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A DEEP SURVEY FOR GALACTIC WOLF-RAYET STARS. II. IMPLICATIONS FOR GALACTIC STRUCTURE AND MASSIVE STAR FORMATION[1]

MICHAEL M. SHARA
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; mshara@stsci.edu

ANTHONY F. J. MOFFAT
Département de Physique, Université de Montréal, C.P. 6128, Succursale Centre-Ville, Montreal, QC H3C 3J7, Canada; and Observatoire du Mont Mégantic; moffat@astro.umontreal.ca

LINDSEY F. SMITH
School of Physics, University of Sydney, Sydney, NSW 2006, Australia; lsmith@email.edu.au

VIRPI S. NIEMELA[2]
Facultad de Ciencias Astronómicas y Geofísicas, Universidad Nacional de La Plata, Paseo del Bosque s/n, 1900 La Plata, Argentina; virpi@fcaglp.fcaglp.unlp.edu.ar

MICHAEL POTTER
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218; potter@stsci.edu

AND

ROBERT LAMONTAGNE
Département de Physique, Université de Montréal, C.P. 6128, Succursale Centre-Ville, Montreal, QC H3C 3J7, Canada; and Observatoire du Mont Mégantic

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ABSTRACT

We have completed a direct narrowband-broadband Schmidt plate survey of large areas of the southern Milky Way for new Wolf-Rayet (W-R) stars as faint as 19th b magnitude. The 31 newly detected stars in the completed survey are among the reddest and/or most distant known in the Galaxy. We have obtained spectra of all candidate W-R stars in the 22 fields stretching from $l = 282°$ to $l = 341°$ in longitude and $\Delta b = 3.°5$ in latitude, covering about 180 square degrees. We also observed two isolated Milky Way fields centered at $l = 0°$ and $l = 8°$. Eighteen new W-R stars are reported here for the first time. Combined with the 13 new W-R stars we have already reported in Carina, our list of 31 new Galactic W-R stars reaches 3–4 mag fainter than previous surveys. Thirteen of our 18 new W-R stars reported here are of subtype WN, while five are of subtype WC. We present and describe their spectra and subtypes, derive their distances, and discuss the significance of their locations along with all other W-R stars in the Galaxy. Our new W-R stars clearly demonstrate an increasing number ratio of WN to WC stars with increasing Galactocentric distance. We conclude with predictions of the total number of Galactic W-R stars that should be discovered in future IR surveys.

Key words: stars: Wolf-Rayet — surveys

1. INTRODUCTION AND MOTIVATION

Wolf-Rayet (W-R) stars are excellent tracers of the massive star populations in the Milky Way and in nearby galaxies. Their strong, broad emission lines of helium, and carbon or nitrogen, make them relatively easy to locate. Their very high luminosities make them observable over much of the Galaxy, and in all the galaxies of the Local Group.

Remarkable trends are obvious in the distributions of W-R stars in nearby galaxies. First, W-R stars are most strongly concentrated in regions of active star formation; striking examples are NGC 3603 in the Milky Way (Moffat, Drissen, & Shara 1994; Drissen et al. 1995) and 30 Dor in the LMC (Moffat, Seggewiss, & Shara 1985; Walborn & Blades 1997). Second, the number ratio of WC to WN stars varies strongly with Galactocentric radius in spiral galaxies. This has been explained as a metallicity effect (Smith & Maeder 1991). The initial mass function (Garmany, Conti, & Chiosi 1982) was also suggested to be an important factor, but this no longer appears to be the case (Massey 1996).

It remains easier to find new extragalactic W-R stars than their Galactic counterparts. Narrowband-broadband or on-line–off-line imagery can pick out the few dozen W-R star candidates in M31 (Moffat & Shara 1983, 1987), M33 (Massey et al. 1987), and other nearby galaxies covering less than 1 square degree. Objective-prism surveys have been needed to cover the entire Milky Way; crowding and plate limits have generally limited completeness to 13th–14th magnitude. Only 12 of the 157 previously cataloged Galactic W-R stars are fainter than $v = 15$.

The prime motivation and scientific driver of this survey is to search for the predicted WC/WN gradient in the Galaxy. To do this we must push the completeness of Galactic W-R stars to much fainter magnitudes than has yet been achieved. Our preliminary results (Shara et al. 1991, hereafter Paper I) were the detection of 13 new W-R stars in 40 square degrees in Carina, where 19 W-R stars were pre-

[1] Respectfully dedicated to the memory of Karl Henize—astronaut, astronomer, seeker and finder of Wolf-Rayet stars.

[2] Member of the Carrera del Investigador Científico, CIC, Província de Buenos Aires, Argentina.

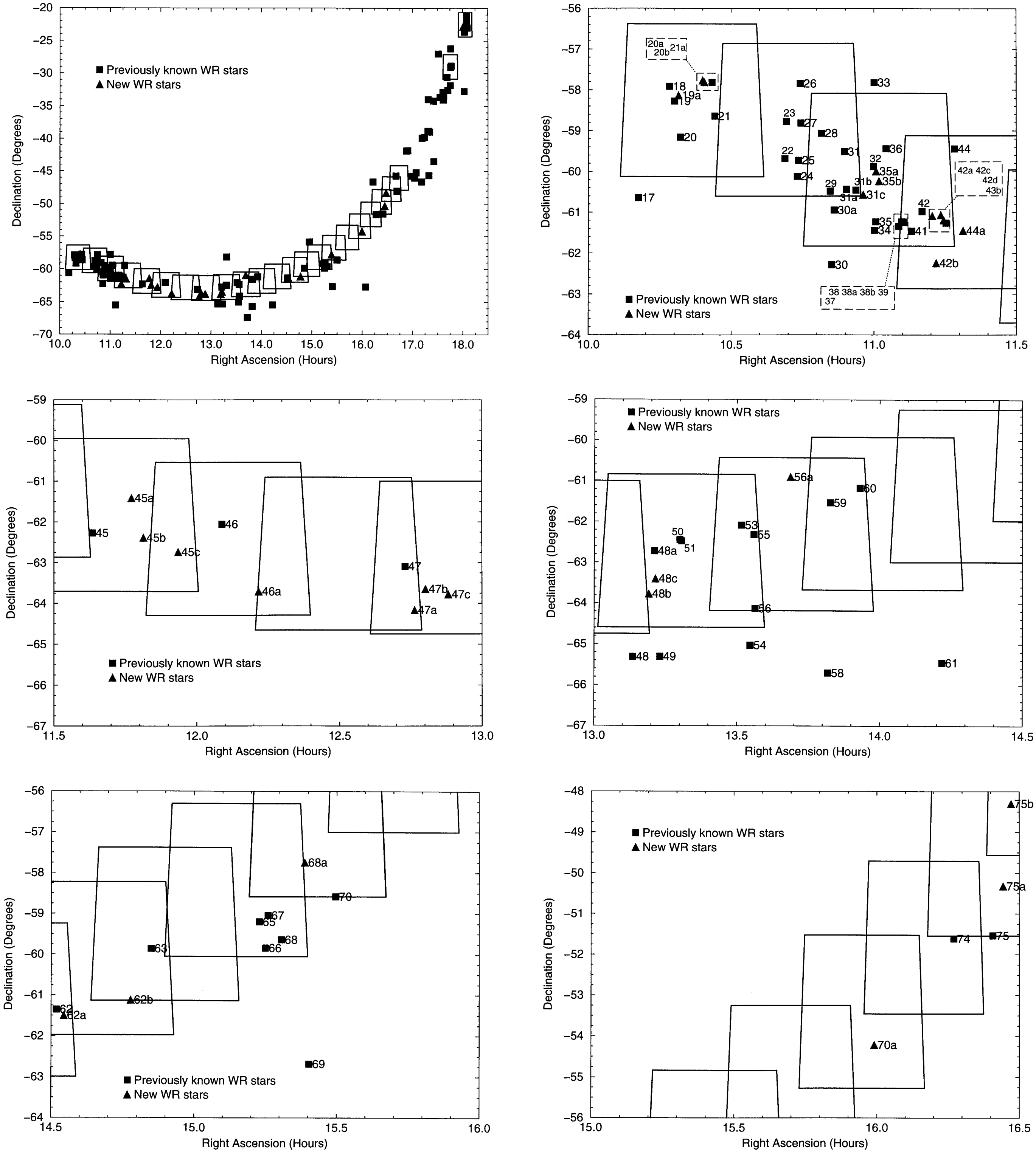

FIG. 1.—Areal coverage of the completed survey and locations of new and known W-R stars

viously known. Eleven new WN stars and only two WC stars were found, supporting the Maeder (1991) scenario of Z-controlled WN/WC ratio. A significantly larger areal coverage and sample of W-R stars are needed to strengthen or refute our early conclusions and to more rigorously test the Maeder (1991) scenario. As we describe below, this has largely been achieved: the Galactic WC/WN ratio is clearly observed to be monotonically increasing with decreasing Galactocentric distance (and hence with increasing metallicity).

In § 2, we describe our observations, and in § 3 we detail the magnitudes and colors of the newly discovered W-R stars, and the completeness of our survey. The spectra of the new W-R stars are presented in § 4. The Galactic distribu-

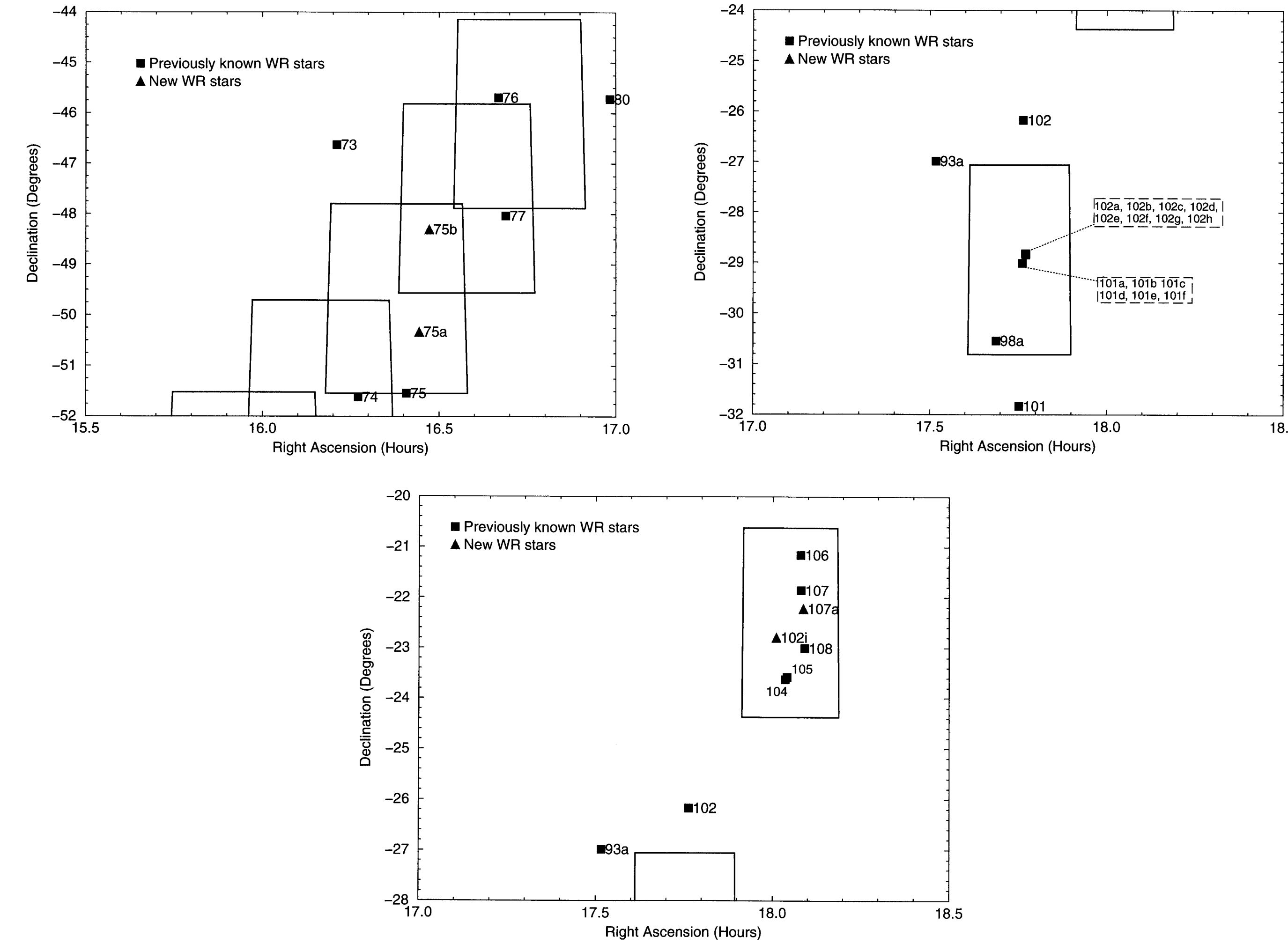

FIG. 1.—*Continued*

tion of these stars and its implications for theories of W-R star evolution are presented in § 5. Our conclusions are summarized in § 6.

2. OBSERVATIONS

We have concentrated our survey within 1°.5 of the Galactic plane, where 80% of all known W-R stars are found. Even so, we have had no alternative to Schmidt plates in order to cover about one-sixth of the Galactic plane, about 150 square degrees. Our broadband-narrowband imaging technique, filters used, digitization and data analysis procedures, quality control, and photometric calibrations have been extensively described in Paper I. Our completed survey involved the digitization and analysis of 100 direct-image (narrowband and broadband) Schmidt plates covering 24 fields and the photometry of ∼25 million stars. The regions covered are shown schematically in Figure 1. The candidates selected were those stars that appeared at least 3 σ brighter (than nearby stars of similar brightness) in the narrowband images than in the broadband images. We obtained follow-up spectra of nearly 1000 such photometric candidates, including almost every previously known W-R star in our survey area. The 18 new W-R stars in the present survey were confirmed during observing runs in 1993 May at the Cerro-Tololo Inter-American Observatory (CTIO) 1.5 m telescope; in 1993 June at the CASLEO[3] 2.1 m telescope; and in 1995 May/June on the CTIO 1.5 m and 4 m telescopes. CCD Cassegrain spectrographs yielding ∼5 Å resolution were used in all runs. All data reductions were carried out with the IRAF package.

3. FINDER CHARTS, MAGNITUDES, COMPLETENESS, AND COLORS

An overview of our complete survey area is given in Figure 1, and finder charts for the 18 new W-R stars are given in Figure 2. Numbering of the stars is by right ascension interpolation into the catalog of van der Hucht et al. (1981, 1988), with recent updates given by van der Hucht (1996). The names, spectral types, magnitudes, and derived quantities (discussed below) are summarized in Table 1.

To assess our rate of success in detecting Galactic W-R stars, we note that 33 of the 38 known W-R stars in van der Hucht (1988) fainter than $v = 10$ (brighter stars saturate the photographic plates) in the 22 contiguous regions were recovered. However, the completeness of the van der Hucht (1988) catalog is not known, because it is a compilation of several different catalogs.

[3] Operated under an agreement between CONICET, SeCyT, and the Universities of La Plata, Córdoba, and San Juan, Argentina.

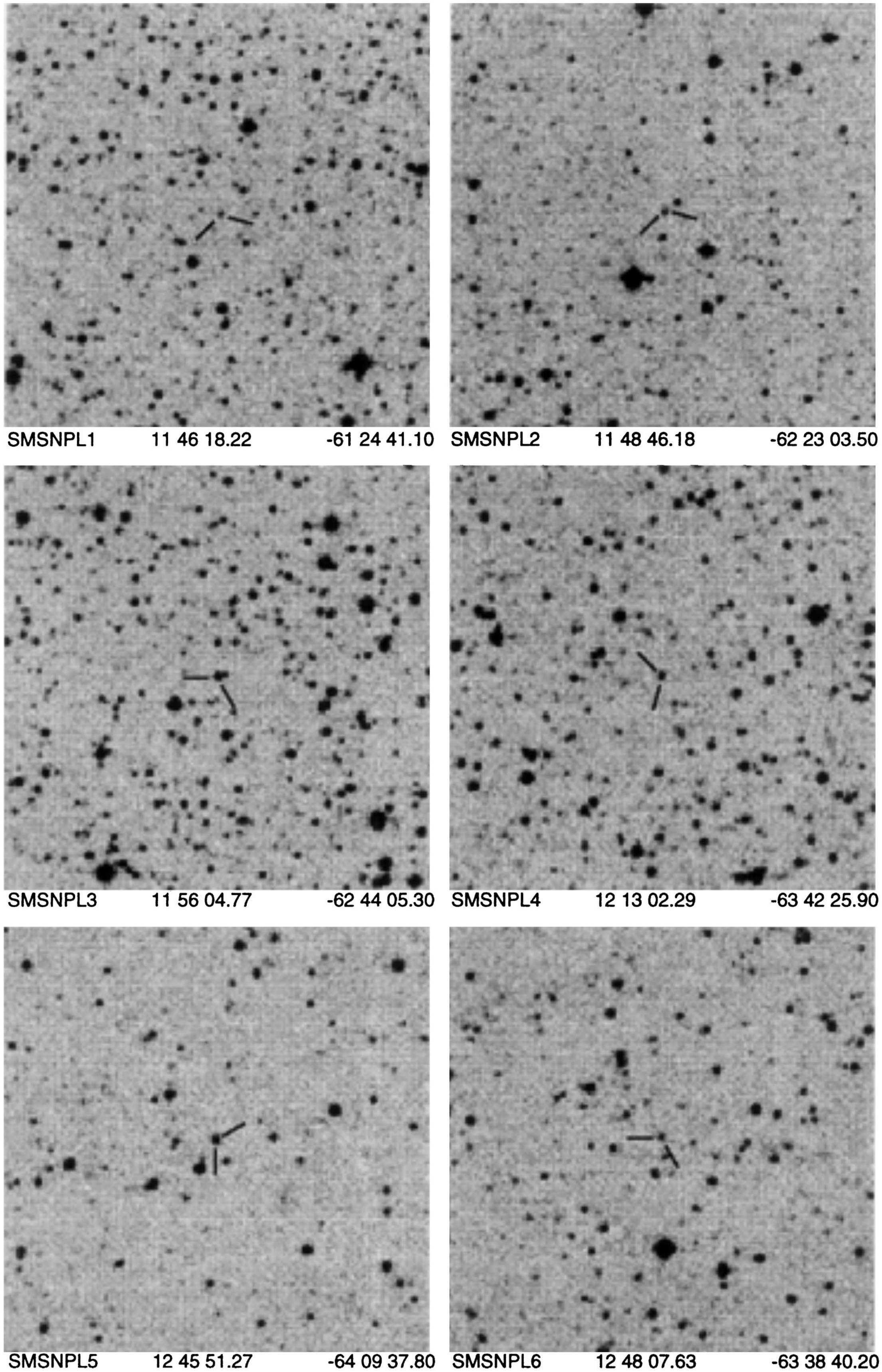

FIG. 2.—Finder charts for the 18 new W-R stars from the STScI Digitized Sky Survey. All images are V-band exposures except for SMSPNL 10, SMSPNL 11, and SMSPNL 12, which were taken with IIIa-J plates. North is up, and east is left. The scale is indicated by the tick marks locating the W-R star, which are each 18″ long.

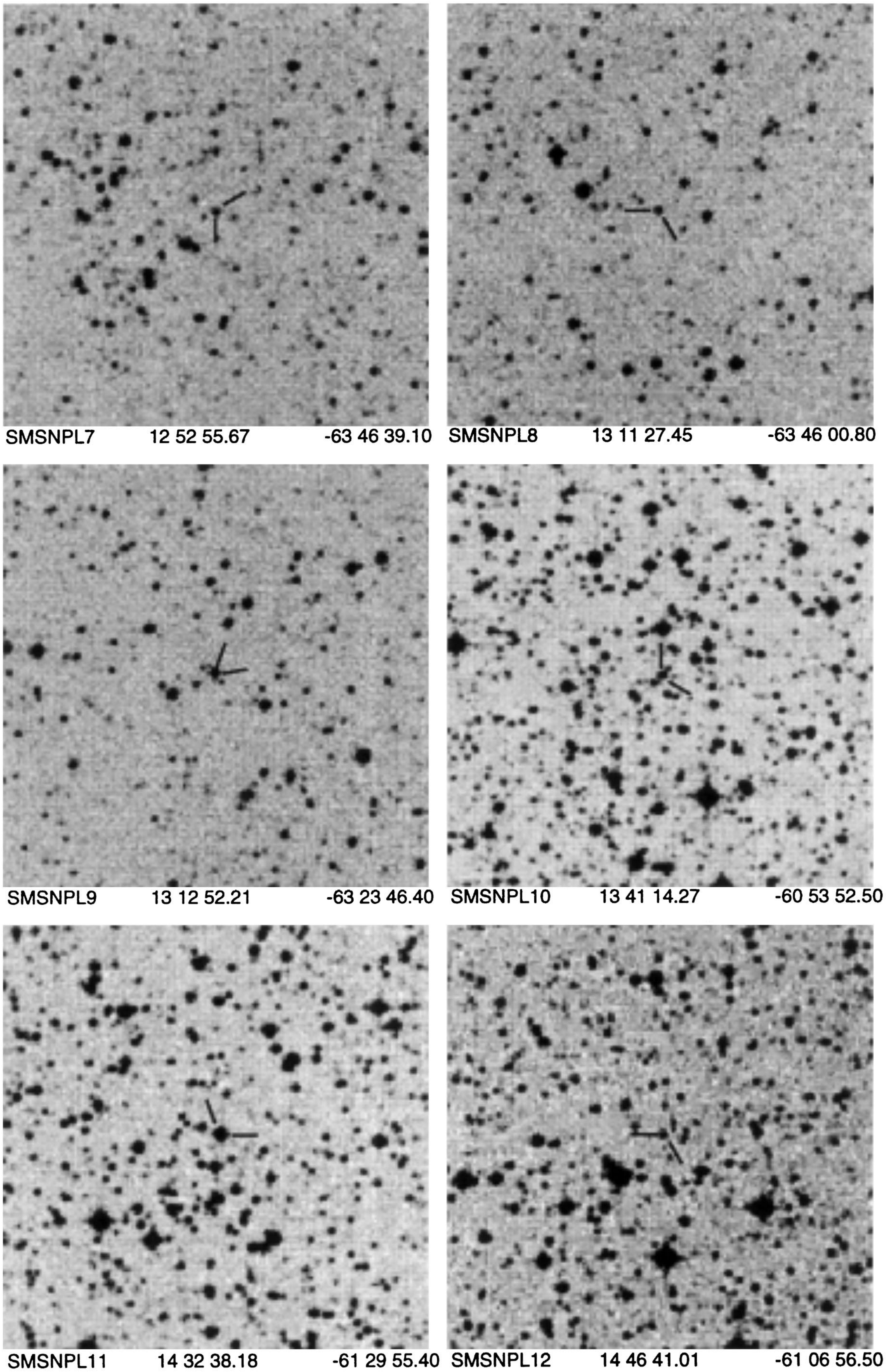

FIG. 2.—*Continued*

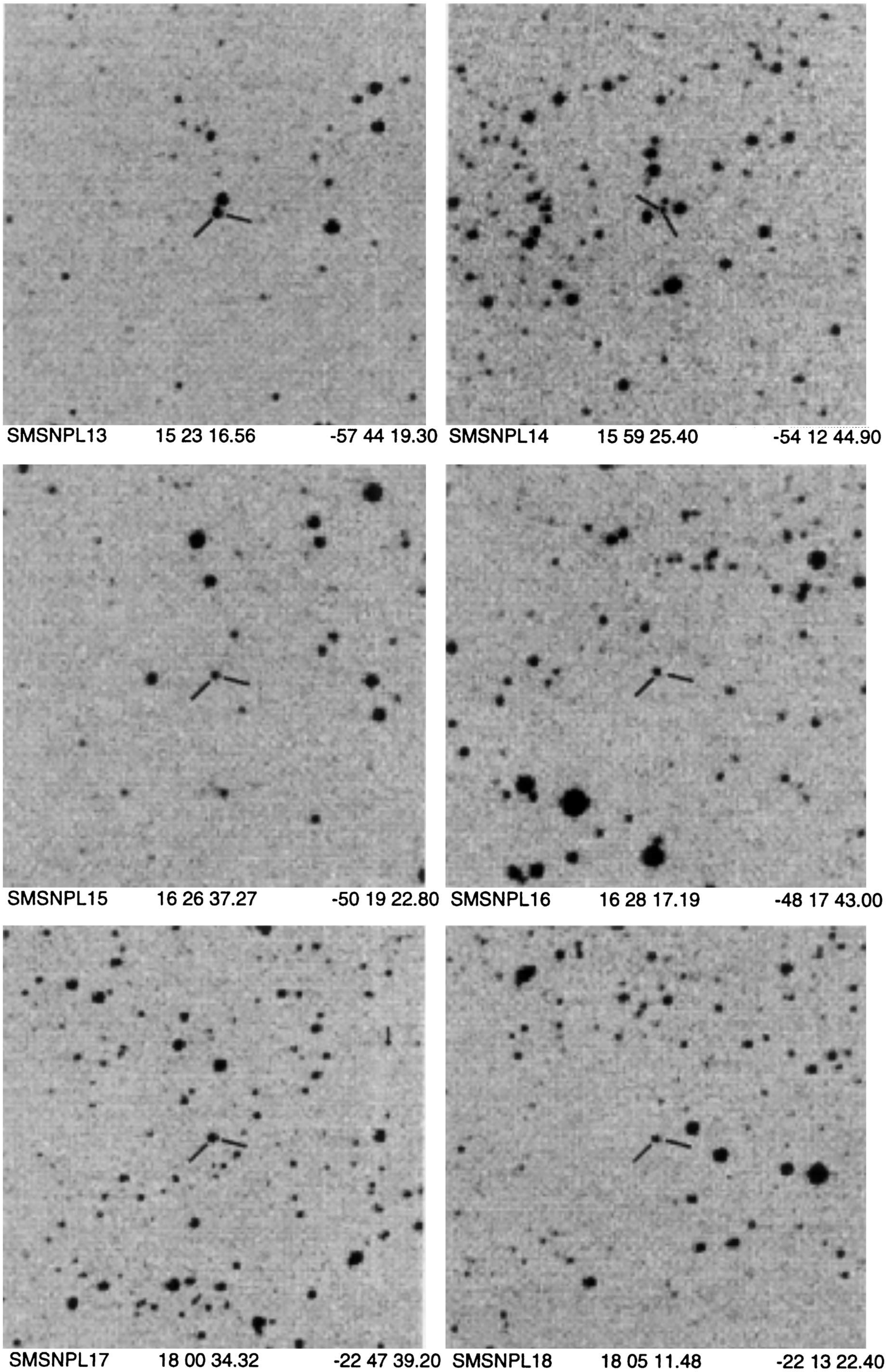

FIG. 2.—*Continued*

TABLE 1

OVERVIEW OF SURVEY RESULTS

Star	W-R Number	Spectral Type[a]	α (J2000.0)	δ (J2000.0)	l (deg)	b (deg)	v	$b-v$	$(b-v)_0$	E_{b-v}	A_v	v_0	$v_0 - M_v$	d (kpc)	Z (pc)	R (kpc)
SMSNPL 1	45a	WN5o WN4.5	11 46 18.22	−61 24 41.1	295.22	0.48	16.69	1.19	−0.23	1.42	5.82	10.87	15.7	13.8	+120	12.8
SMSNPL 2	45b	WN4b WN3–5	11 48 46.18	−62 23 03.5	295.74	−0.39	≤18.08	1.40	−0.27	1.67	6.85	≤11.23	≤14.7	≤8.7	≥−60	≤9.1
SMSNPL 3	45c	WN5o WN4.5	11 56 04.77	−62 44 05.3	296.64	−0.54	15.44	0.91	−0.23	1.14	4.67	≤10.77	15.6	≤13.2	≥−120	≥12.1
SMSNPL 4	46a	WN4o WN4	12 13 02.29	−63 42 25.9	298.69	−1.15	16.00	1.04	−0.27	1.31	5.37	10.63	14.1	6.6	−130	7.9
SMSNPL 5	47a	WN8h WN8	12 45 51.27	−64 09 37.8	302.32	−1.30	15.98	1.73	−0.27	2.00	8.20	7.78	14.5	7.9	−180	7.9
SMSNPL 6	47b	WN9h WN8–9	12 48 07.63	−63 38 40.2	302.56	−0.78	17.05	1.93	−0.27	2.20	9.02	8.03	14.7	8.7	−120	8.3
SMSNPL 7	47c	WC5 WC5	12 52 55.67	−63 46 39.1	303.10	−0.91	16.09	1.40	−0.27	1.67	6.85	9.24	12.9	3.8	−60	7.2
SMSNPL 8	48a	WC9 WC9	13 11 27.45	−63 46 00.8	305.14	−0.98	15.96	1.07	−0.41	1.48	6.07	9.89	14.7	8.7	−150	7.9
SMSNPL 9	48c	WN3h/CE WN3/C4	13 12 52.21	−6 23 46.4	305.33	−0.62	13.98	0.39	−0.27	0.66	2.71	16.69	13.8	5.8	−60	7.0
SMSNPL 10...	56a	WN6o WN5–6	13 41 14.27	−60 53 52.5	308.95	1.39	15.91	1.32	−0.23	1.55	6.36	9.56	14.4	7.6	+180	7.0
SMSNPL 11...	62a	WN4–5o WN3–4	14 32 38.18	−61 29 55.4	314.70	−0.96	13.80	1.24	−0.26	1.50	6.15	7.65	12.2	2.8	−50	6.8
SMSNPL 12...	62b	WN5o WN5	14 46 41.01	−61 06 56.5	316.40	−1.29	17.26	1.77	−0.23	2.00	8.20	9.06	13.9	6.0	−140	5.9
SMSNPL 13...	68a	WN6o WN7	15 23 16.56	−57 44 19.3	322.10	−0.63	14.41	1.46	−0.28	1.74	7.13	7.28	12.6	3.3	−40	6.2
SMSNPL 14...	70a	WN6o WN7	15 59 25.40	−54 12 44.9	328.25	−0.86	16.90	1.23	−0.28	1.51	6.19	10.71	16.0	15.8	−240	9.7
SMSNPL 15...	75a	WC9 WC9	16 26 37.27	−50 19 22.8	333.95	−0.88	14.51	1.53	−0.41	1.74	7.95	6.56	11.4	1.9	−30	6.8
SMSNPL 16...	75b	WC9 WC9	16 28 17.19	−48 17 43.0	335.59	0.33	16.09	1.71	−0.41	2.12	8.69	7.40	12.2	2.8	+20	6.1
SMSNPL 17...	102i	WN8o WN8	18 00 34.32	−22 47 39.2	7.00	−0.42	15.53	1.80	−0.27	2.07	8.49	7.04	13.7	5.5	−40	3.1
SMSNPL 18...	107a	WC6 WC6	18 05 11.48	−22 13 22.4	8.02	−0.42	16.43	1.32	−0.27	1.59	6.52	9.91	13.6	5.2	−40	3.4

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] The first spectral type is from criteria of Smith et al. 1990, 1996, and the second is from criteria of Smith 1968a, 1968b.

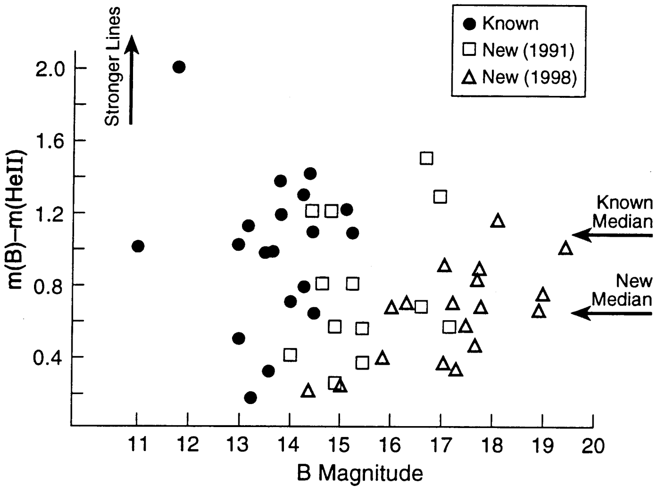

FIG. 3.—Measured broadband-minus-narrowband magnitude difference (or "detectability index") as a function of W-R star brightness. The median detectability indexes of the new and the already known W-R stars (in Carina) are indicated by horizontal arrows.

The strongest argument in favor of a high degree of completeness in the present survey is given in Figure 3, where we plot the "detectability index" (broadband minus narrowband instrumental magnitude) versus b magnitude. New weak-lined stars are detected about as readily as strong emission-line stars at least to $b \sim 17.5$, confirming the Shara et al. (1991) claim of near-completeness to this limit. That we detected no new W-R stars brighter than $b \sim 14$ suggests that the van der Hucht (1988) catalog is highly complete to that limit. Just as important, we (rather easily) detected three new WC9 stars, one new WN9 star, and two WN8 stars. These are the most difficult subtypes to detect because of their weak lines. Our greatest source of incompleteness is likely to be due to Wolf-Rayet stars with O-type companions. The above arguments indicate that we are complete in our detection of new, single W-R stars at the ~85%–90% level, at least to $b \sim 17.5$.

Figure 4 is a histogram of the number of known and new W-R stars in the contiguous region of our survey. This figure again demonstrates that our new W-R stars are significantly fainter than those previously known. Older surveys in this region appear complete to $b = 14$. Figure 4

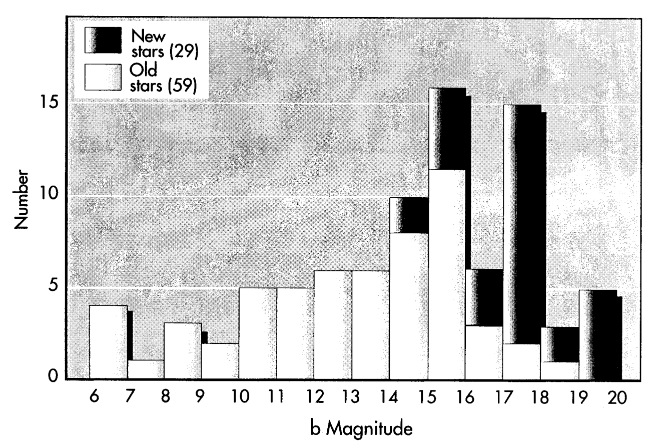

FIG. 4.—Histogram of the number of the 88 known Galactic W-R stars (*light histogram*) and new W-R stars (*dark histogram*) in the contiguous region of search covering $l = 282°–341°$ shown in Fig. 1.

also supports our claim of a high degree of completeness to $b \sim 17.5$.

In order to derive distances to study the Galactic distribution, we need calibrated magnitudes, colors, and spectral subclasses. We discuss here how the (v, $b-v$) photometry was extracted from the observed fluxed spectra. In the 1995 spectra, we converted the monochromatic magnitudes at the wavelengths corresponding to v and b (5160 and 4270 Å, respectively) into true v and b magnitudes using fluxed spectra of nine Galactic W-R stars of various subtypes and known (v, b) (van der Hucht et al. 1988). No color-term corrections were found to be necessary. The standard deviation of the difference between instrumental and calibrated catalog values was found to be $\sigma = 0.10$ mag in v and 0.06 mag in $b - v$.

The 1993 4 m data lacked observations of W-R stars with known (v, b). Thus, to convert from instrumental to standard magnitudes, we adopted the same calibration from fluxed spectra to magnitude as found for the 1995 data. The derived values of v and $b-v$ are listed in Table 1.

4. SPECTRAL CLASSIFICATION OF THE NEW WOLF-RAYET STARS

The spectra of the 18 newly spectroscopically confirmed W-R stars are shown in Figure 5. Tables 1 and 2 give classifications on the systems of Smith (1968a), upgraded by van der Hucht et al. (1981) and Smith, Shara, & Moffat (1990). The new WN stars (11 from Paper I, 13 from this paper) are also classified on the recently published quantitative three-dimensional system of Smith, Shara, & Moffat (1996). The detailed criteria on which the subtypes are based are summarized in Table 2. Table 3 lists the subtypes, based on the Smith et al. (1996) classification scheme, of the 11 WN stars and two WC stars from Paper I.

Two stars deserve comment:

SMSNPL 5 = WR 47a was not in van der Hucht et al. (1981, 1988) but was already found independently as an emission-line star by Weaver (1974) and classified WN8 by Duerbeck & Reipurth (1990) and Crawford & Barlow (1991).

SMSNPL 9 = WR 48c is a very unusual hybrid WN/WC, of which only five are previously known in the Galaxy. With subclasses assigned the classification is WN3h/C4, which is particularly unusual because most WN/C spectra have broad lines and none has hydrogen. Normally, WCE stars have broad lines and no H. The star with the most similar hybrid subtype known in the Galaxy is WR 58, WN4b/CE (Smith et al. 1996), but with broad emission lines and no H. Our two spectra, taken several days apart, show very different flux levels, suggesting possible intrinsic variability.

Besides W-R stars, six other objects with He II λ4686 emission were detected: five planetary nebulae and a symbiotic star. All are previously cataloged objects. No magnetic cataclysmics, helium double degenerates, or SS 433–like stars were found.

5. GALACTIC DISTRIBUTION OF THE NEW WOLF-RAYET STARS

The equatorial and Galactic coordinates of the 18 newly discovered W-R stars are listed in Table 1. The new and known W-R stars' locations along the Galactic plane are

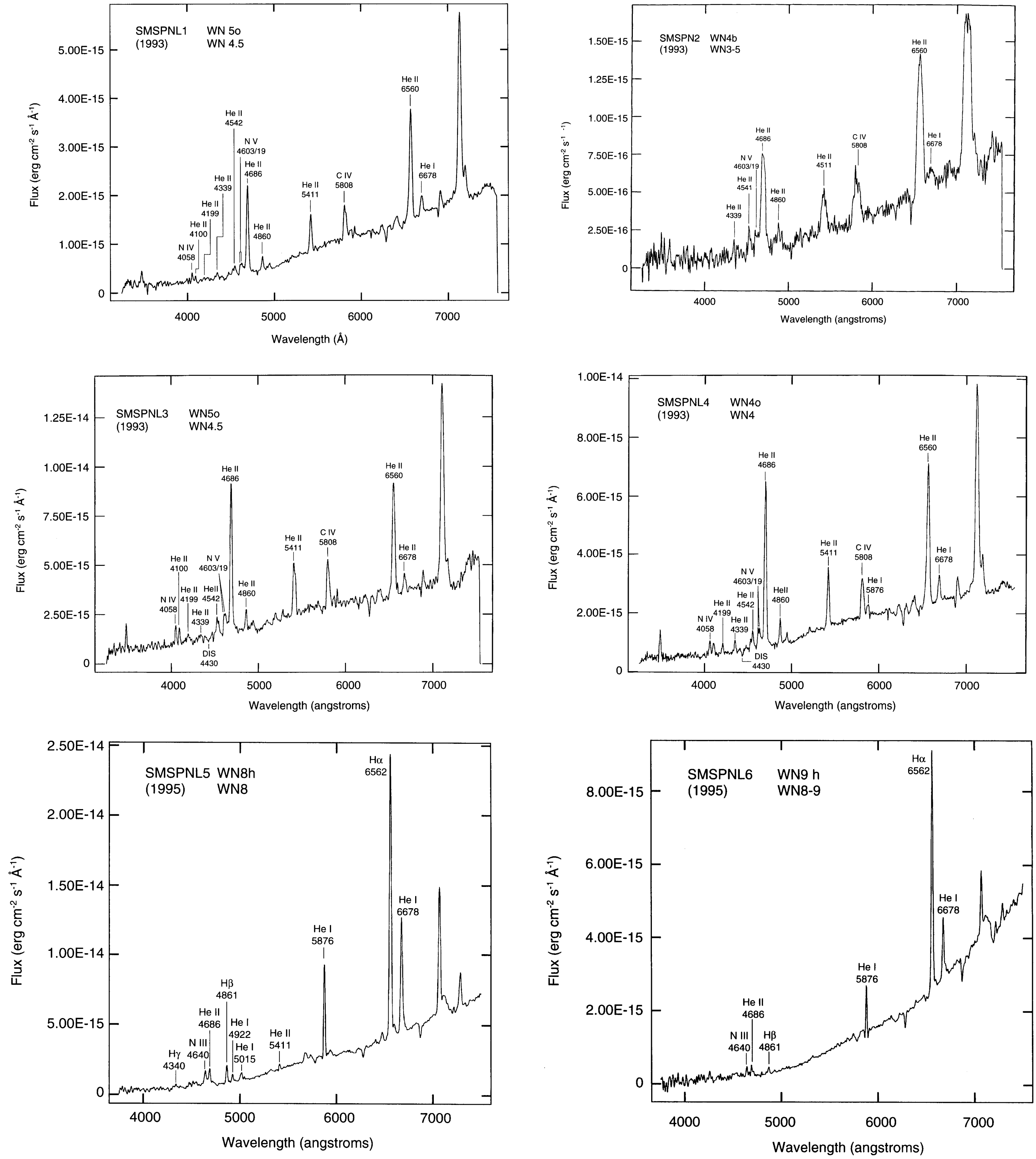

FIG. 5.—Spectra of the 18 new W-R stars. ID number, year of observation, and spectral types using the systems of Smith, Shara, & Moffat (1996) and Smith (1968a), respectively, are indicated.

plotted in Figure 1. Conti & Vacca (1990) noted the tendency for Wolf-Rayet stars to lie below the Galactic plane; 28 of our 31 new stars do so. This may indicate a warp in the Galactic disk, or a peculiar dark cloud distribution.

We have used the van der Hucht et al. (1988) extinction, absolute magnitude–spectral subtype, and intrinsic color–spectral subtype calibrations. The resulting Galactocentric distances R (in kiloparsecs), heights above the Galactic plane z (in parsecs), and heliocentric distances d (in kiloparsecs) are listed in Table 1.

In Figure 6, we plot $b-v$ versus v for the new and already known W-R stars in our contiguous survey area. The 29 new W-R stars are significantly fainter and redder than the previously known stars. The increased reddening is most

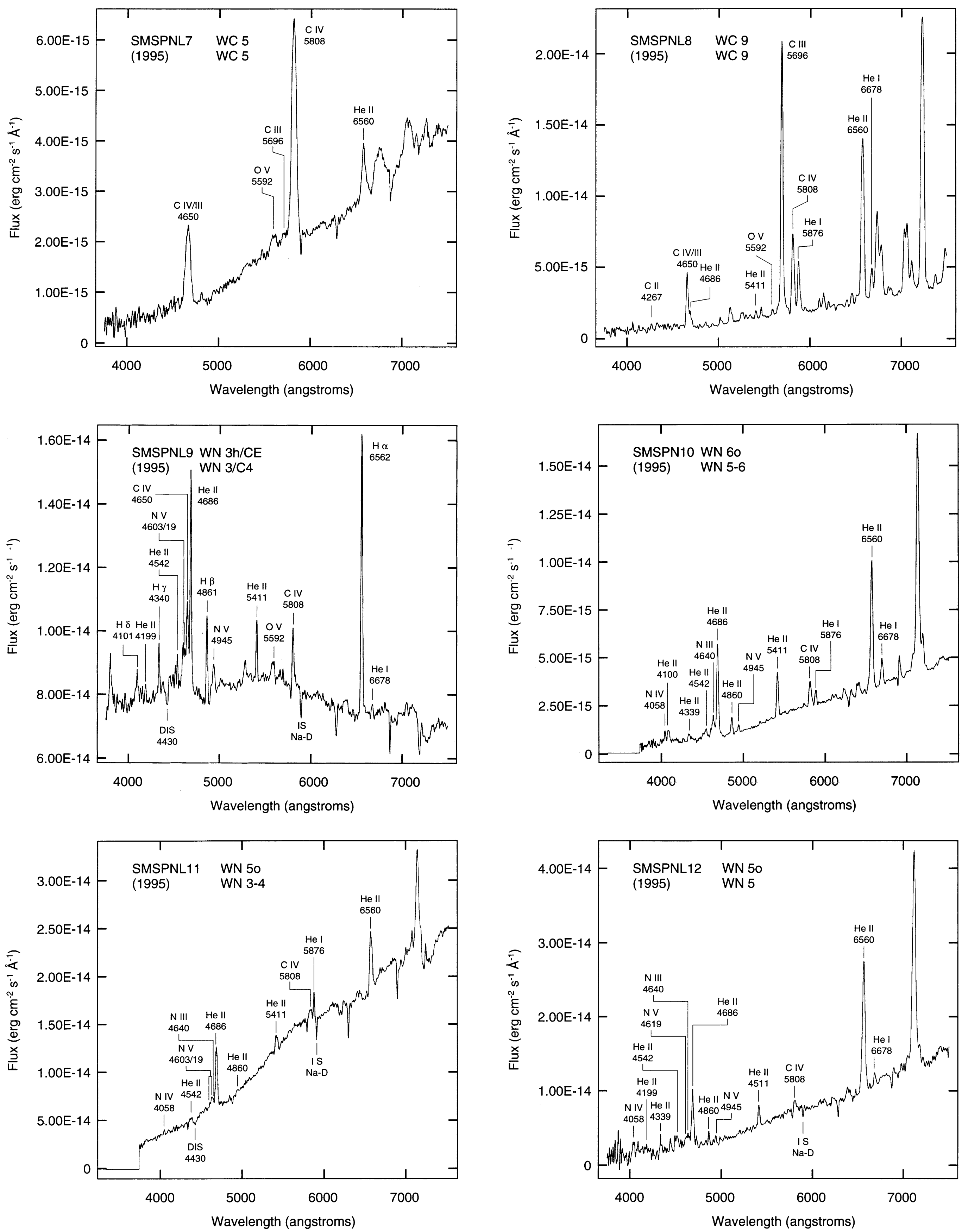

FIG. 5.—*Continued*

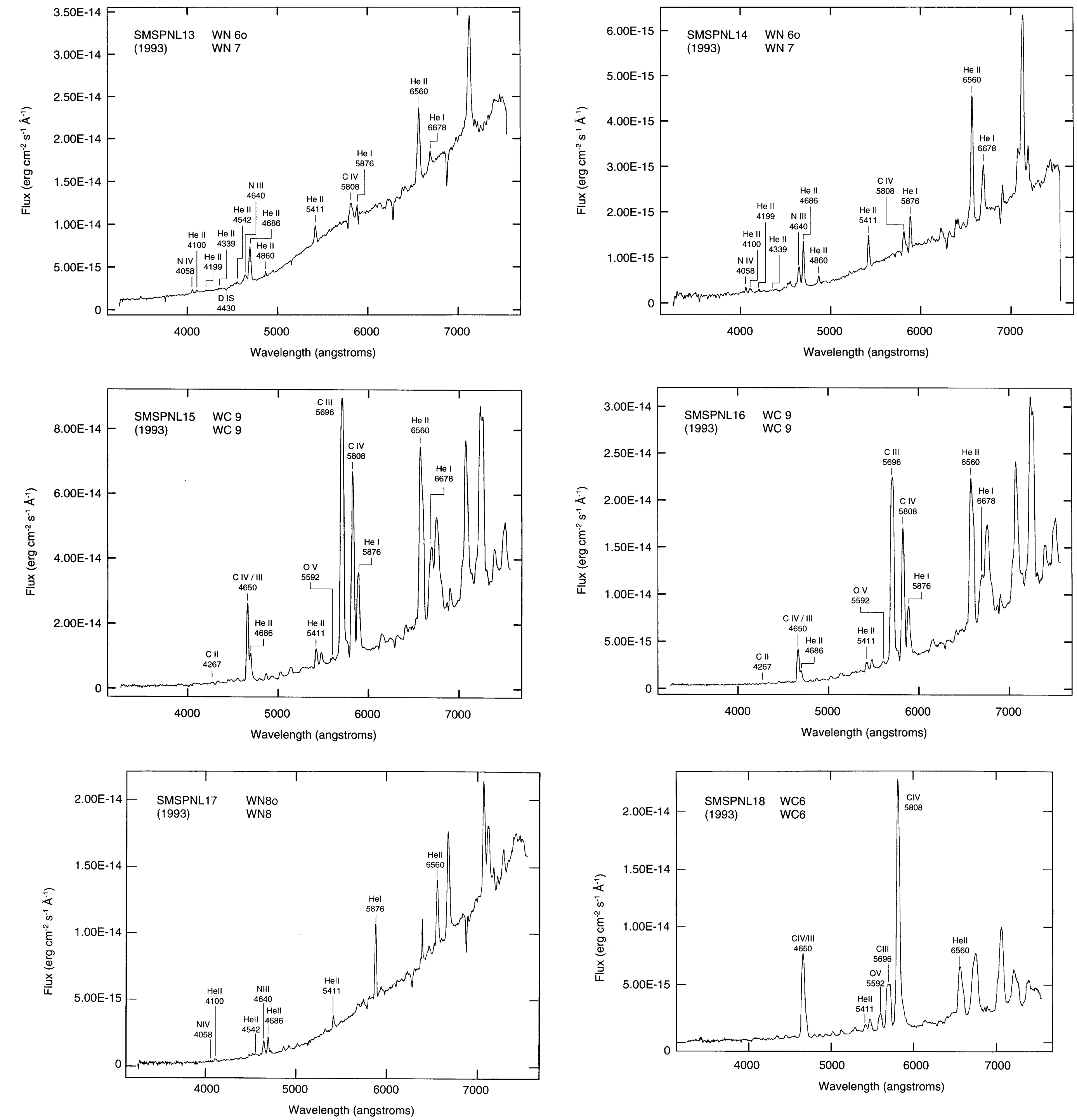

FIG. 5.—*Continued*

simply explained as being due to increased heliocentric distance. In Paper I, we showed that a simple interstellar absorption law and the assumption of a constant W-R absolute magnitude ($M_v = -5$) leads to the predicted $(b-v)$-v curve shown in Figure 6 (see Paper I for details).

To display the WC/WN gradient (predicted by, e.g., Maeder 1991) we have plotted in Figure 7 the cumulative fraction of all new and already known WC and WN stars in the contiguous areas of our survey. WN stars are clearly the dominant population in the zone $l = 282°$–$303°$, while WC stars become increasingly common in the zone $l = 303°$–$340°$. *A Kolmogorov-Smirnov test determines that the WC and WN stars' longitudinal distributions are different at the 95% level of certainty*. Infrared surveys for still fainter W-R stars will be needed to significantly improve on this result (see below). Nevertheless, this is the strongest quantitative determination of the existence of a WC/WN spatial gradient for Galactic W-R stars that we are aware of.

The fraction of W-R stars that are of subtype WC is plotted as a function of Galactocentric distance in Figure 8, using, again only those new and already known stars that fall within our survey region. We find the same trends dis-

TABLE 2

SPECTRAL CLASSES

A. NEW WN STARS

WN STAR	SMITH 1968 CRITERIA[a]	SPECTRAL Type	SMITH ET AL. 1996 CRITERIA[b] He II/He I	N V/N III	N IV/N V, III	C IV/He II	C IV/He I	Mean Spectral Type
SMSNPL 1 = WR 45a........	N III weak, N IV > N V	WN4.5	4 WN5	1.6 WN5	1.5 WN5	0.8 WN5	3 WN5	WN5o
SMSNPL 2 = WR 45b	N III $\lesssim$ N V, N IV < N V	WN3–5	$\gtrsim$5 WN5	$\gtrsim$1 WN5	<0.7 WN3–4	~1 WN5	$\gtrsim$5 WN4	WN4b
SMSNPL 3 = WR 45c........	N III weak/absent, N IV $\gtrsim$ N V	WN4.5	$\gtrsim$5 WN4–5	$\lesssim$2: WN4–5	$\gtrsim$1 WN5	0.8 WN5	$\gtrsim$5 WN4–5	WN5o
SMSNPL 4 = WR 46a........	N III weak/absent, N IV ~ N V	WN4	6 WN4–5	$\gtrsim$2 WN4	$\gtrsim$1 WN5	0.6 WN4–5	4 WN4–5	WN4o
SMSNPL 5 = WR 47a........	N III $\gg$ N IV, N III ≈ He II	WN8	0.1 WN9	$\gtrsim$0.1 WN7–8	0.04 WN7–8	0.04 WN6–8	0.05 WN8	WN8h
SMSNPL 6 = WR 47b	N III ≈ He II, He I/lower H I P Cygni	WN8–9	0.04 WN9	~0 WN9	? ...	? ...	$\lesssim$0.1 WN8–9	WN9h
SMSNPL 9 = WR 48c........	N III very weak (?), N IV $\ll$ N V, C III $\ll$ C IV, C III $\ll$ O V, O V moderate	WN3/CE	$\gtrsim$20 WN2–3	>2: WN3–4	<0.1 WN3	... (C strong!)	... (C strong!)	WN3h/CE
SMSNPL 10 = WR 56a	N III ~ N IV, N IV $\gtrsim$ N V	WN5–6	4 WN5	0.5 WN5–6	~1 WN5	$\gtrsim$0.4 WN4	1.9 WN5	WN6o
SMSNPL 11 = WR 62a	N III weak:, N IV < N V	WN3–4	1–2 WN5–7	1–3 WN4–5	0.3 WN3–4	$\lesssim$1 WN4–6	1–2 WN5–6	WN5o
SMSNPL 12 = WR 62b	N III ≃ N V, N IV > N V	WN5	6 WN5	0.7: WN5	1.5 WN5	$\lesssim$0.5 WN4	3 WN4–5	WN5o
SMSNPL 13 = WR 68a	N III > N IV, N V weak	WN7	$\gtrsim$2 WN6	$\lesssim$0.5 WN6	0.8 WN6	$\gtrsim$0.7 WN5	1.3 WN6	WN6o
SMSNPL 14 = WR 70a	N III > N IV, N V weak	WN7	1.5 WN6	$\lesssim$0.3 WN6	0.6 WN7	0.4 WN6	$\gtrsim$0.7 WN6	WN6o
SMSNPL 17 = WR 102i......	N III $\gg$ N IV, N III ≈ He II, He I strong	WN8	0.3 WN8	0.2 WN7–8	0.2 WN8	$\gtrsim$0.4 WN8	0.1 WN8	WN8o

B. NEW WC STARS

WC STAR	SMITH 1968 CRITERIA[a]	TYPE	SMITH ET AL. 1990 CRITERIA[b] C IV/C III	C II/O V	Mean Spectral Type
SMSNPL 7 = WR 47c........	C III $\ll$ C IV, C III < O V	WC5	19 WC5	0.7 WC5	WC5
SMSNPL 8 = WR 48a........	C II present, C III $\gg$ C IV, O V weak	WC9	0.3 WC9	34 WC9	WC9
SMSNPL 15 = WR 75a	C II present (?), C III > C IV, O V weak	WC9	0.6 WC8–9	56 WC9	WC9
SMSNPL 16 = WR 75b	C II present (?), C III > C IV, O V weak	WC9	0.6 WC8–9	35 WC9	WC9
SMSNPL 18 = WR 107	C III $\ll$ C IV, C III > O V	WC6	5 WC6–7	2.5 WC6	WC6

[a] For the Smith 1968a, 1968b classification, N III is at 4640 Å, N IV is at 4058, N V is at 4603/4619, He II is at 4686, He I is at mainly 5876, 4471, H I is at Balmer, C II is at 4267, C III is at 5696, C IV is at 5808, and O V is at 5592.

[b] For the Smith et al. 1990, 1996 classification, N III is at 4640 Å, N IV is at 4058, N V is at 4603/4619, He II is at 5411, He I is at 5876, C III is at 5696, C IV is at 5808, and O V is at 5592.

TABLE 3

RECLASSIFICATION OF THE 11 WN AND TWO WC SUBTYPES

Star (SMSP)	Paper I	This Paper
1............	WN7	WN7:(h)
2............	WN7	WN7:h/C
3............	WN7	WN7:h
4............	WC6	WC6
5............	WN6	WN6h
6............	WN4	WN4b
7............	WN6	WN5o
8............	WC7	WC7
9............	WN4.5	WN5b
10	WN3:+C	WN4b
11	WN6	WN5o
12	WN4	WN5b
13	WN3:	WN5b

NOTE.—For Paper I in the Smith et al. 1996 and Smith et al. 1990 systems.

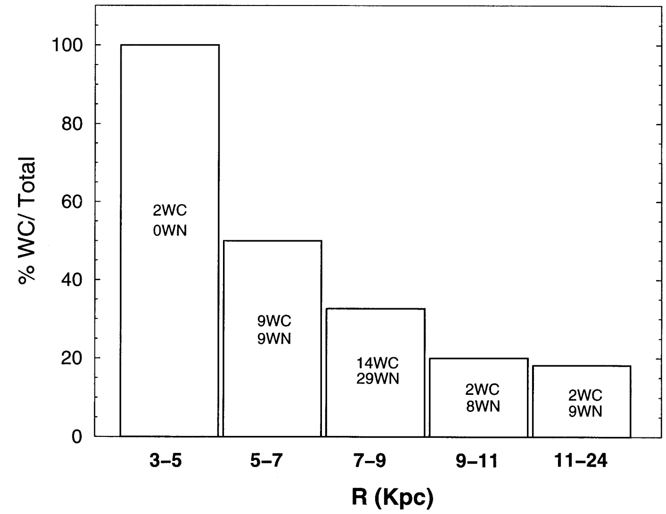

FIG. 8.—Local percentage of W-R stars that are of type WC as a function of Galactocentric distance in the contiguous region of the present survey.

covered by Smith (1968b) and confirmed by van der Hucht et al. (1988), namely, that WC stars are more commonly found toward the Galactic center and that WN stars are found at all Galactocentric distances. This is in accord with the predictions of Maeder (1991): W-R stars forming in regions of higher Z (smaller *R*) tend to lose their envelopes faster as a result of higher opacity and radiation pressure–induced mass loss.

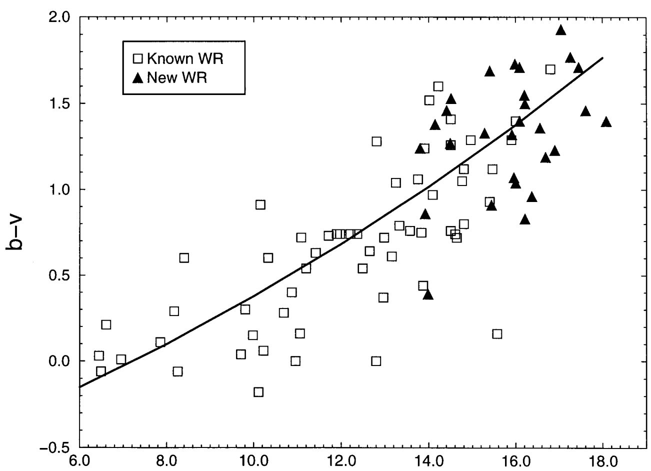

FIG. 6.—Plot of $b - v$ vs. v for the 29 new (*filled triangles*) and the 59 previously known (*open squares*) (K. A. van der Hucht 1997, private communication) Galactic W-R stars with reliable magnitudes in our contiguous field. The curve is a simple model of Galactic reddening (see text).

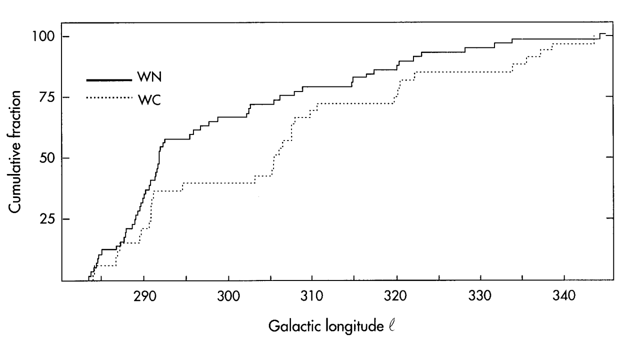

FIG. 7.—Cumulative fraction of all detected WN and WC stars in the contiguous region of the present survey.

6. COMPARISON WITH OTHER SPIRAL ARM TRACERS

The Galactic warp toward negative latitudes observed in the locations of the W-R stars has been also observed in the Galactic disk as defined by H I observations (e.g., Henderson, Jackson, & Kerr 1982). Also, the giant molecular clouds observed at the fourth Galactic quadrant (Grabelsky et al. 1988; Bronfman et al. 1989) show a tendency of higher concentration toward negative Galactic latitudes.

H II regions are the principal spiral arm tracers in other galaxies and therefore are expected to follow the spiral structure of our own Galaxy. Because of obscuration along the Galactic plane, the H II regions in our Galaxy are best seen at radio wavelengths, as sources of recombination-line emission. Thus, we have compared the positions of our new W-R stars with the catalog of southern radio H II regions of Caswell & Haynes (1987), and also with the 5 GHz radio continuum maps of the Galactic plane (Haynes, Caswell, & Simons 1978). We note the following remarkable spatial coincidences between the new W-R stars and H II regions:

WR 19a is located inside the strong radio continuum peak of the H II region 284.0 − 0.9, which also has a faint optical counterpart.

WR 20a and WR 20b coincide with the radio continuum peak of the H II region 284.3 − 0.3, which corresponds to the optical H II region RCW 49.

WR 31c is coincident with the faint radio H II region 289.06 − 0.35 with positive radial velocity, and thus corresponding to the far side of the Carina spiral arm

WR 38a and WR 38b are seen within the boundaries of the radio H II region 290.5 − 0.8, which also has positive radial velocity and is located at the far side of the Carina spiral arm.

WR 42a is coincident with the radio H II region 291.2 − 0.3.

WR 45b is located within the faint, distant radio H II region 295.7 − 0.2.

WR 47b coincides with the radio H II region 302.5 − 0.75, with positive radial velocity and thus at the far distance.

WR 47c is located within the radio continuum peak of the H II region 303.1 − 0.95, also with positive radial velocity.

To discuss whether the spatial coincidences imply that the W-R stars are at the same distance as the H II regions is beyond the scope of this paper.

7. THE NEED FOR INFRARED SURVEYS

As is clear from Figure 6, the main limitation to detecting all of the Galaxy's W-R stars using optical filters is the rapid cumulative increase of interstellar (IS) extinction with distance in the Galactic disk. As a result, Galactic surveys for W-R stars are very incomplete, especially toward the Galactic center region, where the IS extinction increases most rapidly with distance.

One way around this is to go to the near-infrared. Although W-R emission lines in the near-IR are generally weaker than the strong He II 4686 Å line in WN stars and C III/IV 4650 Å in WC stars, the gain in reduced extinction more than compensates. Probably an ideal wavelength region is situated around 2 μm: At that wavelength, the reduction in extinction is close to an order of magnitude compared with the visual, yet the emission is still little affected by wind free-free or dust emission. Here we illustrate the gain in going from visual (v-band) to IR (K-band) wavelengths by constructing a simple model that allows for the Galactocentric dependence of dust extinction and star density in a realistic way.

We assume a thin, exponential disk in which both general star and dust densities follow the same radial exponential law:

$$N_*(R) = N_0\, e^{-(R-R_0)/\alpha_R} ,$$
$$a_v(R) = a_{v,0}\, e^{-(R-R_0)/\alpha_R} ,$$
$$a_K(R) = a_{K,0}\, e^{-(R-R_0)/\alpha_R} ,$$

in which the solar Galactocentric distance $R_0 = 8$ kpc (Bahcall 1986), $\alpha_R = 3500$ pc (Bahcall 1986), $a_{v,0} = 0.001$ mag pc^{-1} (i.e., 1 mag kpc^{-1}, which fits well the v vs. $b - v$ plot in Paper I, although 1.5 mag kpc^{-1} may be more appropriate for the local solar environment out to $r = 1$ kpc; Hakkila et al. 1997), and $a_{K,0} = a_{v,0}/9.3$ (for a normal extinction law; Mathis 1990). Also, the integrated visual IS extinction from the Sun to the Galactic center according to our model is

$$A_v(\text{Galactic center}) = \int_0^{R_0} a_v(R)dR = 31 \text{ mag} ,$$

which is quite reasonable. N_0 is the local projected density (number of stars per pc^2), which is discussed below for W-R stars.

While the O stars do probably follow this exponential law, we must make a modification for their descendants, the W-R stars, that allows for the metallicity (Z) dependence of W-R formation. According to Maeder & Meynet (1994), the W-R/O number ratio falls with Z; a linear dependence appears to represent this correlation quite well:

$$\text{WR/O} = 0.13 Z/Z_0$$

(the actual constant of proportionality here is not important; see below). Furthermore, it is now well established that the metallicity distribution in the Galactic disk for relatively young stars and emission nebulae also follows an exponential drop-off:

$$Z(R) = Z_0\, 10^{-k(R-R_0)}$$

(Smartt & Rolleston 1997), where $k = 0.00007$ dex pc^{-1} (i.e., 0.07 dex kpc^{-1}). This dependence is valid over $R \approx 6$–18 kpc; nevertheless, we assume it to be valid at all Galactocentric radii. This may lead to an overestimate at the Galactic center ($Z = 3.5Z_0$), but the number of stars there is relatively low, considering the reduced volume.

This leads to the desired W-R density profile in the Galactic disk:

$$N_{\rm WR}(R) = N_{\rm WR,0}\, e^{-(R-R_0)/\alpha'_R} ,$$

where $\alpha'_R = 1/(1/\alpha_R + k \ln 10) = 2240$ pc. We also take $N_{\rm WR,0} = 2.2 \times 10^{-6}$ W-R stars per pc^2 from direct observations in the local environment (Massey 1996).

The next step is to convert the density of W-R stars from a spatial to a magnitude dependence. This is best done by forcing the conservation of stars in the two coordinate systems:

$$\eta_v(v, l)dv\, dl = \eta_K(K, l)dv\, dl = N_{\rm WR}[R(r, l)]r\, dr\, dl ,$$

where $R^2 = r^2 + R_0^2 - 2rR_0 \cos l$. Here r is the distance from the Sun and l is the Galactic longitude. The actual link between the magnitude v or K and r is given by the inverse square law of light attenuation. Allowing for IS extinction and taking $l = \text{const}$,

$$5 \log r - 5 = v - M_v - \int_0^r a_v(R)dr$$
$$= K - M_K - \int_0^r a_K(R)dr ,$$

in which we adopt as reasonable the mean values for all W-R stars, $M_v = -5$ and $M_K = -4$. The fact that the absolute magnitudes of W-R stars vary, for example, from −3 to −7 in v will cause extra scatter but will not affect our global conclusions. The above integrals can be written as

$$\int_0^r a_v(R)dr = a_{v,0}\, e^{R_0/\alpha_R} \int_0^r e^{-[(x^2 + R_0^2 - 2xR_0 \cos l)/\alpha_R]^{1/2}} dx ,$$

$$\int_0^r a_K(R)dr = a_{K,0}/a_{v,0} \int_0^r a_v(R)dr .$$

After integrating over Galactic longitude, we display the results for the magnitude density function $\eta_m(m)$ and its cumulative value up to magnitude m, respectively, for v and K, in Figures 9a and 9b. These plots show that the number of W-R stars peaks at $K = 13$–14 mag and that virtually all W-R stars can be found in the Galaxy down to $K = 20$ (97% to $K = 18$). Going as faint as $v = 25$ will not even reveal one-third of the Galaxy's W-R stars! The advantage of working in the IR is unequivocal.

Despite the somewhat crude nature of our model, it predicts some 200 W-R stars down to 15th visual magnitude. This is quite compatible with the number of known W-R stars in the Galaxy. The total number of W-R stars predicted by our model is high, close to 2500. This is double that predicted some time ago by Maeder & Lequeux (1982), based on empirical scaling and extrapolating of

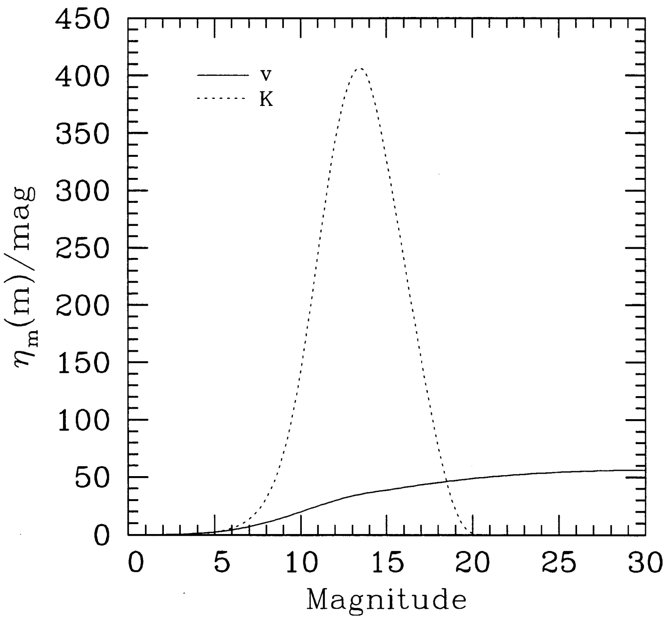

FIG. 9a

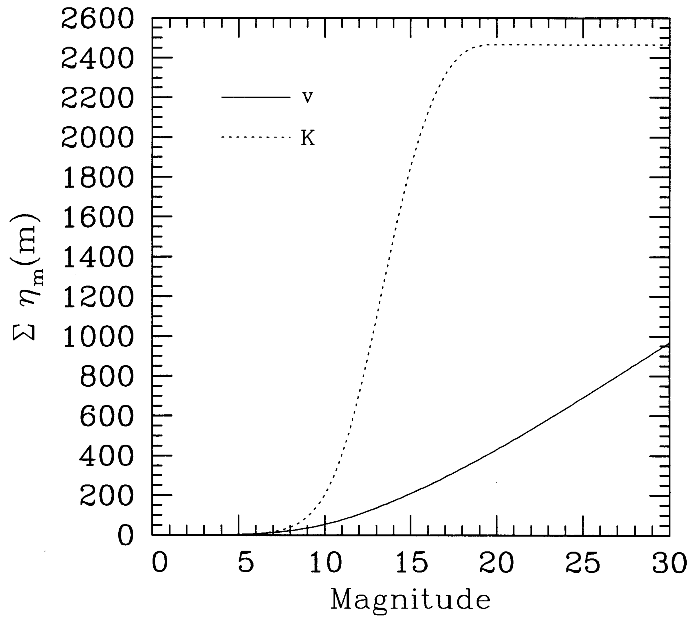

FIG. 9b

FIG. 9.—Number of predicted Galactic W-R stars according to our model (see text) in the v and K bands (a) per magnitude interval and (b) cumulatively.

known W-R stars at the time, with the Galactic distribution of H II regions.

The largest uncertainty in our model occurs in the Galactic center region, where the IR counts are more useful. Therefore, in order to straddle the most likely extreme possibilities, we repeat the above calculation but omit all (model) W-R stars interior to $R = 3$ kpc. This is the Galactocentric distance that corresponds to the maximum molecular cloud density in the disk (see, e.g., Scheffler & Elsässer 1982); inside this radius, the CO density falls dramatically (although not to zero) before rising again within some 0.5 kpc of the center itself. Assuming that W-R (and all) stars are formed in proportion to the CO density, one would expect relatively few W-R stars to be found inside $R = 3$ kpc, with some increase at the center. Figure 10 illustrates this extreme case (lower limit) for the cumulative counts. Although the total number of W-R stars estimated has fallen to about 1500, the shapes of the curves are similar to those in Figure 9b, so that our conclusion still holds concerning the dramatic difference between visual and IR searches for W-R stars in the Galaxy.

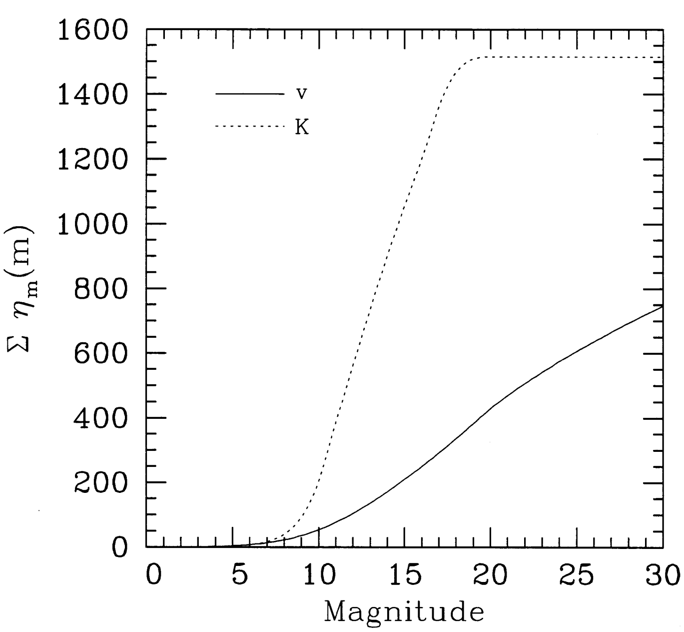

FIG. 10.—As in Fig. 9, except with a hole (no W-R stars) assumed for $R < 3$ kpc.

8. CONCLUSIONS

We can briefly summarize our survey and conclusions as follows:

A direct narrowband-broadband Schmidt plate survey of one-sixth of the Milky Way has led to the discovery of 31 new Wolf-Rayet stars in an area of sky where 59 W-R stars were previously known. The newly discovered W-R stars are among the reddest, faintest, and most distant Galactic W-R stars known. The new W-R stars clearly demonstrate an increasing number ratio of WN to WC stars with increasing Galactocentric distance. A model of the Galactic distribution of absorption and of Wolf-Rayet stars predicts that 1500–2500 W-R stars exist in the Galaxy, and that 97% of the W-R stars are brighter than $K = 18$. The vast majority of Galactic W-R stars have yet to be found, and the near-infrared is the clear choice for future surveys.

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