his (*b*–*v*) values.

The absolute magnitudes and intrinsic colours of binary stars have been derived by the following procedure: if an accurate classification is available for the OB component of the binary, the luminosity is taken to be the sum of the luminosities of the components. The luminosity of the WR star is taken from Table I and that of

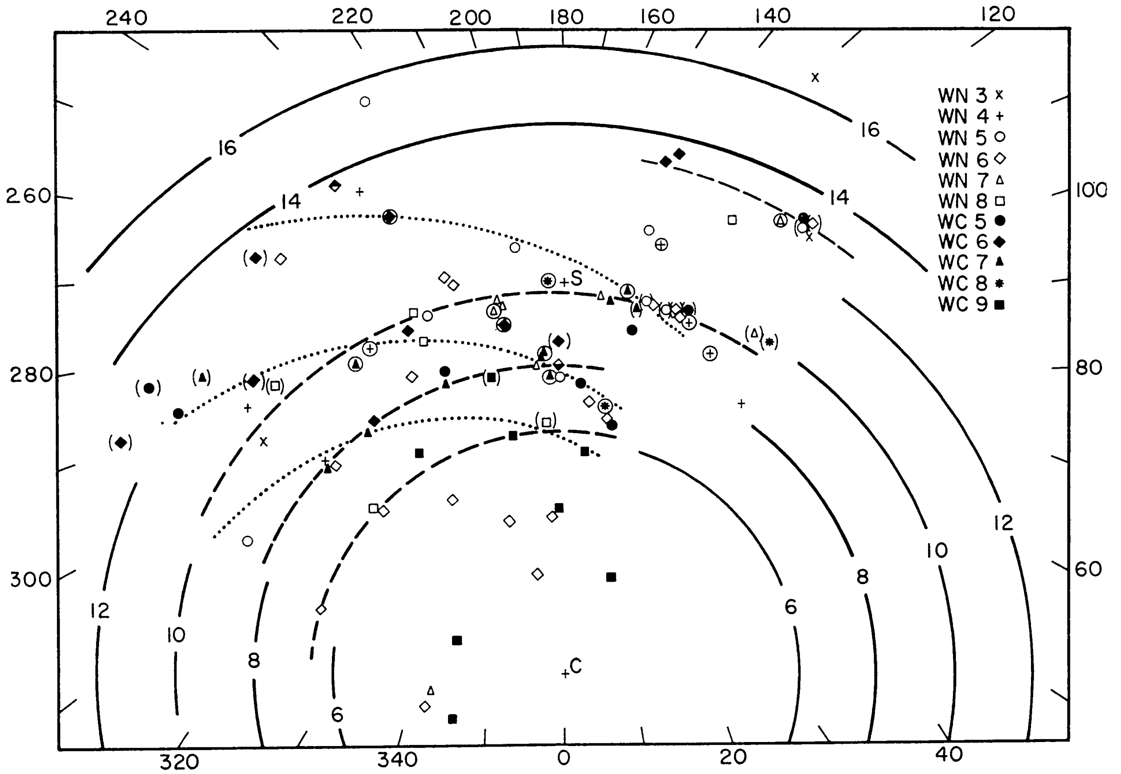

FIG. 1. *The galactic distribution of Wolf-Rayet stars. New galactic co-ordinates are given at the periphery. Distances from the galactic centre are marked in kpc. Dashed lines indicate parts of spirals with inclinations of about 3°. Dotted lines indicate parts of spirals with inclinations of about 25°. The Sun is marked +S. The galactic centre is marked +C.*

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the OB component from the table given by Schmidt-Kaler (1965). (We take $M_V \approx M_v$, as in Paper II.) These stars are represented in Fig. 1 by the symbol used for a single WR star of the relevant class within a circle.

If an accurate classification is not available for the OB component, I have estimated the total luminosity by deciding, from the strength of the emission lines with respect to the continuum, which of the two stars is the more luminous. Such stars are represented in Fig. 1 by the symbol for a WR star of the relevant subclass in brackets. Distances for these stars are, clearly, rather uncertain.

For WN 4 + OB and for WC 5 + OB stars, the mean values of $(b\text{–}v)_0$ found in the Large Magellanic Cloud (LMC) for these types of binaries are used; for other binaries, for lack of better information, the intrinsic colour is, in each case, assumed to be equal to that of the WR component.

Fig. 1 shows the distribution of WR stars, projected onto the galactic plane. Heliocentric longitudes are marked at the periphery. The Sun's distance from the galactic centre is taken to be 10 kpc (Arp 1965a; Schmidt 1965). The symbols used to represent stars of each subclass are given in the legend. The three WR stars in the Carina nebula have been plotted at the distance derived by Graham (1965) (see Paper II).

The stars tend to fall along three approximately circular arcs centred on the galactic centre with radii of 6, 8 and 10 kpc. These correspond to the Cygnus–Carina, Sagittarius and Norma–Scutum arms, so named by Bok (1959). The Perseus arm and the Vela spur are also discernible.

Bok (*loc. cit.*) suggests that the spiral arms in the neighbourhood of the Sun are nearly circular. Alternatively, it has been suggested (Becker 1964; Bidelman 1958; Kopylov 1958) that the spiral features in the neighbourhood of the Sun are inclined to the circular direction by as much as 30°. The latter pattern links the Sagittarius arm north of the galactic centre with the Carina arm south of the galactic centre and the Cygnus arm with the Orion and Vela spurs. Arcs with inclinations of approximately 3° and 25° are marked in Fig. 1 by dashed and dotted lines respectively. The WR stars are sparsely scattered and resolution between the two possibilities is not definitive. However, the smaller inclination gives a better fit to the observed distribution. This is in qualitative agreement with the model of Lin (1967a, b) and Lin & Shu (1967), and supports the suggestion made by Lin (*loc. cit.*) that the larger inclination corresponds to an interarm link in the solar neighbourhood.

Lin & Shu (1967, Fig. 3) give the spiral pattern predicted by the theory of a quasi stationary spiral pattern maintained by density waves for the case where the pattern speed is 11 km s^{-1} kpc^{-1} and the galactic disk is infinitely thin. Comparison with the observed distribution of the WR stars shows that the WR arms fall consistently inside the predicted arms; that is, the WR stars delineate a slightly tighter spiral than is predicted by this particular model. The pattern predicted by Yuan (reported by Lin (1967b)) for a pattern speed of 12·5 km s^{-1} kpc^{-1} in a disk of finite thickness places the arms at essentially the same position as does the pattern for a speed of 11 km s^{-1} kpc^{-1} in an infinitely thin disk. A pattern speed of 13·5 km s^{-1} kpc^{-1} in a disk of finite thickness (Yuan 1968) predicts an even looser spiral with no arm in the solar neighbourhood; Lin suggests that *all* optical spiral features in the solar neighbourhood belong to an interarm link. The strength of the WR features in the solar neighbourhood and their consistency with a small arm-inclination implies that they do belong to a density wave feature and that a model with pattern speed less than 12·5 km s^{-1} kpc^{-1} is required to obtain good agreement.

TABLE II

Distances for galactic WR stars

MR	HD	Sp	$(b-v)_0$	E_{b-v}	v_0	M_v	v_0-M_v	D (kpc)	l^{II}	b^{II}
1	4004	WN 5	−0·14	0·70	7·74	−4·3	12·0	2·51	122·1	+1·9
2	6327	W(He)	−0·21	0·39	9·87				124·6	−2·4
3	9974	WN 3	−0·18	0·18	10·07	−4·5	14·6	8·31	129·2	−4·1
4	16523	WC 6	−0·21	0·44	8·85	−4·4	13·2	4·36	137·6	−3·0
5	17638	WC 6	−0·21	0·63	8·60	−4·4	13·0	3·98	138·9	−2·2
6	50896	WN 5	−0·14	0·07	6·66	−4·3	11·0	1·59	234·8	−10·1
7	56925	WN 5	−0·14	0·47	9·84	−4·3	14·2	6·92	227·8	−0·1
9	62910	WN 6−C7	−0·17	0·60	8·16	−5·8	14·0	6·31	247·1	−3·8
10	63099	WC 6+O7 : I	−0·26	1·02	6·96	−6·4	13·4	4·79	249·3	−4·8
11	65865	WN 4·5	−0·16	0·34	9·72	−4·1	13·8	5·75	246·0	+0·6
12	68273	WC 8+O7	−0·32	0·00	1·74	−6·6	8·3	0·46	262·8	−7·7
13	CD−45° 4482	WN 6	−0·17	0·65	8·46	−5·8	14·3	7·24	265·2	−2·0
15		WC 6+OB	−0·26	1·08	9·51	−5·0	14·5	7·94	265·1	−0·8
16	76536	WC 6	−0·21	0·36	7·98	−4·4	12·4	3·02	267·6	−1·6
17	79573	WC 6	−0·21	0·96	7·89	−4·4	12·3	2·88	271·4	−1·1
19	86161	WN 8	−0·15	0·40	6·83	−6·2	13·0	3·98	281·1	−2·6
20	88500	WC 7+OB	−0·26	0·30	9·91	−5·0	14·9	9·55	284·4	−3·7
21	89358	WN 5	−0·14	0·68	8·48	−4·3	12·8	3·63	283·6	−1·0
LS 3		WC 5+OB	−0·26	1·21	9·01	−6·2	15·2	10·96	283·9	−1·2
23	90657	WN 4−C+OB	−0·19	0·49	7·84				285·0	−0·9
25	92740	WN 7	−0·20	0·23	5·52	−6·8	12·3	2·88	287·2	−0·8
26	92809	WC 6	−0·21	0·25	8·71	−4·4	13·1	4·16	286·8	0·0
28	93131	WN 7	−0·20	0·14	5·93	−6·8	12·7	3·47	287·7	−1·1
29	93162	WN 7+O7	−0·20	0·49	6·21	−7·0	13·2	4·36	287·5	−0·7
LS 4		WC 6+OB	−0·26	1·29	9·57	−5·0	14·6	8·32	287·2	+0·1
30	94305	WC 6+OB	−0·26	0·53	10·61	−4·8	15·4	12·02	289·5	−2·6
31	94546	WN 4+BOn::	−0·19	0·47	8·81	−4·8	13·6	5·25	288·5	0·0
32		WN 8+OB	−0·15	0·78	7·76	−6·7	14·5	7·94	289·8	−1·2
33	95435	WC 5	−0·21	0·41	10·70	−4·4	15·1	10·47	288·5	+1·9
34	96548	WN 8	−0·15	0·26	6·81	−6·2	13·0	3·98	292·3	−4·8
36	97152	WC 7+BOV	−0·26	0·20	7·45	−6·4	13·8	5·75	290·9	−0·5
39		WN 4	−0·17	0·54	10·80	−3·9	14·7	8·71	291·2	+1·3
40	104994	WN 3	−0·18	0·18	10·24	−4·5	14·7	8·71	297·6	+0·4
42		WN 6	−0·17	0·89	7·53	−5·8	13·3	4·57	302·1	−0·2
43	113904	WC 6+O9·5I	−0·26	0·15	5·09	−6·4	11·5	2·00	304·7	−2·5
44		WC 6	−0·21	0·75	9·49	−4·4	13·9	6·03	306·0	+0·3
46	115473	WC 5	−0·21	0·36	8·54	−4·4	12·9	3·80	306·5	+4·5
47	117297	WC 7	−0·21	0·37	9·58	−4·4	14·0	6·31	307·5	+0·4
48		WN 4	−0·17	0·63	10·47	−3·9	14·4	7·59	307·3	−2·5
LS 8		WC 6	−0·21	0·47	12·09	−4·4	16·5	20·00	307·5	−1·6
49	117688	WN 6−C	−0·17	0·57	8·59	−5·8	14·4	7·59	307·8	+0·2
50	119078	WC 7	−0·21	0·03	9·99	−4·4	14·4	7·59	307·9	−5·0
51		WN 5	−0·14	0·56	10·84	−4·3	15·1	10·46	308·8	−3·5
52	121194	WC 7	−0·21	1·15	8·65	−4·4	13·0	3·98	310·6	+0·8
LS 9		WC 9:	−0·32	1·01	9·64	−6·2	15·8	14·45	310·8	−2·9
53		WN 6	−0·17	0·45	10·76	−5·8	16·6	20·89	311·3	−3·9
54	134877	WN 8	−0·15	0·88	8·19	−6·2	14·4	7·59	320·1	−1·8
55		WN 6	−0·17	0·91	8·57	−5·8	14·4	7·59	320·6	−1·2
56	136488	WC 9	−0·32	0·46	7·59	−6·2	13·8	5·75	319·5	−4·8
57	137603	WC 9+OB	−0·32	1·23	5·23	−7·2	12·4	3·02	322·3	−1·8

TABLE II (*continued*)

MR	HD	Sp	$(b-v)_0$	E_{b-v}	v_0	M_v	v_0-M_v	D (kpc)	l^{II}	b^{II}
LS 10		WN 6	−0·17	0·23	9·30	−5·8	15·1	10·47	323·1	− 7·6
60	147419	WN 6	−0·17	0·80	8·22	−5·8	14·0	6·31	332·8	− 1·5
62		WC 9+OB:	−0·32	0·92	9·48	−6·8	16·3	18·20	337·3	− 1·1
64	151932	WN 7	−0·20	0·41	4·97	−6·8	11·8	2·29	343·2	+ 1·4
65	152270	WC 7+O5−8	−0·26	0·27	5·87	−5·5	11·4	1·90	343·5	+ 1·2
66		WC 9	−0·32	1·46	6·91	−6·2	13·1	4·17	341·1	− 2·6
LS 11		WN 7	−0·20	1·01	8·38	−6·8	15·2	10·96	341·9	− 2·4
67		WN 6	−0·17	0·82	9·51	−5·8	15·3	11·48	341·5	− 4·1
LS 12		WN 6	−0·17	1·35	8·15	−5·8	14·0	6·31	347·1	− 0·2
LS 13		WC 9:	−0·32	1·6	8·7	−6·2	14·9	9·55	343·0	− 4·4
68	156327	WC 7+BOV	−0·26	0·70	6·93	−5·0	11·9	2·40	352·2	+ 1·8
69	156385	WC 7	−0·21	0·09	7·09	−4·4	11·5	2·00	343·2	− 4·8
70		WN 8+OB	−0·15	1·38	6·12	−6·7	12·8	3·63	352·6	+ 2·0
71	157451	WC 9	−0·32	0·38	9·08	−6·2	15·3	11·48	345·5	− 4·4
72	157504	WC 6+OB	−0·21	1·36	6·02	−5·0	11·0	1·58	353·2	+ 0·8
73	158860	WN 6	−0·17	0·91	8·63	−5·8	14·4	7·59	354·6	− 0·2
74		WN 5:	−0·14	1·63	7·58	−4·3	11·9	2·40	355·1	− 0·7
75	320102	OB+WN	−0·21	0·89	7·59				354·7	− 1·1
76		WC 7−N6	−0·21	1·29	7·35	−4·4	11·8	2·29	355·2	− 0·9
77		WN 6	−0·17	1·34	8·08	−5·8	13·9	6·03	356·5	− 1·3
79	164270	WC 9	−0·32	0·35	7·61	−6·2	13·8	5·75	358·5	− 4·9
80		WC 9	−0·32	1·63	7·02	−6·2	13·2	4·36	6·4	− 0·5
82		WC 9	−0·32	1·04	8·20	−6·2	14·4	7·59	8·9	+ 0·1
LS 14		OB+WN	−0·21	0·89	6·60				7·7	− 0·4
83	165688	WN 6	−0·17	0·88	6·71	−5·8	12·5	3·16	10·8	0·4
84	165763	WC 5	−0·21	0·14	7·69	−4·4	12·1	2·63	9·2	− 0·6
85	168206	WC 8+BO:	−0·32	0·79	6·27	−6·3	12·6	3·31	18·9	+ 1·8
86	169010	WC 5	−0·21	1·11	8·48	−4·4	12·9	3·80	17·5	− 0·1
87		WN 6	−0·17	1·31	7·02	−5·8	12·8	3·63	17·0	− 1·0
93		WC 5	−0·21	1·56	7·24	−4·4	11·6	2·09	54·5	+ 1·0
94	186943	WN 4+B	−0·19	0·40	8·76	−4·3	13·1	4·17	64·0	+ 1·7
95	187282	WN 4	−0·17	0·19	9·80	−3·9	13·7	5·50	55·6	− 3·8
97		WN 7	−0·20	2·25	3·30	−6·8	10·1	1·05	69·9	+ 1·7
98	190002	WC 7	−0·21	1·34	6·19	−4·4	10·6	1·32	69·5	+ 1·1
99	190918	WN 4·5+O9·5Ia	−0·19	0·32	6·20	−6·4	12·6	3·31	72·7	+ 2·1
100	191765	WN 6	−0·17	0·42	6·63	−5·8	12·4	3·02	73·4	+ 1·6
101	192103	WC 8+OB	−0·32	0·26	7·47	−6·2	13·7	5·50	73·6	+ 1·3
102	192163	WN 6	−0·17	0·42	6·05	−5·8	11·8	2·29	75·5	+ 2·4
103	192641	WC 7+Be	−0·26	0·41	6·54	−5·1	11·6	2·09	74·3	+ 1·1
104	193077	WN 5+OB	−0·14	0·40	6·61	−5·7	12·3	2·88	75·2	+ 1·1
105	228766	WN 7+O	−0·20	0·65	6·73	−6·8	13·5	5·01	75·2	+ 1·0
106	193576	WN 5+O6	−0·14	0·52	6·19	−5·7	11·9	2·29	76·6	+ 1·4
107	193793	WC 7p+O5	−0·26	0·50	5·19	−5·9	11·1	1·66	80·9	+ 4·2
108	193928	WN 6+OB	−0·17	0·92	6·47	−5·8	12·3	2·88	75·3	+ 0·1
109	195177	WC 5+OB	−0·26	1·45	6·52	−6·0	12·5	3·16	77·5	0·0
113	197406	WN 7	−0·20	0·62	8·02	−6·8	14·8	9·12	90·1	+ 6·5
114		WN 5+OB	−0·14	0·84	9·04	−5·0	14·0	6·31	102·6	+ 1·4
115	211564	WN 3	−0·18	0·53	9·50	−4·5	14·0	6·31	102·2	− 0·9
116	211853	WN 6+BO : I	−0·17	0·49	7·24	−6·8	14·0	6·31	102·8	− 0·6
117	213049	WC 5:	−0·21	0·52	9·61	−4·4	14·0	6·31	103·9	− 1·2
118	214419	WN 7+O7	−0·20	0·53	6·82	−7·0	13·8	5·75	105·3	− 1·3
119		WN 8	−0·15	1·03	7·06	−6·2	13·3	4·57	109·8	+ 0·9
120	219460	WN 4·5+BO	−0·19	0·71	7·19	−4·9	12·1	2·63	111·3	− 0·2

As shown first by Roberts (1962) and confirmed by Stephenson (1966), there appears to be a complete lack of WR stars in the directions between $l^{\rm II} = 140°$ and 220°. From Fig. 1 it is clear that there are comparatively few WR stars outside a galactocentric radius of 11 kpc altogether. Even so, the gap appears to be significant. Since interstellar absorption is comparatively slight in these directions (Khavtasi 1960), we must conclude that the gap is real and that the Perseus arm ends at about $l^{\rm II} = 150°$. Kraft & Schmidt (1963) tentatively arrived at a similar conclusion from a consideration of the galactic distribution of classical cepheids.

There also appears to be a gap in Fig. 1 in directions between $l^{\rm II} = 19°$ and 50°. This is not real. Six WR stars are known between these longitudes; all are fainter than 11th mganitude and have not been observed photometrically. Distances for these objects would clearly be valuable for determining the inclination of the inner spiral arms.

3. *Galactic distribution of the subclasses.* It is clear from Fig. 1 that the different subclasses are differently distributed in the galactic plane. In particular, the WC 9 stars are found almost exclusively in directions within 45° of $l^{\rm II} = 0°$, while the WC 7 and WN 6 stars also show a tendency to concentrate towards the centre. We apply, below, a series of tests to confirm the statistical significance of these observations.

First of all, we test the hypothesis that all subclasses are distributed symmetrically about $l^{\rm II} = 0°$. Table III gives the numbers of WR stars brighter than $v = 13·0$ mag in each subclass occurring in the intervals $0° < l^{\rm II} < 180°$ and $180 < l^{\rm II} < 360°$ and the values of χ^2 derived on the assumption that all subclasses occur with the same frequency in both sectors. No distinction has been made between binary and single stars. The column marked ' ? ' includes stars of doubtful spectral type. The probability of χ^2 with one degree of freedom exceeding 3·84 is 0·05. This is called the 5 per cent confidence limit and will be used below to define a significant deviation from a hypothetical distribution. None of the values of χ^2 in Table III exceeds this limit, i.e. none of the distributions deviated significantly from symmetry about $l^{\rm II} = 0°$.

TABLE III

Distribution of WR stars about $l^{\rm II} = 0°$

	Number of stars												
$l^{\rm II}$	Class N 3	N 4	N 5	N 6	N 7	N 8	C 5	C 6	C 7	C 8	C 9	?	Total
0°–180°	2	4	4	6	5	2	3	2	3	2	3	5	41
180°–360°	1	5	3	10	5	5	2	8	8	1	5	2	56
χ^2	0·3	0·1	0·1	1·0	0·0	1·3	0·2	3·6	2·3	0·3	0·5	1·3	

TABLE IV

Comparison of directions inside and outside 60° from centre

	Number of stars												
Region	Class N3	N 4	N 5	N 6	N 7	N 8	C 5	C 6	C 7	C 8	C 9	?	Total
A	3	7	7	6	7	4	5	8	5	2	0	17	71
B	0	2	1	12	3	3	4	4	8	1	10	8	56
χ^2 (I)	2·3	1·8	3·2	3·8	0·8	0·0	0·0	0·6	1·6	0·2	*12·7*	1·4	
χ^2 (II)	2·0	1·0	2·5	*5·6*	0·3	0·0	0·1	0·2	2·7	0·0		0·5	
χ^2 (III)	1·5	0·6	1·6		0·1	0·2	0·4	0·0	*4·1*	0·0		0·0	

To test the degree of concentration towards the galactic centre, Table IV gives the numbers in each subclass occurring in the intervals of l^{II}: A, 60°–180°–300° and B, 300°–360°–60°. This effectively separates stars inside a galactocentric radius of 9 kpc from those outside this radius. All stars are included. No distinction has been made between binaries and single stars. Successive rows give:

1. Spectral subclass.
2, 3. Numbers of stars in the subclass in region A and region B, respectively.
4. Values of χ^2 derived on the assumption (I) that all classes are distributed in the same way. The expected number ratio is A : B = 71 : 56, the mean value over all subclasses.
5. Values of χ^2 derived on the assumption (II) that all classes except WC 9 are distributed in the same way. The expected ratio is A : B = 71 : 46.
6. Values of χ^2 derived on the assumption (III) that all classes except WC 9 and WN 6 are distributed in the same way. The expected ratio is A : B = 65 : 34.

Row 4 shows that the distribution of stars in class WC 9 is significantly different from the mean distribution, in the sense that WC 9 stars show a stronger concentration towards the galactic centre (region B). Similarly, row 5 shows that the distribution of WN 6 stars differs significantly from the mean of all classes excluding WC 9 in the sense that WN6 stars are concentrated to region B. Row 6 shows that the distribution of WC 7 stars differs significantly from the mean distribution of all classes excluding WC 9 and WN 6, also in the sense that WC 7 stars are concentrated to region B.

Table V gives the number of stars in each of the subclasses, WN 6, WC 7 and WC 9, occurring in the intervals of l^{II}: C, 45°–180°–315° and D, 315°–360°–45° and the values of χ^2 derived on the assumption that the stars in the three classes have the same distribution. Clearly, WC 9 stars are strongly concentrated to region D.

Table V

Comparison of directions inside and outside 45° *from the centre*

		Number of stars		
Region	Class	N 6	C 7	C 9
C		9	8	0
D		9	5	10
χ^2		0·5	2·1	7·2

In the above discussion, no allowance has been made for the effect of the different luminosities of the stars on the apparent distribution. As noted above, there appear to be almost no WR stars in the 120° centred on the anticentre. Thus, a comparision between regions A and B is effectively a comparison between regions towards the galactic centre and regions towards the Cygnus and Carina complexes. The two have effectively the same angular extent. Interstellar absorption is severe in all of these directions, and will probably affect the numbers of stars observed in regions A and B equally. Thus, although more luminous stars may be seen to greater distances, the resulting increase in the observed area of the galactic plane should be comparable in the two regions. Consequently, we conclude that the luminosities of the subclasses will have no systematic effect on the apparent distribution.

If the above calculations are repeated with only the stars brighter than $v = 13$

mag, the conclusions are similar, but the degree of significance decreases. In particular, the concentration of WC 7 stars towards the centre ceases to be significant at the 5 per cent confidence level. This must be a result of either the reduction of the sample to a point where a genuine difference is not detectable, or the removal of selection effects caused by uneven researches in the regions compared. The author favours the former explanation; clearly these calculations should be repeated when the completeness of the catalogue at fainter magnitudes has been improved.

We conclude that:

(1) WC 9 stars are exclusively concentrated to within 45° of galactic longitude $l^{\mathrm{II}} = 0°$. If we assume that their distribution is symmetrical around the galactic centre, this implies that all WC 9 stars occur within 7 kpc of the galactic centre.

(2) WC 7 and WN 6 stars are more strongly concentrated to directions within 60°, (or 9 kpc) of the galactic centre than are WN 3, 4, 5, 7 and 8 and WC 5 and 6 stars.

It is remarkable that the classes that are found to be concentrated towards the galactic centre, i.e. WC 7 and 9 and WN 6, are among the classes absent, or nearly absent, from the Large Magellanic Cloud (LMC) (see Paper II). Not one example of class WC 9 or of class WC 7 is found in the LMC, and only three possible WN 6 stars are found.

It is also true that WC 6 and WC 8 stars are not observed in the LMC. There are only three WC 8 stars in the Galaxy so that we have no reliable information regarding their distribution. WC 6 stars are definitely not concentrated towards the galactic centre, so the correlation is not complete. However, it remains true that the population of WR stars in the LMC is quite similar to the population in the Galaxy outside 9 kpc from the centre, but quite unlike the population inside that radius.

The Small Magellanic Cloud (SMC) contains only two WR stars, classified WC 5+OB and OB+WN. It is therefore quite different, in this regard, from any part of the Galaxy. However, the paucity of WR stars in the SMC makes it most like the outer parts of the Galaxy.

4. *Comparison with the neutral hydrogen and with the OB star distributions.* It seems inappropriate, at this time, to make a detailed comparison between the distribution of the WR stars and that of the neutral hydrogen. The latter is uncertain because of the incorrectness of the assumption of circular orbits (e.g. Kerr & Hindman (1967); Miller (1968)). However, one obvious fact should be noted: the WR stars are strongly concentrated near the *inner* edges of the H I features in the directions of Cygnus and Carina. The WR concentrations are found at $l^{\mathrm{II}} = 75°$ and 290°. The positions of the H I edges are given by Kerr (1962) as 80° and 285°.

Similarly, it may be seen from the diagrams given by Rohlfs (1967) that the directions in which the WR stars are concentrated tend to be closer to that of the galactic centre than are the directions in which the O and B stars show maximum concentration.

Both the above observations are independent of the distance scales. We conclude that the WR stars are strongly concentrated near the *inner* edges of the local spiral features defined by most of the rest of the extreme Population I objects.

5. *Discussion.* We have found that, in the Galaxy, the WR population varies qualitatively from the inner to the outer parts. We have also found that the WR population in the LMC is quite similar to that in the solar neighbourhood, while the

paucity of WR stars in the SMC makes it most like the outermost regions of the Galaxy.

Variations of this type have been noted before, both in our own Galaxy and in other galaxies. In the Galaxy, a comparison of the total density model given by Schmidt (1965) with the H I densities given by Kerr & Westerhout (1965) shows that the ratio of H I to total density increases from less than 1 per cent at the centre to about 9 per cent in the solar neighbourhood and then falls off again in the outer parts of the Galaxy. The LMC, with a ratio of 9 per cent (Bok 1966), again compares well with the solar neighbourhood, while the ratio of 25 per cent found in the SMC (Bok 1966) is greater than found in any part of the Galaxy.

Baade & Swope (1965) found that the mean period of cepheids in M 31 decreases from 17 days near the centre to 7 days in the outermost spiral arm. Shapley & Nail (1948) found a similar phenomenon in the SMC. For cepheids in the Galaxy, Kraft & Schmidt (1963) find a suggestion that cepheids with periods greater than 11 days tend to concentrate in the spiral arm that is interior to the Sun. Kraft (1963) finds that the mode of (log P) is less for cepheids in the Per–Cas arm than for cepheids in the local arm. He also shows that the mode of (log P) for cepheids in the SMC is lower than for those in either of the above mentioned arms. Shapley & Nail (*loc. cit.*) found that the mode of the period for the cepheids in the LMC is greater than that in the SMC and approximately equal to that in the solar neighbourhood.

I suggest that all of these phenomena are a result of different rates of star formation in the various regions. It is reasonable to suppose that star formation has proceeded most rapidly in the central regions of our Galaxy. This would be expected to result in a depletion of the interstellar hydrogen, as observed and would presumably result in an increase in the heavy element abundance in the interstellar medium and, therefore, in the young stars. I suggest that, in the galactic disk, the rate of star formation and the resulting heavy element content in the interstellar medium decreases monotonically from the centre of the Galaxy to the outer edges. Reports by Kraft (1963) that the cepheids in the Per–Cas arm appear to be underabundant in metals and by Williams (1966) that cepheids in the Sagittarius arm are richer in metals than those in the Cygnus arm, are consistent with this suggestion. Similarly, Arp (1962) concludes that clusters originating in the outer regions of the Galaxy have lower metal abundance than those in the inner regions. However, Arp (1965b) suggests that metal abundance in the galactic centre is only as high as that in the solar neighbourhood, whereas the present data suggest that the metal abundance in the galactic centre is significantly higher than is found in the solar neighbourhood.

It is known from the work of Hofmeister (1965a, b) that the properties of the cepheid population are very sensitive to the abundance of helium and heavier elements. Thus, while the exact effects are not yet known, differences in the chemical composition of stars in the various regions are clearly capable of causing the observed phenomena.

No direct evidence is yet available regarding the chemical compositions of the WR stars. However, the present data strongly suggests that the initial chemical composition plays a definitive role in distinguishing the subclasses among the WC stars. Since most subclasses of the WN stars share a common distribution, we conclude that stars in these subclasses share a common initial chemical composition. The exception is the subclass WN 6 in which stars apparently have a higher initial heavy element abundance than do stars in the other WN subclasses.

The similarity of the LMC to the solar neighbourhood must result from rather similar past and present rates of star formation and metal enrichment of the interstellar medium in the two regions. It would follow from this argument that the rate of star formation in the SMC has probably been less than in the LMC or in the solar neighbourhood and most similar to that in the outer parts of the Galaxy.

Arp (1967) also reaches the conclusion that stars in young clusters in the SMC have lower metal abundances than do stars in young clusters in the LMC. However, Arp suggests that the metal abundance is less in the LMC than in the solar neighbourhood, a conclusion that is not supported by the present data.

It has been shown (Section 1) that the overall pattern of the distribution of the WR stars is similar to that predicted by the density wave model for spiral structure proposed by Lin & Shu. It has also been shown (Section 3) that in Cygnus and Carina the WR stars are strongly concentrated to the inner edges of the spiral features delineated by the O and B stars and by the neutral hydrogen.

The density wave theory predicts a pattern speed that is much less than the gravitational circular speed. Thus, stars formed in an arm will subsequently move out of the arm in the direction of rotation. If the arm is trailing (as is believed to be the case in the Galaxy) then stars will move towards the *outer* edge of the arm. If this theory is correct and if the arms in the Galaxy are indeed trailing, then the only possible explanation for stars being concentrated to the inner edge of an arm is that they were formed there. Three propositions then seem plausible: (1) star formation occurs preferentially on the inner edges of the spiral arms; (2) WR stars are too young to have moved a significant distance from their place of origin; (3) WR stars are, on the average, younger than O and B stars.

The occurrence of star formation on the inner edges of spiral arms may find an explanation in the calculations of Roberts (1968) who demonstrates the possible presence of shock phenomena along the inner edges of the spiral arms where there is a sudden change in the gas density. It seems likely that shock phenomena assist the precipitation of star formation. Westerlund & Mathewson (1966) suggest that the formation of large circular super-associations in the LMC is precipitated by the explosion of a Type I supernova. Similarly, the shape of the thin spheroidal shells of stars discovered by Isserschedt & Schmidt-Kaler (1967) suggests a connection with shock waves originating within the spheroid.

Acknowledgments. I am happy to thank Professor B. J. Bok and Dr B. E. Westerlund for helpful discussions throughout all stages of this project. The work is based upon observations obtained at Mount Stromlo and Siding Spring Observatories during the tenure of an Australian National University Research Scholarship. Work on the interpretation of the observations has been supported by National Science Foundation grant GP5182 to the University of California, Los Angeles.

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1968 *April.*

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