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THE WOLF-RAYET POPULATION IN 30 DORADUS AND ITS SURROUNDINGS

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ABSTRACT

An assessment of the Wolf-Rayet (W-R) stars in the central 5′ (64 pc for distance modulus 18.2) diameter of the 30 Dor Nebula yields ~15 genuine W-R stars. Of these, an overwhelming proportion (~75%) are late-type WN, luminous (i.e., WNL) stars of type WN6 and WN7. This contrasts with the immediate surroundings from ∅ = 15′ out to ∅ = 90′, where only 2 of 28 (7%) W-R stars are WNL, and even a lower fraction in the rest of the LMC. On the basis of the radial distribution of WN6,7 stars, the central cluster has a diameter of ~260 pc. As in the case of the WN6,7 stars, the fraction of WC stars tends to increase toward the center of 30 Dor, while WN8–10 and WN2–5 stars show no preference for the 30 Dor core.

Assuming coeval star formation and that WC stars are more evolved than WN stars, the young age (~2×10^6 yr) of the central cluster implies that the luminous WNL stars must have evolved from very massive progenitors and that the WC stars came from even more massive ones.

The visual multiple system R140 in the 30 Dor Nebula contains at least three W-R stars, one of type WC5, the others of type WNL. One of the WNL components is found to be a close spectroscopic binary with a period of 2.76 days.

The other WC star close to the core of 30 Dor is the faintest of four stars comprising the object Melnick E. It has an absolute magnitude similar to that of other single WC stars in the LMC.

Using the currently claimed smaller distance modulus 18.2 of the LMC, we find that the absolute visual magnitudes M_v of the W-R stars in the 30 Dor central cluster are similar to those of their Galactic counterparts.

Subject headings: galaxies: Magellanic Clouds — nebulae: individual — stars: binaries — stars: evolution — stars: stellar statistics — stars: Wolf-Rayet

I. INTRODUCTION

The bright 30 Doradus nebula in the Large Magellanic Cloud is well known as the most massive giant H II region among the Local Group galaxies. Its central cluster, NGC 2070, contains ~15 Wolf-Rayet (W-R) and ~60 O stars of type hotter than O5, in the central diameter of 2′–3′ (Breysacher 1981; Melnick 1983, 1985; Walborn 1986). In addition to these, there are numerous bright supergiants.

a) 200 blue supergiants (BSGs), mainly of late O and early B type with $V \lesssim 13$ mag fairly uniformly distributed out to ∅ = 1°5 from 30 Dor and merging into the LMC background (Isserstedt 1984). They appear to peak in density only weakly at the position of 30 Dor (see also Walborn 1986).

b) 12 red supergiants (RSGs) in a 12′ × 12′ surveyed area centered on NGC 2070 (McGregor and Hyland 1981).

More recently, other generally fainter BSGs have been revealed in the central 30 Dor area (Melnick 1985; Walborn 1986).

Among the W-R stars, the visually brightest are clearly those classified as WN6 and WN7, which we call WNL. In fact they are among the brightest of any individual stars in the 30 Dor cluster. We denote the WN8–10 stars by WNLL. Only four BSGs (R137, R138, R141, and R142) are visually brighter than the brightest WNL stars in the central ∅ = 2′5. In the ultraviolet the hot O3 stars probably dominate in brightness. If star formation was instantaneous during the last burst that produced the present early-O star population, one must conclude that the W-R stars in 30 Dor evolved from main-sequence stars of spectral type ~O3. If star formation was not instantaneous (i.e., a continuous process over several times 10^6 yr), then one can conclude little about the nature of the W-R star progenitors.

Particularly noteworthy are the two WC stars (Phillips 1982) located in very tight stellar subgroups (R140 and Mk E)

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in the central region of 30 Dor. This is reminiscent of the two WC stars B9 and B28 (notation from the catalog of Breysacher 1981), which are located in very compact multiple systems in other regions of the LMC (cf. Prévot-Burnichon *et al.* 1981; Heydari-Malayeri and Testor 1983). WN stars are also found in very compact multiple systems in the LMC, such as B58 and B65 outside the 30 Dor nebula (Lortet and Testor 1984). Since the two WC stars in the central part of 30 Dor are tightly associated with other very early, luminous stars of the same kind as seen in the remaining parts of 30 Dor, they must belong to the young central cluster. However, it is still not certain how these two WC stars fit into the evolutionary picture in 30 Dor, since we have no reliable estimate of their magnitudes, due to crowding effects.

Clearly, there is a need for more systematic studies of stars in the central region of 30 Dor, e.g., high angular resolution narrow-band imagery to isolate W-R stars, or spectroscopy and photometry using small apertures to scrutinize the stellar content and reveal spectroscopic binaries. In this work we emphasize the WC stars, but in a global context relative to the remaining stellar population in 30 Dor and in the LMC at large.

II. OBSERVATIONS

We have obtained three kinds of data: imagery, spectroscopy, and precision photometry. These are discussed in turn with some immediate results, if applicable. A more general discussion follows.

a) Imaging

i) Direct photographic plates in a relatively wide field ($\varnothing \approx 60'$) centered on 30 Dor were obtained by one of us (Y. H. C.) in 1983 at the f/2.67 prime focus of the CTIO 4 m telescope, in order to carry out a general search for W-R stars in the 30 Dor central cluster. Baked IIIa-J emulsion was used for high resolution in the 0."8 FWHM seeing and 18."6 mm^{-1} plate scale. Two narrow-band interference filters were employed: one centered at 4680 Å with FWHM $\approx$ 41 Å in the fast beam, which is sensitive to the strongest optical emission lines of virtually all W-R stars (C III/IV λ4650 and He II λ4686 in WC and He II λ4686 in WN); the other filter served as a reference continuum at the neighboring wavelength 4765 Å, FWHM $\approx$ 43 Å. Figure 1 (Plates 4–5) shows a "long" exposure ($\sim$1 minute) pair of plates in the central 2'.5. All known W-R stars are identified, as well as the multiple components of the two crowded WC stars R140 and Mk E and the brightest BSGs and RSG in the field. Some W-R stars are evident at a glance. No new W-R stars are revealed in this survey down to magnitude $V \approx 17$ compared to Breysacher's (1981) catalog of W-R stars in the whole LMC, or the central narrow-band CCD search of Moffat, Seggewiss, and Shara (1985, hereafter MSS). The two new very faint ($V \approx 18.5$) WC stars found in the 30 Dor area by Morgan and Good (1985) are below our detection limit. Whether these are genuine Population I W-R stars or central objects of planetary nebulae has not been settled yet (Breysacher 1986).

We note in passing that the overall star density clearly tends to peak toward the central object R136. We checked this quantitatively on CCD *U* images obtained by P. Seitzer at the prime focus of the CTIO 4 m telescope. The light distribution in strips 1'.2 wide in either R.A. or Decl. show clearly a peak position exactly coinciding with R136a, the dominant component of R136.

ii) Direct CCD images of the central 3' × 5' of 30 Dor were obtained by M. M. P. in 1983 with the same telescope and focus as above, in order to make a deep narrow-band search for WC stars at a wavelength unique to WC stars. The seeing had a FWHM = 1."5. One filter at 7710 Å was sensitive to C IV λ7726 emission in WC stars (continuum in WN); the other filter served as a reference continuum at 7515 Å (cf. Nassau and Velghe 1964). The filters have FWHM bandpasses of 100 and 140 Å respectively. They allow easy detection of the C IV λ7726

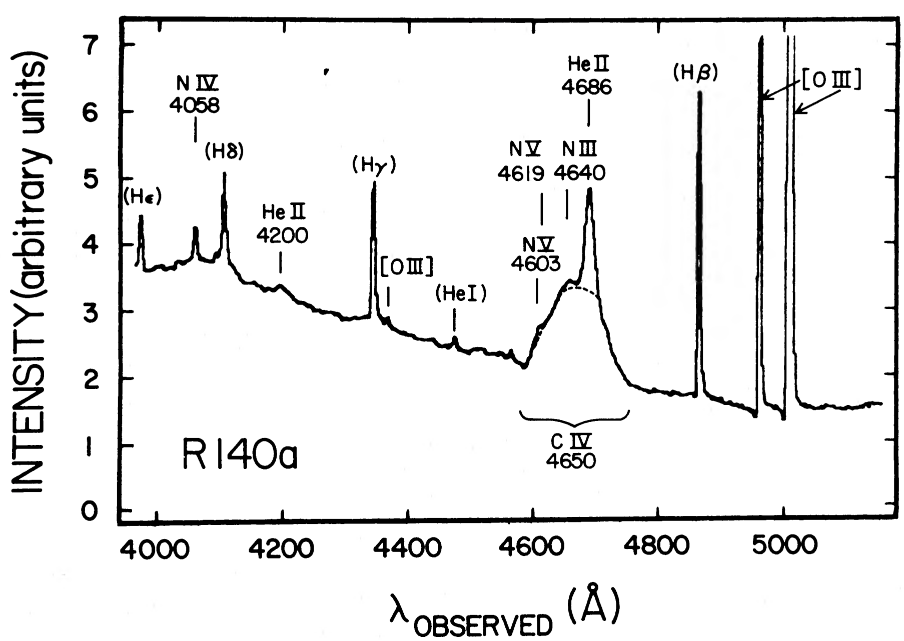

FIG. 2.—The sum of all SIT Vidicon blue spectra of R140a from 1984 January 28/29. With no sky subtraction or flux calibration, the intensity scale is in arbitrary intensity units. Note the presence of two W-R stars, one a narrow-line WN6 star, the other a broad-line WC5 star, whose underlying C IV λ4650 emission we have attempted to sketch in.

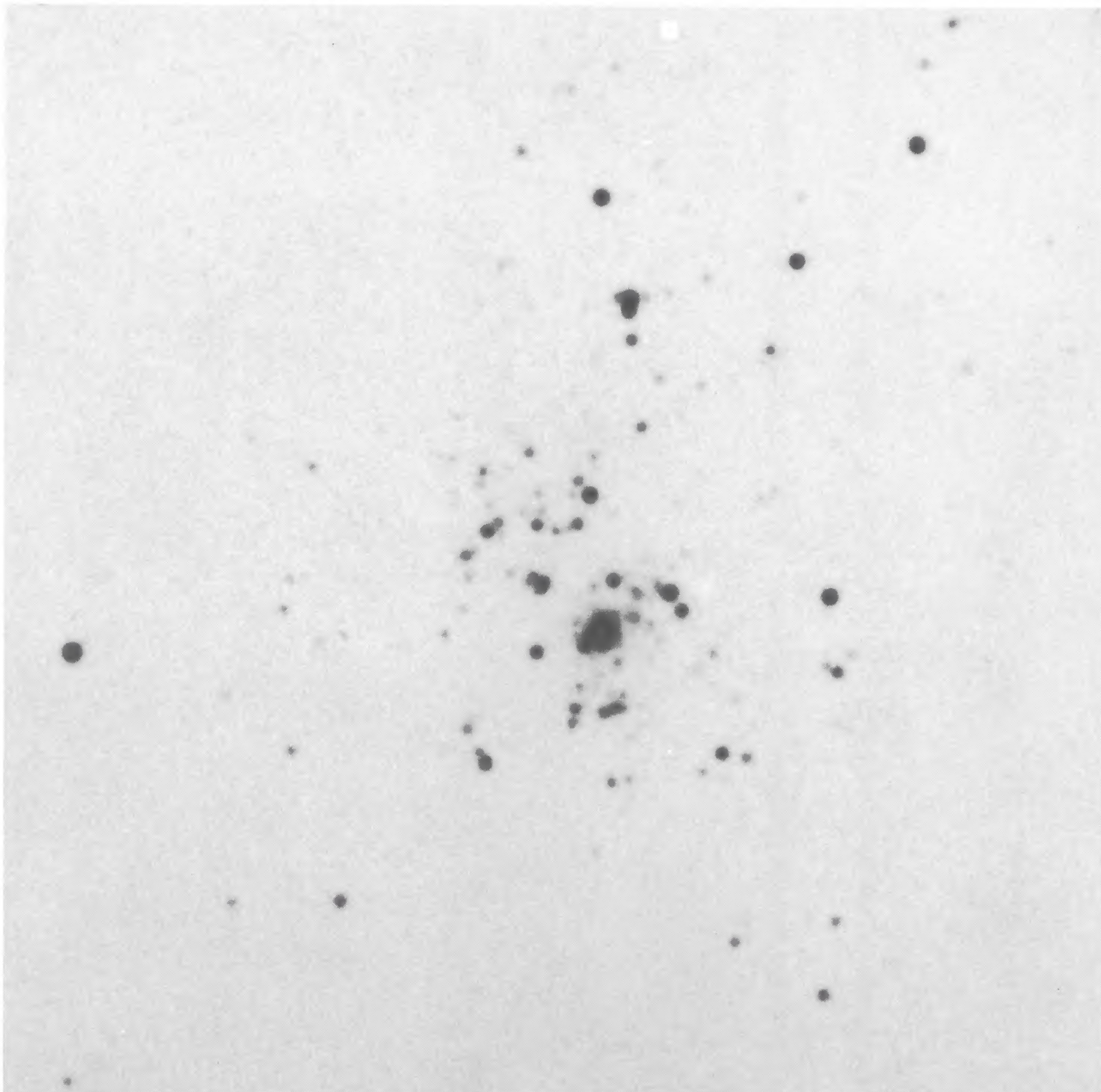

FIG. 1*a*

FIG. 1.—Direct CTIO prime focus photographs of the 2′.5 × 2′.5 central core of 30 Dor. (*a*) In narrow-band 4680 Å, which enhances stars with strong He II λ4686 or C IV λ4650 emission in W-R stars. (*b*) In narrow-band 4765 Å, which serves as a continuum reference. In (*b*) all known W-R and W-R/Of stars from Table 5 are identified, along with the four brightest BSGs and one RSG (in parentheses).

MOFFAT *et al.* (*see* page 613)

1987ApJ...312..612M

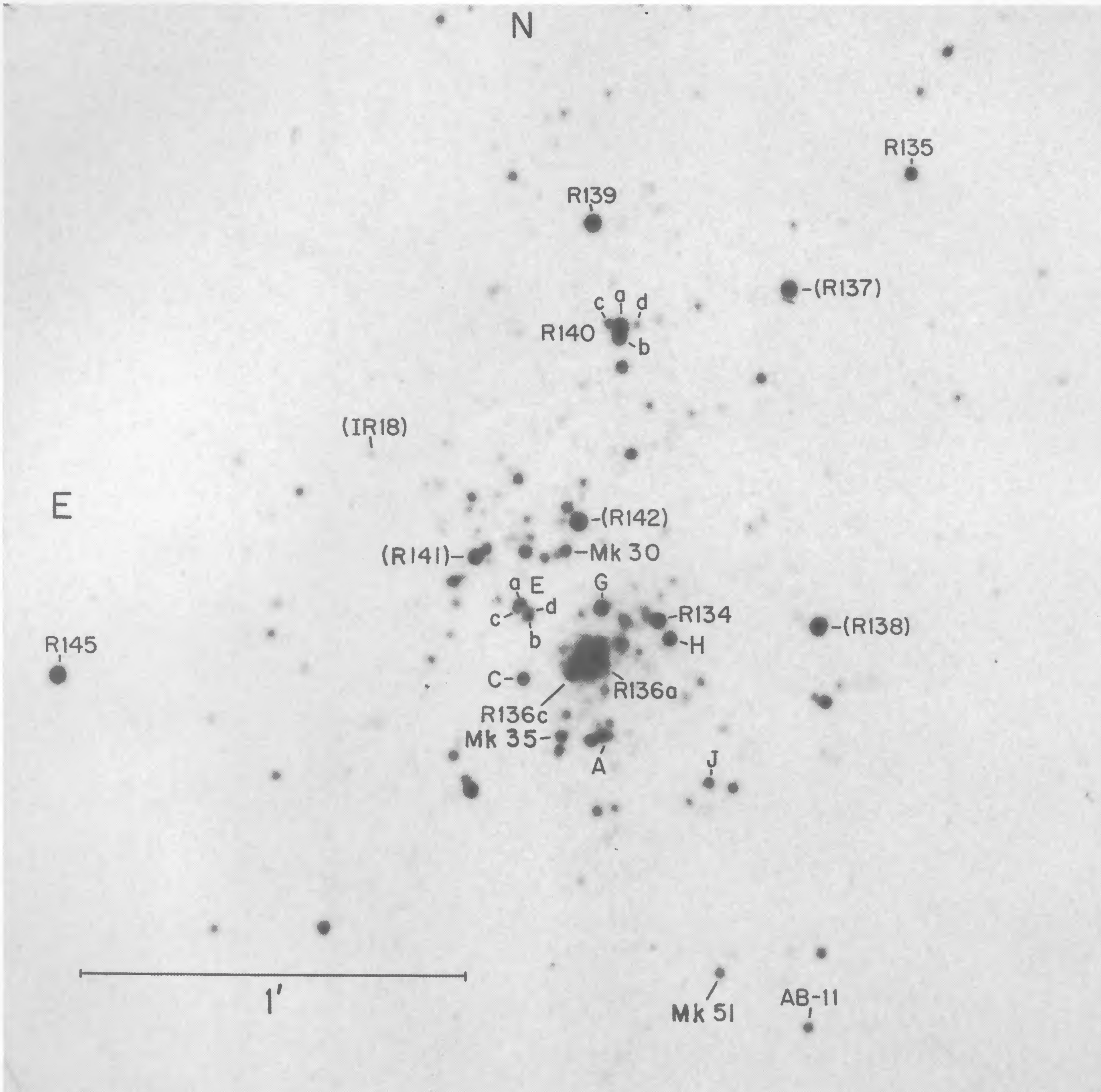

FIG. 1b

MOFFAT *et al.* (*see* page 613)

line with $W_e = -200$ Å in a typical WC5 spectrum (Sivertsen 1981), the most common WC subclass in the LMC. Only two WC stars were revealed by this technique; they are the already known WC5 stars in the compact groups R140 and Mk E, as noted above. This confirms the previous findings of Phillips (1982) and MSS. The latter authors used a narrower filter centered at the carbon line C IV λ4650 to reveal WC stars.

b) *Spectroscopy*

Here we concentrate only on the two WC stars R140 and Mk E, with the following techniques:

i) SIT Vidicon long-slit (1″ north-south × 3′.5 east-west) spectra were obtained by one of us (M. M. P.) during three nights in 1983 October (R140) and one night in 1984 January (R140 and Mk E) at the CTIO 1.5 m telescope. The spectra cover varying portions in the 4000–7000 Å range with spectral resolution FWHM ≈ 4.8 Å in 1″–2″ seeing. Although the radial velocities (RVs) of these spectra are not accurate enough for study of binary motion, the mean spectra (e.g., R140 in Fig. 2) are useful for resolving some spectral features.

ii) The largest body of spectroscopic data was obtained for R140 by two of us (A. F. J. M. and V. S. N.) during 1978–1984 using the Carnegie image tube spectrograph attached to the 1 m telescope at CTIO. The photographic plates mainly cover the 3600–5000 Å region of the spectrum of R140, with a 2″ north-south × 8″ east-west slit. With inverse dispersion ~45 Å mm^{-1}, the spectral resolution is ~1.5 Å FWHM. The IIa-O plates (A. F. J. M.) have 0.65 mm wide spectra, which were scanned in photographic density mode and analyzed using standard techniques on a PDS. The IIIa-J plates (V. S. N.) have 1 mm wide spectra and were measured for RV on a Grant machine. A few IIIa-J plates were also obtained at twice the previous inverse dispersion over 5000–7000 Å. From the blue image tube spectra, RVs of the strongest, well-resolved W-R lines in R140a are listed in Table 1. Wavelengths were calibrated by He-Ar comparison spectra.

iii) Flux-calibrated IDS spectra were secured for R140 in 1982 December by two of us (A. F. J. M. and W. S.) at the 1.5 m telescope at the European Southern Observatory. They cover the red region from 5000–7000 Å at resolution FWHM ≈ 6 Å. Dual slits of 2″ × 2″, separated by 60″, were used to facilitate quasi-simultaneous sky subtraction. The seeing was generally 1″–2″. RVs of the strong C IV λ5800 line of the WC component of R140a are given in Table 2. The mean IDS spectrum of R140a is presented in Figure 3 in comparison with the WC5 + O6 binary HD 36402 = B31 and the nearby component R140b.

A comparison of the nebular RVs using different spectroscopic techniques is given in Table 3. These show a fair degree of stability from one source to another.

c) *Photometry*

One of us (W. S.) obtained differential photoelectric photometry for R140 in the Walraven system in 1982 at the 0.9 m Dutch telescope at ESO. Using two comparison stars, the observations cover a contiguous interval of 14 nights. The 11″.6 diaphragm includes all four components of R140 (abcd; cf. Fig. 1), although the brighter northern component dominates in continuum light. Table 4 lists the nightly means of ~5 measures per night, each measure being of 32 s duration.

TABLE 1

IMAGE-TUBE HELIOCENTRIC RADIAL VELOCITIES OF WNL EMISSION LINES IN R140a (km s^{-1})

JD (2,440,000+)	Phase[a]	N IV λ4057.759	N V λ4603.64	He II λ4685.682
3838.76.........	0.500	229	...	197
3839.81.........	0.881	104	...	194
3840.83.........	0.250	302	...	325
3842.81.........	0.968	232	...	172
3844.80.........	0.689	88	...	130
3845.85.........	0.069	249	...	348
3846.80.........	0.414	271	...	267
4255.78.........	0.616	269	...	198
4256.82.........	0.993	236	...	262
4257.81.........	0.352	303	...	259
4258.83.........	0.721	163	...	177
4259.80.........	0.073	309	...	283
4260.79.........	0.432	247	...	277
4261.81.........	0.801	183	...	206
4262.85.........	0.178	286	...	305
4279.76.........	0.966	291	...	233
4980.81.........	0.346	314	...	294
4981.54.........	0.611	167	...	178
5254.74.........	0.611	223	425	287
5255.87.........	0.020	207	448	264
5256.84.........	0.372	265	515	345
5258.83.........	0.093	250	...	301
5385.69.........	0.063	236	...	274
5386.71.........	0.433	276	503	348
5387.70.........	0.792	187	414	282
5388.59.........	0.114	269	501	362
5389.58.........	0.473	170	...	294
5391.66.........	0.227	300	699	395
5392.67.........	0.593	200	...	323
5393.67.........	0.955	222	489	286
5769.55.........	0.163	233	...	373
5769.64.........	0.196	361	...	446
5770.54.........	0.522	...	...	348
5773.51.........	0.598	124	...	261
5773.64.........	0.645	178	...	276
5775.51.........	0.323	266	...	386
5775.58.........	0.348	299	546	405
5842.47.........	0.587	240	303	277
5843.47.........	0.950	195	557	224
5844.46.........	0.308	317	471	296
5847.49.........	0.406	247	468	302

NOTES.—Plates before JD 2,445,000 obtained by A. F. J. M. (1978–1982) on baked IIa-O emulsion, those thereafter by V. S. N. (1982–1984) on baked IIIa-J.

All but the last group of four IIIa-J plates yield more negative residuals for the He II velocities than the IIa-O plates, while no such trend is seen in the N IV velocities.

[a] Based on the N IV ephemeris JD 2,445,769.1 + 2.7596 E, i.e., time of passage through the gamma-velocity from negative to positive.

TABLE 2

IDS HELIOCENTRIC RADIAL VELOCITIES AND LINE STRENGTHS OF THE WC COMPONENT OF R140a

		C IV λ5800.0	
JD (2,440,000+)	PHASE	RV (km s^{-1})	W_e (Å)
5310.74.........	0.903	776	−331
5313.74.........	0.992	797	−297
5314.73.........	0.349	750	−308
5315.74.........	0.715	781	−298
Mean		776	−308
σ		20	16

NOTE.—Phase refers to N IV of the WN component of R140a.

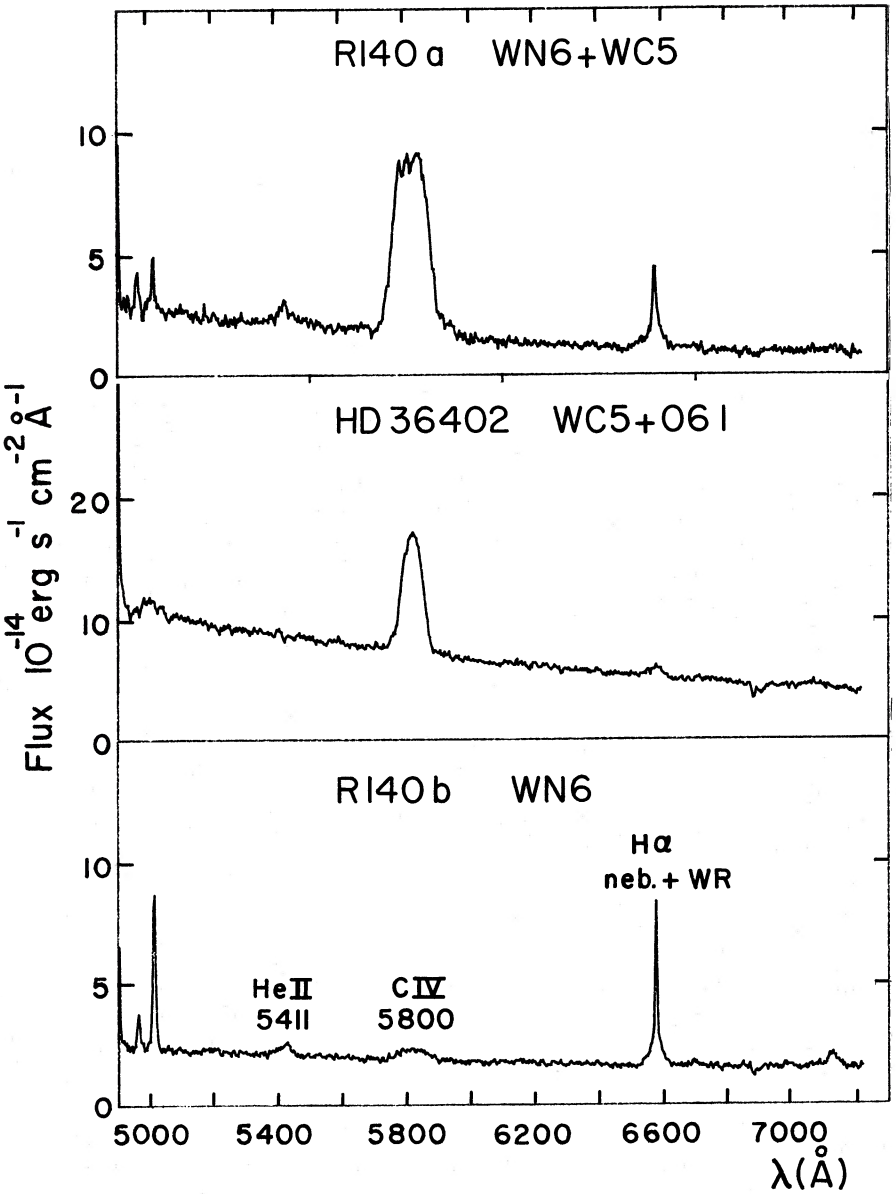

FIG. 3.—Flux-calibrated mean of several IDS spectra in the red of R140a (2″ × 2″ aperture) compared to the spectroscopic binary HD 36402 (4″ × 4″) and the southern component R140b (2″ × 2″).

III. DETAILED OVERVIEW OF WOLF-RAYET STARS IN THE 30 DORADUS CENTRAL CLUSTER

A list is presented in Table 5 of all the 15–16 W-R and 7 W-R/Of stars known in the central 2′.5 × 2′.5 area centered on the core, R136a, of the 30 Dor cluster. The W-R group includes the 4–5 estimated W-R stars in R136a (MSS). The spectral types in Table 5 are gleaned from various sources as noted. When He II emission is weak and unshifted absorption lines are present, we denote the star (WN + abs)/Of; since LMC WN stars are known to have He II lines roughly twice as strong as their Galactic counterparts (Smith and Willis 1983), it may also be that the He II emission of the Of stars in the LMC may stand out more than in their Galactic cousins. The V magnitudes were taken from Breysacher (1981) for relatively isolated images. In crowded regions, we have obtained magnitudes by interpolation among the isolated stars in Figure 1*b* (i.e., the non-emission plate); these values are indicated in parentheses.[5] We note that the V magnitudes from Breysacher (1981) are inhomogeneous, although the new self-consistent values of Breysacher (1986) result in only negligible changes.

A large fraction of the visually brightest stars in the 30 Dor cluster are of type WNL or Of. We have estimated their intrinsic brightnesses using the short distance modulus of the LMC, $V_0 - M_v = 18.2$, obtained through intermediate-age cluster main-sequence fitting by Schommer, Olszewski, and Aaronson (1984) and confirmed by others (e.g., IR photometry of Cepheids by Schmidt 1984; old cluster main-sequence fitting by Andersen, Blecha, and Walker 1985), and a mean interstellar

[5] The photometry of Feitzinger and Isserstedt (1983) was obtained using a relatively large, 18″ diaphragm, making crowding a serious problem in this area. Thus we do not use their magnitudes, which are often spuriously too bright.

TABLE 3

MEAN RADIAL VELOCITIES TOWARD R140a FOR UNBLENDED NEBULAR EMISSION LINES

			Heliocentric RV (km s^{-1})										
Year	Number of Observations	Source	[Ne III] λ3868.76	H8 λ3889.051	Hδ λ4101.737	Hγ λ4340.468	[O III] λ4363.19	He I λ4471.479	Hβ λ4861.332	[O III] λ4958.9	[O III] λ5006.8	He I λ5875.621	Hα λ6562.817
1978 Dec	7	1	285 ± 9	271 ± 10	282 ± 6	273 ± 2	...	262 ± 11	268 ± 6	...	...	...	...
1980 Jan	8	1	285 ± 7	273 ± 11	283 ± 9	280 ± 4	...	270 ± 8	258 ± 6	...	...	...	...
1982 Jan	3	1	254 ± 1	224 ± 11	276 ± 7	268 ± 5	...	273 ± 18	270 ± 3	...	...	...	...
1982 Nov ...	4	2	264 ± 1	255 ± 4	272 ± 5	270 ± 0	272 ± 4	280 ± 3	285 ± 7	...	...	...	...
1982 Dec	4	3	...	...	...	...	...	...	...	271 ± 46	281 ± 17	...	302 ± 4
1983 Feb	8	2	268 ± 6	258 ± 6	277 ± 3	282 ± 4	280 ± 11	281 ± 5	299 ± 20	...	...	...	...
1984 Mar ...	7	2	267 ± 7	256 ± 9	272 ± 7	272 ± 4	269 ± 9	271 ± 7	285 ± 11	...	...	...	...
1984 Mar ...	2	2	...	...	...	...	...	...	...	...	...	277 ± 22	284[a]
1984 May ...	4	2	268 ± 5	256 ± 5	277 ± 2	275 ± 5	268 ± 11	273 ± 10	273 ± 12	...	...	...	...

NOTE.—Errors are standard deviations from the mean for one observation.

[a] $n = 1$.

SOURCES.—(1) Carnegie image tube + IIa-Ob, FWHM resolution ~2 Å. (2) Carnegie image tube + IIIa-Jb, FWHM resolution ≲2 Å. (3) Image dissecting scanner, FWHM resolution ~6 Å.

TABLE 4

WALRAVEN PHOTOMETRY (log I) FOR R140a + b

JD (2,440,000+)	PHASE[a]	NUMBER OF OBSERVATIONS	W-R MINUS COMPARISON STAR c1[b] ΔV	$\Delta(V-B)$	$\Delta(V-L)$
4985.68	0.111	4	−0.426	−0.053	−0.140
4986.73	0.492	8	−0.440	−0.053	−0.141
4987.71	0.847	7	−0.427	−0.056	−0.147
4988.71	0.209	6	−0.421	−0.057	−0.145
4989.72	0.575	7	−0.430	−0.056	−0.142
4990.70	0.930	6	−0.438	−0.057	−0.144
4991.73	0.303	5	−0.405	−0.054	−0.135
4992.73	0.666	5	−0.414	−0.054	−0.139
4993.72	0.024	6	−0.422	−0.054	−0.135
4994.73	0.390	5	−0.410	−0.057	−0.140
4995.72	0.749	5	−0.406	−0.054	−0.129
4996.73	0.115	5	−0.417	−0.057	−0.147
4997.71	0.470	5	−0.440	−0.057	−0.144
4998.71	0.833	6	−0.421	−0.057	−0.139
Mean			−0.423	−0.055	−0.141
σ[c]			0.012	0.002	0.005
$\sigma(O-C)$[c]			0.006	0.002	0.005
σ(rms)[c]			0.005	0.003	0.004
σ(c2 − c1)[b]			0.002	0.003	0.003

NOTES.—log differences can be converted to magnitude differences via multiplication by −2.5. Diaphragm size $\phi = 11''.6$.

[a] Phases are calculated from the RV orbit of N IV for the WN component.

[b] Comparison stars are c1 = R130 (a W-R binary with constant light; cf. Moffat and Seggewiss 1986) and c2 = R103F (B9I).

[c] Standard deviations: σ refers to the scatter of the nightly mean values; $\sigma(O-C)$ is obtained from the curve in Fig. 6; σ(rms) refers to the rms value for the mean of an average night, based on the scatter of values during an individual night.

extinction $A_v = 1.2$ mag (Fitzpatrick and Savage 1984; MSS) for the central 30 Dor region. This leads to values of M_v for all stars in Table 5 except R136a and R140a. Note that attempts to allow for variations in extinction from one star to another are not justified with the sparse and generally imprecise data available at present.

Mean values of M_v according to spectral class are given in Table 6. From this table we note that the W-R and W-R/Of stars in the core region of 30 Dor have similar scatter to their Galactic counterparts and only slightly brighter absolute magnitudes. (Note that Lundström and Stenholm's 1984 $M_v = -6.1$ for Galactic WN8 stars is based on only one uncertain member of an association; hence, we ignore WN8 stars here.) This could be the result of residual crowding effects in 30 Dor or of lower extinction than that assumed for the 30 Dor stars (cf. Breysacher 1986). For Galactic members of clusters and associations, Lundström and Stenholm (1984) give $M_v = -6.5 \pm 0.4$ (s.d.) for WN7 stars and -5.2 ± 0.4 (s.d.) for WN6 stars, compared to -6.7 ± 0.5 (s.d.) for the central 30 Dor WN6/7 stars in Table 6. We make no attempt to distinguish WN6 stars from WN7 stars in 30 Dor since they are often confused in the literature for this particular area of the LMC. However, their absolute magnitudes do favor WN7. Humphreys and McElroy (1984) give a range of $M_v = -6.3$ to -7.2, with standard deviations of ~0.5 mag for a given subtype, for Galactic O-type supergiants (usually Of), similar to -6.2 ± 0.7 (s.d.) for the (WNL + abs)/Of stars in Table 6.

Among the objects in Table 5, four in particular are in extremely crowded areas and deserve some comments.

a) R136a, the bright, diffuse central object probably contains 4–5 W-R stars (MSS), since the W-R component in its

TABLE 5

KNOWN W-R OR W-R/Of STARS IN A 2'.5 SQUARE FIELD CENTERED ON R136

Breysacher Number	Other Names	Adopted Spectral Type[a]	V mag[b]	Spectroscopic Binary?[c]
75	R134 = FD63	WN6/7	12.36	Constant RV
76	MkA = Mk37	(WNL + abs)/Of	(13.6)	?
77	MkG = Mk42	(WNL + abs)/Of	(12.4)	?
78	MkH = Mk39	(WNL + abs)/Of	13.0	?
79	MkJ = Mk49	WN6/7	13.70	?
80	R135 = FD64	WN6/7	13.15	?
81	AB11 = Mk53	WN8	14.50	?
82	{R136a[d], R136c} = FD66	WNL + O	...	Contains SB
		WN6/7	(12.4)	?
83	MkEd = Mk33d	WC5	(15:)	?
84	MkC = Mk34	WN4.5	13.5	?
86	R139 = FD67	(WNL + abs)/Of	11.87	SB1, $P = 28$ days
87	{R140a1, R140a2, R140b} = FD68	{WC5, WN6}	(12.3)	?
				SB1, $P = 2.7$ days
		WN6	(12.5)	?
90	R145 = FD71	WN6/7	12.16	SB1, $P = 25$ days
...	Mk30	(WNL + abs)/Of	13.6	?
...	Mk35	(WNL + abs)/Of	13.6	?
...	Mk51	(WNL + abs)/Of	14.0	?

[a] From Breysacher 1981 and references therein, Conti 1982, Melnick 1982, 1983, 1985, Walborn 1986, and Moffat 1986.

[b] From Breysacher 1981 or, if crowded, visually interpolated among stars of known magnitude from Fig. 1*b* (indicated by parentheses).

[c] Sources for the spectroscopic binaries: B75, B86, and B90: Moffat 1986; R136a: MSS; R140a2: this work.

[d] R136a may contain ~4–5 WN stars, probably ~WN6 (MSS).

TABLE 6

MEAN ABSOLUTE VISUAL MAGNITUDES OF W-R AND W-R/Of STARS IN THE CENTRAL 2'.5 × 2'.5 OF 30 DORADUS

Type	$\langle V \rangle$	$\langle M_v \rangle$	σ	n	Stars
WN6, 7	12.7	−6.7	0.5	6	R134, R135, R136c, R140b, R145, Mk 49
(WNL + abs)/Of ...	13.2	−6.2	0.7	7	Mk 30, 35, 37, 39, 42, 51, R139
WN4.5[a]	13.5	−5.9	...	1	Mk 34
WN8	14.5	−4.9	...	1	Mk 53
WC5	15:	−4.4:	...	1	Mk 33d

NOTE.—Values of $V_0 - M_v = 18.2$ and $A_v = 1.2$ adopted.

[a] The WN4.5 star may have an O-type companion (Melnick 1978), possibly making it even brighter than usual for WNE, or possibly the subclass should be later than that given.

spectrum changes across its face and there are now eight relatively bright resolved stars in R136a found using speckle interferometry (Weigelt and Baier 1985). It is this multiplicity of the W-R spectrum that diminishes the RV amplitude for the orbit of one of the W-R components (MSS). The adjacent component, R136b, is not a W-R star, while the third bright component, R136c, is of type WNL (MSS).

b) The object Mk A is a multiple system of which the brightest component is probably the W-R star (MSS; see also Fig. 1).

c) The bright components "a" and "b" of R140 both show W-R–type emission lines. The southern "b" component is of type WN6. The northern "a" component shows a dual WN/WC spectrum which could be accounted for in three mutually exclusive ways: (1) a transition W-R type (WN–C), (2) a close WN + WC binary, or (3) two distinct stars, visually not well separated. The last possibility is most likely, as we see in § IV*a*; it also may yield a plausible explanation for the elongated image of component "a."

d) Mk E consists of four visual components of which the faintest is a WC star of absolute magnitude similar to other single WC stars in the LMC (cf. Fig. 1).

The above two WC stars, namely those contained in the multiple visual systems R140 and Mk E, are the only WC stars detected in the central 30 Dor area; both are located in regions of extreme crowding, so that there is little doubt that they are associated with the 30 Dor cluster. If there exist any very faint WC stars here of the kind recently discovered elsewhere in the LMC by Morgan and Good (1985), they should probably have been seen already on narrow-band CCD images.

Of the four W-R or W-R/Of stars in the 30 Dor central cluster (see Table 5) studied for RV variations so far (excluding R136a, which also contains a spectroscopic binary [SB]), three are SBs, all single-line with relatively high mass functions, implying massive, O-type companions. This yields a 75% binary frequency. If not the result of small number statistics, this high frequency may be partly due to the selection of brighter stars for systematic RV study; they are brighter than average perhaps because of a companion, even though the companion is not evident in the total spectrum. Out to 45′ from the center of 30 Dor, there are five SBs found among a total of 10 W-R stars investigated so far for radial velocity orbits (Moffat 1986).

IV. THE TWO WC STARS

a) *R140*

The spectrum of R140a is depicted in Figures 2 and 3; the latter also compares the spectrum of R140a with that of the WN6 star R140b (see below) and the WC5 + O6 binary HD 36402. The simultaneous presence of broad carbon lines and narrow nitrogen lines in R140a suggests a dual spectrum, WC5 + WN6. The spectral type of the former component is based on the near absence of C III λ5696 compared to the strong line of C IV λ5800. The C IV λ4650 line is also interpreted to be the very broad underlying feature below the much narrower N III, N V, and He II lines. C IV λ5800 is even broader in the spectrum of R140a than in that of the WC5 star HD 36402. The WN6 class of R140a is derived following the spectral classification criteria of WN stars specified in van der Hucht *et al.* (1981) from the relative strengths N IV λ4058 > N V λ4603 and N IV λ4058 ≈ N III λ4640, although the underlying broad C IV line interferes significantly. It is clear that R140a is not a single transition type W-R star of dual WN–WC type since C IV λ4650 is very strong and wide, unlike He II λ4686. Although C IV λ5800 is often seen as a moderately strong emission line of similar width to other lines in WN stars, in R140a this line *is* very much broader than the WN6 emission lines and must therefore arise predominantly in the WC star.

A blue spectrum of R140b is illustrated by MSS, while Figure 3 here shows a red spectrum. This star is probably of subclass WN6, since N III λ4640 is easily seen and N V is barely visible. Its emission line shapes are also much like those of other WN6 stars in 30 Dor (cf. MSS). We note that one cannot use the strength of He II λ4686 as a spectral indicator in WN stars in any way because, as noted above, He II is known to be about twice as strong in LMC stars as in Galactic stars of the same subclass (Smith and Willis 1983). We also point out that the very strong C IV λ5800 emission from R140a has probably spilled over into the spectrum of R140b, which is barely 2″ south of R140a.

On the basis of the RVs in Table 1, it is obvious that the WN6 component of R140a is an SB. Using sine-wave fits and the nonparametric technique of Lafler and Kinman (1965), periodicity was sought among these RVs. In doing so we first subtracted off mean RVs for each of the seven groups in Table 1, each spanning less than a month, in order to eliminate any long-term RV shift. This was particularly necessary for He II λ4686, which lies on the red edge of the strong, broad C IV λ4650 line. The best overall period which unambiguously emerges is $P = 2.7596 \pm 0.0001$ days. The mean circular orbit parameters are presented in Table 7. The phased RV observations along with the orbital fit are depicted in Figure 4.

Figure 5 shows that, with this period, the C IV λ5800 RVs in Table 2 do not participate in the above orbital motion. In fact, no motion is evident on a time scale of days. Furthermore, the C IV λ5800 emission line shows no profile changes with the 2.76 day phase, unlike the other known WC + O binaries of

TABLE 7

Orbital Solution for the WN Component of R140a

Parameter	N IV λ4057.759A	He II λ4685.682A	N V λ4603.64A
P (days)		2.7596 ± 0.0001	
e		0.0 (assumed)	
V_0 (km s^{-1})	230 ± 4	276 ± 6	473 ± 16
K (km s^{-1})	70 ± 7	74 ± 10	103 ± 20
E_0 (JD −2,445,000)	769.1 ± 0.1	769.1 ± 0.1	768.9 ± 0.3
σ (km s^{-1})	25	33	41
$f(m)$ ($M_\odot$)	0.10	0.12	0.31
$a_{\mathrm{W-R}} \sin i$ ($R_\odot$)	3.8	4.0	5.6

short period studied in the LMC (Moffat 1986). Thus, as suspected already above on the basis of spectral line character and the elongated image, R140a probably contains at least two distinct W-R stars. We denote these by R140a1 for the northern component (since it appears to be stronger than the southern component on the emission-line image, this is probably the WC5 component) and R140a2 for the southern component (probably WN6). We also note that, if He II emission is confirmed to show long-period RV variations, as suspected here in contrast to N IV λ4058 (group means of the RVs in Table 1 suggest this may be the case), yet another WN star may be involved.

The light curve of the combined light from the whole system R140 is plotted versus the 2.76 day phase in Figure 6. While the colors remain constant with phase, the intensity varies with relatively large amplitude, 0.08 mag observed, becoming greater if allowance is made for light from a third star, in a double wave per orbit with minimum light at phases 0.0 and 0.5. This kind of behavior is frequently seen in close eclipsing W-R + O binary systems, with a broad minimum occurring when the W-R component passes in front and a narrower minimum when the O star passes in front (e.g., V444 Cyg: Cherepashchuk, Eaton, and Khaliullin 1984). The lack of color variations is best accounted for by electron scattering effects that are independent of wavelength, unlike, e.g., ellipsoidal variations. An upper limit to the orbital inclination must be close to $i = 75°$, like the Galactic short-period eclipsing system CQ Cep with $P = 1.64$ days and light amplitude 0.4 mag (cf. Drissen *et al.* 1986). Without a precise model for the W-R wind, we can only surmise that the inclination lies in the range 30°–70°.

The reality of the light curve drawn in Figure 6 is strongly supported by the standard deviations. In particular, $\sigma_v(O-C) = 0.006$ (in log I units) compared to the internal rms error, $\sigma_v(\mathrm{int}) = 0.005$, based on repeated observations each

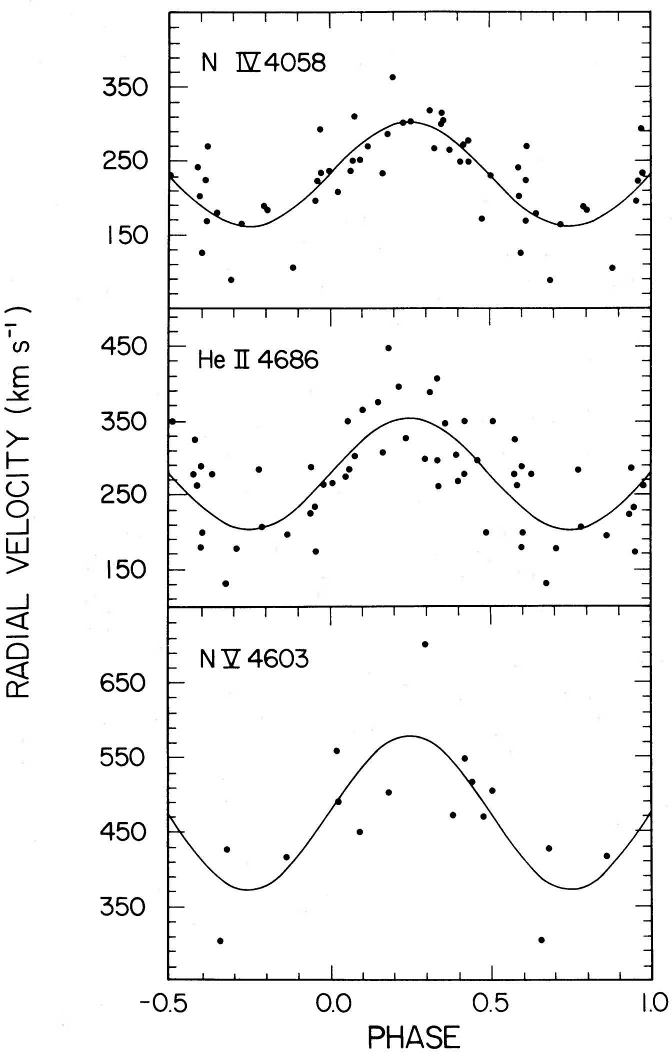

Fig. 4

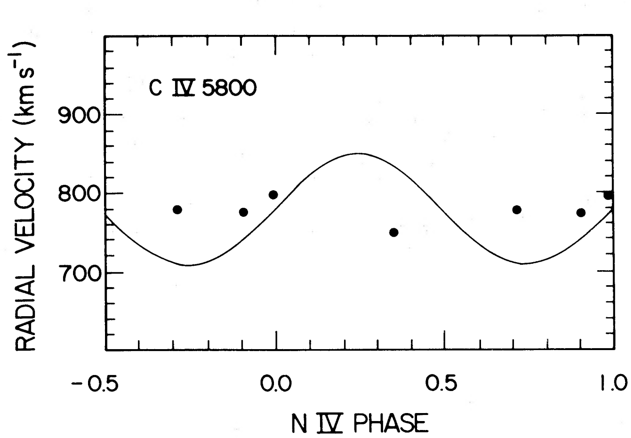

Fig. 5

Fig. 4.—Radial velocity vs. phase for the best emission lines from the blue photographic image tube spectra of R140a with orbits calculated using the parameters in Table 7.

Fig. 5.—Radial velocity of the C IV λ5800 emission line from the WC component of R140a (2″ × 2″ aperture) vs. the N IV phase. The N IV orbit for the WN6 component of R140a is also shown for comparison, with a shift to the same mean velocity.

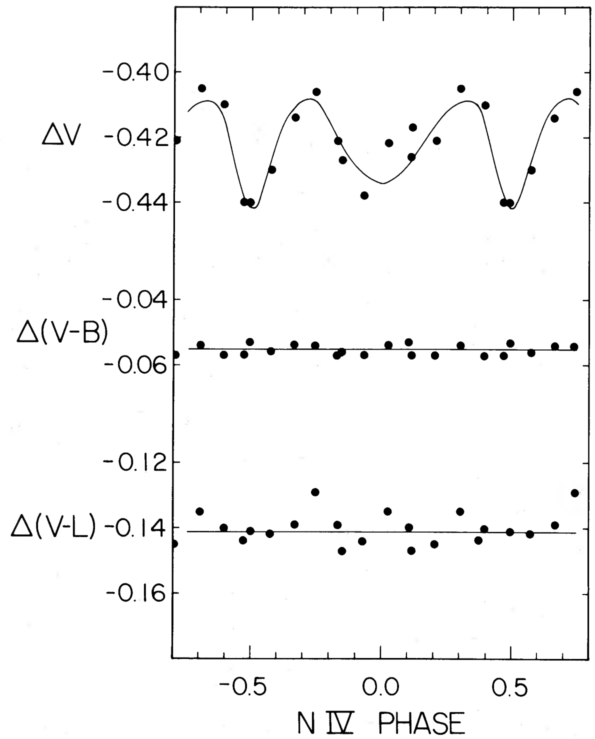

FIG. 6.—Light curves (units of log I) in the Walraven system of R140 using the N IV ephemeris of the WN6 component in Table 7. Mean values of the two-color indices are indicated. A hand-drawn curve is shown through the V light curve.

night. These values can be compared with the much larger scatter from a simple mean, $\sigma_v = 0.012$. An F-test on the ratio $\sigma_v/\sigma_v(O-C)$ yields significant variability at the $\gtrsim 99\%$ level.

Now we turn to an estimate of the masses of the stars in R140a2 related to the 2.76 day orbit. Although He II $\lambda 4686$ may be perturbed by the underlying, strong line C IV $\lambda 4650$ from R140a1 and possibly shows the effect of long-term variations, this line yields nearly the same RV amplitude as the unblended line N IV $\lambda 4058$:

$$K_{\text{W-R}} = 70 \text{ km s}^{-1} \quad (e = 0) ,$$

which we adopt as the best value. This results in the mass function $f(m) = 0.10\ M_\odot$. Thus, if $M(\text{WN6}) = 40\ M_\odot$, like the minimum mass of the WN6 star in the SB2 HDE 311884 in the Galaxy (Niemela, Conti, and Massey 1980), or even much higher, say 80 $M_\odot$, possibly valid for some very luminous WNL stars, one obtains for the unseen companion

$$M_2 = 6 \text{ or } 9\ M_\odot \quad \text{respectively } (i = 90°) ,$$

or

$$M_2 = 13 \text{ or } 20\ M_\odot \quad \text{respectively } (i = 30°) .$$

This assumes no line blending. With $M_{\text{W-R}}/M_2 = 3–9$, one finds

$$a\ (R_\odot) \sin i = 0.0198(1 - e^2)^{1/2}(K_{\text{W-R}} + K_2)(\text{km s}^{-1})\ P\ (\text{days})$$
$$= 15–38\ R_\odot .$$

With a mean inclination $i = 60°$, we obtain $a = 17–44\ R_\odot$, which is reasonable for a close WNL + O system; e.g., the shortest known W-R binary system CQ Cep (WN7 + O) has $a = 21–25\ R_\odot$; Leung, Moffat, and Seggewiss 1983).

We note that the weak He II absorption lines sometimes seen in the IIIa-J image tube spectra of R140a most frequently seem to follow the orbital motion of the WNL star. A few deviating RV values for these absorptions may indicate contributions from the spectrum of the companion star. Thus, the companion would be an O-type star. For a good orbital solution, data with better spectral resolution and signal-to-noise ratio are needed.

For the companion to be an O star, one would need $M_2 \gtrsim 20\ M_\odot$, thereby requiring $M_{\text{WNL}} \gtrsim 200\ M_\odot$ ($i = 60°$) or $\gtrsim 100\ M_\odot$ ($i = 34°$). Alternatively, another WNL star present in the compact group but not involved in the 2.76 day orbit would tend to dilute the RV amplitude of R140a2. If its emission lines were similar in character to those of the orbiting star, the observed RV amplitude could be easily reduced by a factor of ~ 2. This would lead to an increase of the mass function $f(m)$ to $\sim 0.8\ M_\odot$, close to normal for WNL + O systems (cf. MSS). It seems plausible that such a configuration does occur in HD 97950, the dense core of the giant Galactic H II region NGC 3603, where about three WNL stars contribute to reduce the orbital amplitude of one of them (Moffat and Niemela 1984; MSS). Even greater dilution probably occurs in R136a, where MSS estimate a total of $\sim 4–5$ W-R stars.

In summary, R140a appears to be a compact group of mainly massive stars, unlike the fuzzy core object R136a, which probably contains a wide range of masses. If so, then they would be as follows:

$$\text{R140a1} = \text{WC5 (+O?)} ,$$
$$\text{R140a2} = \text{WN6 + O (SB1)}$$
$$\text{and possibly another WNL star} ,$$

and

$$\text{R140b} = \text{WN6} .$$

R140a2 is the southern, fainter component of R140a (see the elongated image in Fig. 1). Since single WC stars are normally fainter than WNL stars, R140a1, which is brighter in the continuum than R140a2, may have a bright O-type companion. In any case, R140 appears to contain *at least* three W-R stars.

b) Mk E

In Figure 7, the SIT Vidicon spectrum of Mk E has the spectral type WC5 + O. Walborn (1986) classifies this tight group of stars as WC5 + O4, where the O4 component probably refers to the visual companions. The strength of the C IV $\lambda 4650$ line in Figure 7 compared to other single WC5 stars in the LMC shows that the line is diluted by O-star light, although we cannot entirely exclude contamination by a visual companion. Two of us (A. F. J. M. and V. S. N.) will report in a later publication on our search for a possible RV orbit of Mk E with the aid of our repeated CCD spectra of this star, as well as of all the other WC stars from Breysacher's (1981) catalog.

V. THE WOLF-RAYET POPULATION IN AND AROUND 30 DORADUS COMPARED TO THE REST OF THE LARGE MAGELLANIC CLOUD

In Figure 1 we showed the distribution of all known W-R and W-R–like stars in the central 2'.5 × 2'.5 (32 × 32 pc) around R136a. In Figure 8 we illustrate the distribution of W-R stars outside this central region but within a concentric box of dimensions 90' × 90' (1140 × 1140 pc). This covers the whole extent of the Hα nebula 30 Dor (cf. Davies, Elliott, and Meaburn 1976). An even larger overview of the LMC W-R stars is given by Pitault (1983).

1987ApJ...312..612M

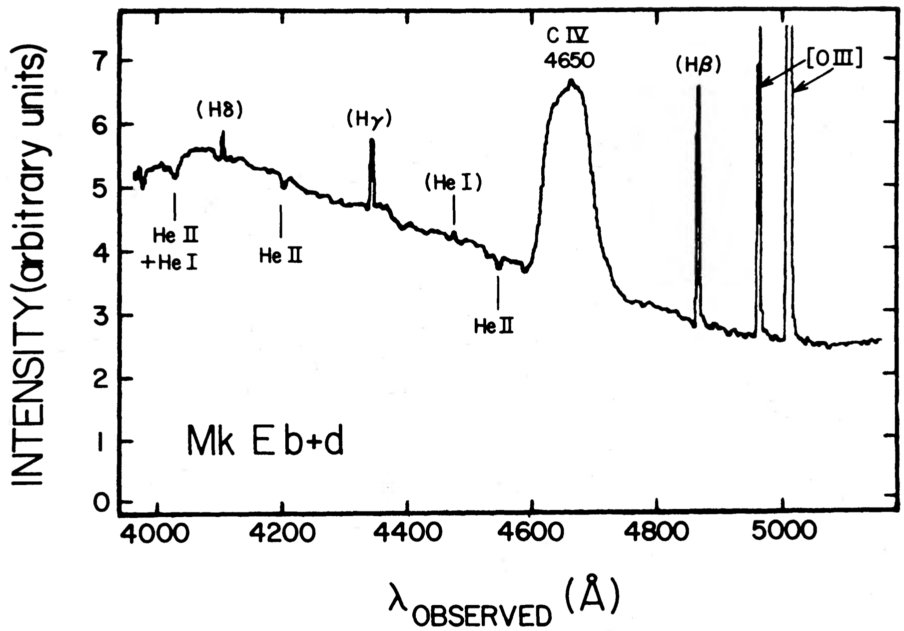

FIG. 7.—Spectra of Mk E as in Fig. 2. Note the presence of strong He II λλ4200, 4541 absorption, from the other visual early-O components.

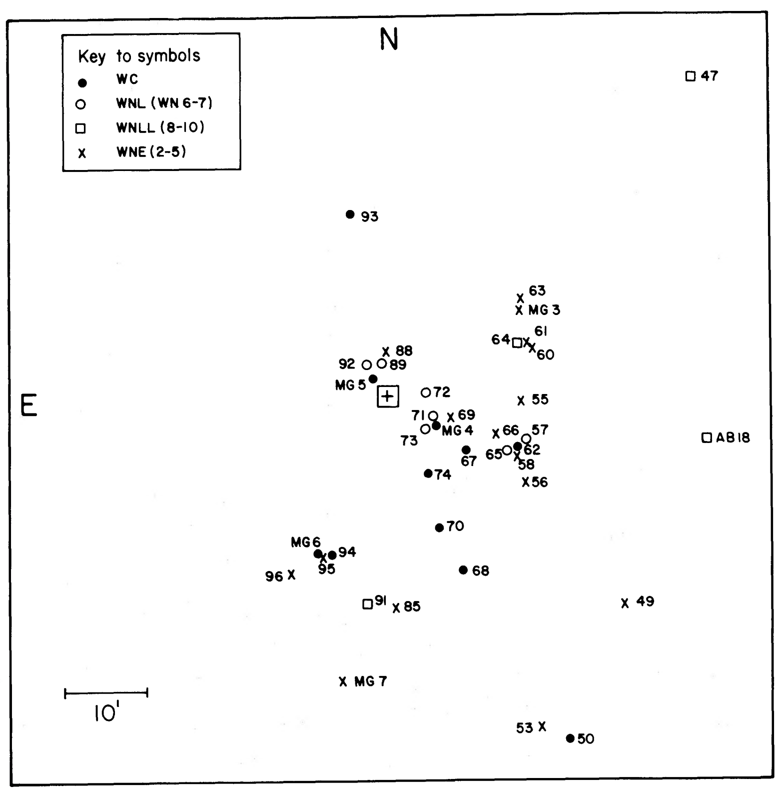

FIG. 8.—The distribution of all presently known W-R stars in a region 90′ × 90′ centered on R136 in 30 Dor but excluding the central 2′.5 × 2′.5 (cf. Fig. 1). Identification numbers without letters are from Breysacher (1981), MG numbers are from Morgan and Good (1985), and AB from Azzopardi and Breysacher (1985). Note that due to rounding errors of the published coordinates, some stars may be displaced an arcminute or more from their true relative position on the sky.

TABLE 8

WOLF-RAYET STARS IN THE LARGE MAGELLANIC CLOUD RELATIVE TO THE CENTER OF 30 DORADUS

Star	Type[a]	r'
A. $r' < 2'.5$		
R136a	WNL (n = 4–5)	0
R136c	WNL	0.06
MkC	WNE	0.18
MkEd	WCE	0.20
R134	WNL	0.20
MkJ	WNL	0.44
R140b	WNL	0.84
R140a2	WNL	0.86
R140a1	WCE	0.87
AB11	WNLL	1.11
R145	WNL	1.38
R135	WNL	1.52
B. $2'.5 < r' < 45'$		
MG5	WCE	2.7
B89	WNL	3.9
B92	WNL	4.4
B72	WNL	4.5
B88	WNE	5.4
B71	WNL	5.6
B73	WNL	5.8
MG4	WCE	6.7
B69	WNE	7.6
B74	WCE	10.2
B67	WCE	11.1
B66	WNE	13.4
B65	WNL	15.2
B55	WNE	15.6
B62	WCE	16.0
B58	WNE	16.5
B64	WNLL	16.5
B70	WCE	16.5
B57	WNL	16.9
B61	WNE	17.4
B60	WNE	17.8
MG3	WNE	18.3
B56	WNE	18.7
B63	WNE	19.2
B94	WCE	20.0
MG6	WCE	20.5
B95	WNE	20.5
B93	WCE	21.9
B68	WCE	22.3
B96	WNE	24.1
B91	WNLL	24.5
B85	WNE	25.0
MG7	WNE	33.9
B49	WNE	37.0
AB18	WNLL	37.9
B53	WNE	42.8
C. $r' > 45'$		
B1	WNE	...
B2	WNE	...
B3	WNE	...
C. $r' > 45'$—*Continued*		
B4	WNE	...
B5	WNE	...
B6	WNE	...
B7	WCE	...
B8	WCE	...
B9	WCE	...
B10	WCE	...
B11	WNE	...
B12	WNE	...
B13	WNLL	...
B14	WNE	...
B15	WNE	...
B16	WNE	...
MG1	WCE	...
B17	WNE	...
B18	WNLL	...
B19	WNE	...
B20	WNE	...
B21	WNE	...
B22	WCE	...
B23	WNE	...
B24	WNL	...
B25	WNE	...
B26	WNL	...
B27	WNE	...
B28	WCE	...
B29	WNE	...
B30	WNE	...
B31	WCE	...
B32	WCE	...
B33	WNE	...
B34	WNE	...
B35	WNE	...
B36	WNLL	...
B37	WNE	...
B38	WNE	...
B39	WNE	...
B40	WNE	...
B41	WNE	...
B42	WNE	...
B43	WCE	...
B44	WCE	...
B45	WNE	...
B46	WNE	...
B47	WNLL	...
B48	WNE	...
B50	WCE	...
B51	WNE	...
B52	WNE	...
B54	WNE	...
B59	WNE	...
MG2	WNE	...
B97	WNE	...
B98	WNE	...
B99	WNE	...
B100	WNE	...

NOTE.—Scale: $1' = 12.70$ pc for true distance modulus 18.2; r' measured from R136a.

[a] W-R types: (WCE) WC4–6 or WO. (WNE) WN2–5 (mostly 3, 4 in the LMC). (WNL) WN6, 7. (WNLL) WN8–10 (we neglect absorption lines in the spectrum here).

These W-R stars are drawn primarily from the catalog of Breysacher (1981), updated with the work of Azzopardi and Breysacher (1985) and Morgan and Good (1985). We only include genuinely classified W-R stars, omitting stars with ambiguous WN/Of types. We have also used revised spectral classes in three difficult cases, based on better resolved spectra: B65 = HDE 269828 is a WN7 star in a tight but resolvable group of hot stars (Moffat 1986); B73 is now classified WN7 (Moffat 1986); and B72 = R130 = HDE 269891 now becomes WN6 + B1 Ia (Moffat and Seggewiss 1986). Table 8 gives a summary of all the W-R stars used in studying the radial distribution, with types grouped into the following boxes: WCE, WNE, WNL, and WNLL.

In Figure 9 we examine how the total density and the density ratios of W-R stars of different class vary with projected radial separation from R136a. To do this we have divided the stars

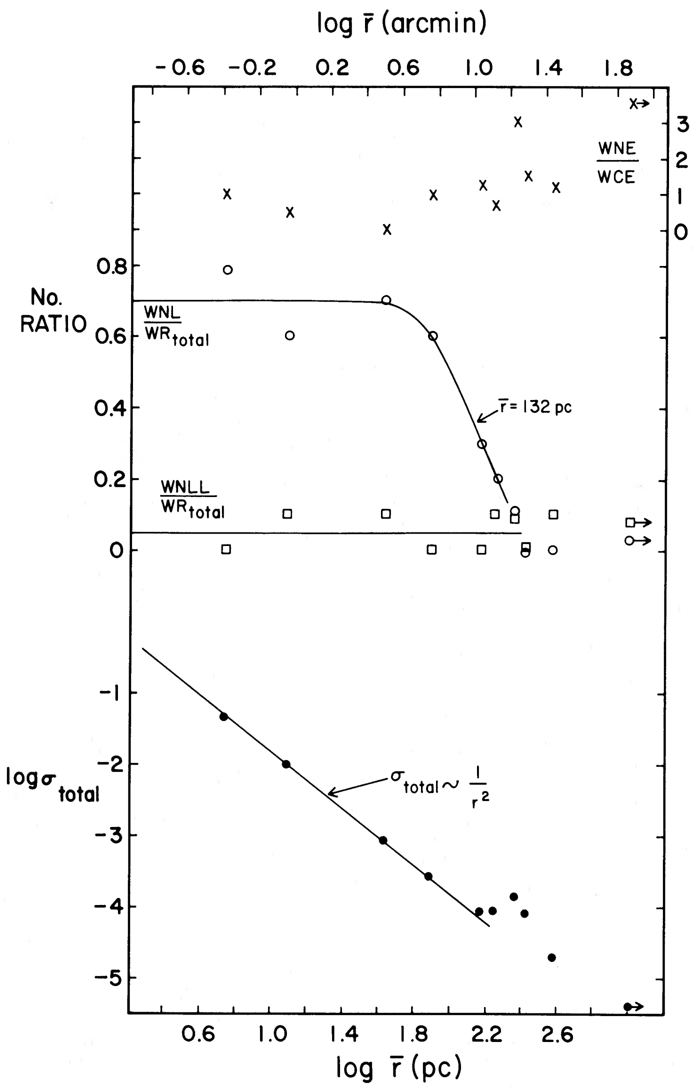

FIG. 9.—Number ratios and surface density (σ_{tot} stars pc^{-2}) vs. projected distance from the center, R136, of 30 Dor. Arrows refer to values for the rest of the LMC outside $r' = 37'$.

into annuli such that 10 stars occur in each annulus. The mean radius of each annulus was calculated from

$$\bar{r} = \int_{r_i}^{r_{i+1}} r r dr \Big/ \int_{r_i}^{r_{i+1}} r dr = \tfrac{2}{3}(r_{i+1}^3 - r_i^3)/(r_{i+1}^2 - r_i^2) ,$$

where r_i and r_{i+1} are the inner and outer radii of each annulus, defined by the midpoint between the star closest to the appropriate edge of the annulus and the next star beyond the annulus. The points in Figure 9 refer to bins of 10 stars, displaced every five stars.

In the case of the total density of W-R stars, a semi-empirical King (1962) profile for isothermal stellar systems gives a good fit out to $r = 130$ pc (10′). Beyond this, the points lie above the curve and the number ratio WNL/W-R$_{tot}$ falls off dramatically. At the level of spatial resolution required here, we have taken zero core radius compatible with the small upper limit (0.2 pc, i.e., 1″) found for the true core within R136 by MSS. Beyond a radius of 37′ (470 pc, which corresponds to the largest radius within Fig. 8 in which there are an integral number of bins with 10 stars each) from R136 we show the average W-R star density for all the rest of the LMC assuming a total surface of radius 2°.9, with a hole of radius 0°.6 for 30 Dor subtracted. This gives an idea of the expected background level, which is very low. The diameter of the central cluster, ∼260 pc, coincides with the overall H II emission region. This implies that the 30 Dor H II nebula is probably spatially limited as opposed to ionization limited.

The relative numbers of W-R stars of different types show dramatic differences as a function of radius from the core of 30 Dor. In particular, the number of WNL stars drops abruptly at $r = 130$ pc, while the WNLL population shows no central concentration compared to the general field of the LMC. This confirms quantitatively the well-known impression (cf. Feast, Thackeray, and Wesselink 1960) that the majority of the luminous WN stars of the LMC are associated with the giant 30 Dor region; in fact, *beyond* $r = 37'$ *there are only two* WNL *stars known in all the rest of the LMC compared to the* 18–19 *inside that area.* The lack of concentration of WNLL stars also confirms the previous impression that such stars are rarely found to be members of open clusters (Lundström and Stenholm 1984) and often show evidence of high space motion, among other peculiarities (Moffat 1983*b*).

The number ratio of WNE to WCE stars shows the opposite trend compared to the WNL stars, although the data are noisier. It appears that the WCE stars are also concentrated toward 30 Dor, although somewhat less dramatically than the WNL stars. There are equal numbers (12) of WCE stars within 37′ of R136a and outside this radius in all of the LMC. Presumably, WCE stars evolve from WN stars of different subclass, whereas WNL stars only evolve from very massive progenitors.

Within ∅ = 2.5′, the ratio of the number of W-R stars (not including stars classified as WN/Of) to O stars is

$$N_{\text{W-R}}/N_{\text{O}} \approx 15\text{–}16/300 \approx 0.05 .$$

The number of O stars is based on Melnick's (1983) observation of ∼60 stars of Sp $\lesssim$ O5 (i.e., $M \lesssim 50\ M_{\odot}$), extrapolated using an initial mass function slope of 2.5 (Scalo 1986), to include all O stars, i.e., O3–O9, down to $M = 20\ M_{\odot}$. This W-R/O number ratio is normal compared to that seen in the solar vicinity in general and in other regions of active star formation. It is not abnormally high in contrast to the initial impression one has, with most of the visually bright stars being of type W-R. Bursts of star formation such as 30 Dor thus do not necessarily imply high W-R/O number ratio, as is sometimes claimed (cf. discussion of Moffat 1983*a*).

We now compare the distribution of W-R stars with that of other luminous stars. Rousseau *et al.* (1978) give a catalog of non–W-R LMC members with known spectral type and $V \lesssim$ 13–14, of which ∼215 lie in a 90′ × 90′ field around R136. Isserstedt (1984) gives a more complete list of luminous stars, even if only photoelectric photometry is available for some stars. This work yields 240 supergiants and Cepheids of $V \lesssim$ 13 in the same area; this number reduces to ∼120 if one limits the sample to stars of ages $\lesssim 10^7$ yr. These densities are ∼2 times higher in the central 45′ × 45′, with centroid just south of R136. Thus, the *average* density of BSGs close to 30 Dor is

$$2 \times 120/(90' \times 90') = 0.03 \text{ stars arcmin}^{-2}, \text{ i.e.,}$$

$$0.13 \text{ stars in } 2'.5 \times 2'.5 .$$

In this field we actually see four bright BSGs (R137, R138, R141, and R142, all $V \approx 12.5$), with seven additional fainter ones given by Walborn (1986). This would imply that the BSGs also peak like the W-R star population toward the core of 30 Dor, although not as sharply. We caution that these remarks may be subject to significant incompleteness in the number of known BSGs especially beyond $\varnothing = 2\overset{'}{.}5$ of R136. We note that the Galactic giant H II region NGC 3603, which is a scaled-down version of 30 Dor, contains two BSGs among a population of ~2–3 WNL stars and some 20 early O stars (Moffat 1983*c*). These are in the same proportion as in 30 Dor.

RSGs have been surveyed in a $12' \times 12'$ region around R136 by McGregor and Hyland (1981). They found 12 M-type supergiants, which yield a mean density of 0.08 RSG arcmin^{-2} and thus a total of 0.4 stars in $2\overset{'}{.}5 \times 2\overset{'}{.}5$. The central $2\overset{'}{.}5 \times 2\overset{'}{.}5$ actually contains one RSG, compatible with this mean, implying no central concentration of RSGs.

There are two possible ways to account for the simultaneous W-R, O and BSG, RSG populations: (*a*) The BSG, RSG population was formed $\sim 10^7$ yr ago during a previous burst in a larger area centered near 30 Dor; this would contrast with the present, more concentrated burst of early O and W-R stars in 30 Dor that must have occurred $\sim 2 \times 10^6$ yr ago. The more recent burst may eventually lead to the formation of a populous cluster of the kind seen in other parts of the LMC, with progressively greater ages (see MSS). (*b*) Alternatively, there may be a widening of the main sequence for the massive stars, as is often seen in other clusters (Mermilliod and Maeder 1984). This could allow nearly the same age for all stars.

The foregoing observations on the distribution of various types of massive stars suggest the following scenario:

1. WNL stars are only seen in large numbers in very young regions (earliest spectral type $\lesssim$O5) of recent star formation, such as 30 Dor in the LMC and the Carina Nebula, NGC 3603, and the cluster Havlen-Moffat 1 in the Galaxy. In such regions, very massive stars are still near the H-burning main sequence, and WNL stars resemble most their likely Of-type progenitors. Thus, for stars of initial mass $\gtrsim 60\ M_\odot$ we suggest the following scenario:

$$\text{O star } (\gtrsim 60\ M_\odot) \rightarrow \text{Of} \rightarrow \text{WNL} \rightarrow \text{WC}\ .$$

The final WC stage for such massive progenitors is probably short-lived, so that WC stars occur with low frequency in such areas. Metallicity may also play a role.

2. WNE together with WC stars are seen in clusters of a broad range of ages. They are generally the true H-poor W-R stars, evolved from progenitors of a broad range of mass above $\sim 30\ M_\odot$, such as one finds in the periphery of and outside 30 Dor.

It is not clear how the WNLL stars fit this evolutionary scenario of massive stars. Possibly they might be involved in another scenario or they represent a peculiar class, e.g., with compact companions (cf. Moffat 1983*b*; Lundström and Stenholm 1984). Also, we have no new information regarding the status of WCL versus WCE stars, since the former are lacking in the LMC. Because WCL stars are generally more massive than WCE stars, there may be some evolutionary connection between them that depends on metallicity (Moffat *et al.* 1986).

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REFERENCES

Andersen, J., Blecha, A., and Walker, M. F. 1985, *Astr. Ap.*, **150**, L12.
Azzopardi, M., and Breysacher, J. 1985, *Astr. Ap.*, **149**, 213.
Breysacher, J. 1981, *Astr. Ap. Suppl.*, **43**, 203.
———. 1986, *Astr. Ap.*, **160**, 185.
Cherepashchuk, A. M., Eaton, J. A., and Khaliullin, Kh. 1984, *Ap. J.*, **281**, 774.
Conti, P. S. 1982, in *IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolution*, ed. C. H. W. de Loore and A. J. Willis (Dordrecht: Reidel), p. 551.
Davies, R. D., Elliott, K. H., and Meaburn, J. 1976, *Mem. R.A.S.*, **81**, 89.
Drissen, L., Moffat, A. F. J., Bastien, P., Lamontagne, R., and Tapia, S. 1986, *Ap. J.*, **306**, 215.
Feast, M. W., Thackeray, A. D., and Wesselink, A. J. 1960, *M.N.R.A.S.*, **121**, 337.
Feitzinger, J. V., and Isserstedt, J. 1983, *Astr. Ap. Suppl.*, **51**, 505.
Fitzpatrick, E. L., and Savage, B. D. 1984, *Ap. J.*, **279**, 578.
Heydari-Malayeri, M., and Testor, G. 1983, *Astr. Ap.*, **118**, 116.
Humphreys, R. M., and McElroy, D. B. 1984, *Ap. J.*, **284**, 565.
Isserstedt, J. 1984, *Astr. Ap.*, **131**, 347.
King, I. R. 1962, *A.J.*, **67**, 471.
Lafler, J., and Kinman, T. D. 1965, *Ap. J. Suppl.*, **11**, 216.
Leung, K. C., Moffat, A. F. J., and Seggewiss, W. 1983, *Ap. J.*, **265**, 961.
Lortet, M. C., and Testor, G. 1984, *Astr. Ap.*, **139**, 330.
Lundström, I., and Stenholm, B. 1984, *Astr. Ap. Suppl.*, **58**, 163.
McGregor, P. J., and Hyland, A. R. 1981, *Ap. J.*, **250**, 116.
Melnick, J. 1978, *Astr. Ap. Suppl.*, **34**, 383.
———. 1982, in *IAU Symposium 99, Wolf-Rayet Stars: Observations, Physics, Evolution*, ed. C. H. W. de Loore and A. J. Willis (Dordrecht: Reidel), p. 545.
———. 1983, *ESO Messenger*, No. 32, p. 11.
———. 1985, *Astr. Ap.*, **153**, 235.
Mermilliod, J. C., and Maeder, A. 1984, in *IAU Symposium 105, Observational Tests of the Stellar Evolution Theory*, ed. A. Maeder and A. Renzini (Dordrecht: Reidel), p. 349.
Moffat, A. F. J. 1983*a*, in *Proc. Workshop, Wolf-Rayet Stars: Progenitors of Supernovae?*, ed. M. C. Lortet and A. Pitault (Paris: Observatoire de Meudon), p. V.3.
———. 1983*b*, in *Proc. Workshop, Wolf-Rayet Stars: Progenitors of Supernovae?*, ed. M. C. Lortet and A. Pitault (Paris: Observatoire de Meudon), p. VII.19.
———. 1983*c*, *Astr. Ap.*, **124**, 273.
Moffat, A. F. J. 1986, in preparation.
Moffat, A. F. J., and Niemela, V. S. 1984, *Ap. J.*, **284**, 631.
Moffat, A. F. J., and Seggewiss, W. 1986, *Ap. J.*, **309**, 714.
Moffat, A. F. J., Seggewiss, W., and Shara, M. M. 1985, *Ap. J.*, **295**, 109 (MSS).
Moffat, A. F. J., Vogt, N., Paquin, G., Lamontagne, R., and Barrera, L. H. 1986, *A.J.*, **91**, 1386.
Morgan, D. H., and Good, A. R. 1985, *M.N.R.A.S.*, **216**, 459.
Nassau. J. J., and Velghe, A. G. 1964, *Ap. J.*, **139**, 190.
Niemela, V. S., Conti, P. S., and Massey, P. 1980, *Ap. J.*, **241**, 1050.
Phillips, M. M. 1982, *M.N.R.A.S.*, **198**, 1053.
Pitault, A. 1983, in *Proc. Workshop, Wolf-Rayet Stars: Progenitors of Supernovae?*, ed. M. C. Lortet and A. Pitault (Paris: Observatoire de Meudon), p. III.117.
Prévot-Burnichon, M. L., Prévot, L., Reiberot, E., Rousseau, J., and Martin, N. 1981, *Astr. Ap.*, **103**, 83.
Rousseau, J., Martin, N., Prévot, L., Rebeirot, E., Robin, A., and Brunet, J. P. 1978, *Astr. Ap. Suppl.*, **31**, 243.
Scalo, J. 1986, in *IAU Symposium 116, Luminous Stars and Associations in Galaxies*, ed. C. W. H. de Loore, A. J. Willis, and P. G. Laskarides (Dordrecht: Reidel), in press.
Schmidt, E. G. 1984, *Ap. J.*, **285**, 501.
Schommer, R. A., Olszewski, E. W., and Aaronson, M. 1984, *Ap. J. (Letters)*, **285**, L53.

Sivertsen, S. 1981, *Astr. Ap. Suppl.*, **43**, 221.
Smith, L. J., and Willis, A. J. 1983, *Astr. Ap. Suppl.*, **54**, 229.
van der Hucht, K. A., Conti, P. S., Lundström, I., and Stenholm, B. 1981, *Space Sci. Rev.*, **28**, 227.
Walborn, N. R. 1986, in *IAU Symposium 116, Luminous Stars and Associations in Galaxies*, ed. C. W. H. de Loore, A. J. Willis, and P. G. Laskarides (Dordrecht: Reidel), in press.
Weigelt, G., and Baier, G. 1985, *Astr. Ap.*, **150**, L18.

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