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WOLF-RAYET STARS IN THE LOCAL GROUP GALAXIES M31 AND NGC 6822

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ABSTRACT

A search to *continuum* magnitude $B \approx 21.5$ ($M_B \approx -3$ to -4) using a narrow-band filter at 4670 Å and a wide B band filter has revealed 21 W-R star candidates in about two-thirds of the giant Sb galaxy M31 and none in the irregular galaxy NGC 6822. Some weak-line W-R stars, most likely WN, may have escaped detection. Subsequent spectrophotometry reveals 17 of the 21 actually to be W-R stars; the rest are non–W-R. The number of detected W-R stars is low but is compatible with the total number of luminous (i.e., massive) stars in each galaxy. In M31, most of the W-R stars lie in the ring of prominent star formation 7–12 kpc from the center. The variation of various W-R subclasses with galactocentric distance implies a metallicity gradient similar to that in the Galaxy.

Subject headings: galaxies: clusters of — galaxies: individual — galaxies: stellar content — stars: Wolf-Rayet

I. INTRODUCTION

A comprehensive search for Wolf-Rayet (W-R) stars in galaxies is potentially important to learn more not only about the nature of W-R stars, their role in stellar evolution, and their relation to their environment, but also about the galaxies in which they lie. Because of their high luminosities ($M_v \approx -4$ for WC and WNE $\equiv$ WN2–6, to -7 for WNL $\equiv$ WN7–9, as single stars: Smith, 1973) and their broad and intense emission lines, most W-R stars can be easily discovered even at faint apparent magnitudes.

So far, we only have systematic information on the W-R content in (*a*) the Galaxy (159 known according to van der Hucht *et al.* 1981), (*b*) the Large Magellanic Cloud (100 known: Azzopardi and Breysacher 1980; Breysacher 1981), (*c*) the Small Magellanic Cloud (eight known, according to Azzopardi and Breysacher 1979), and (*d*) M33 (54 candidates, according to Wray and Corso 1972 and Corso 1975 of which 24 have spectroscopic confirmation: Wampler 1982; Boksenberg, Willis, and Searle 1977; with 14 additional stars from Conti and Massey 1981). Recent observations of the stellar content of some bright H II regions beyond the Local Group have also revealed the presence of W-R emission features in the spectrum (cf. D'Odorico and Rosa 1982*b*). Among the nearby spiral and irregular galaxies of the Local Group, only M31, NGC 6822, and IC 1613 remain to be systematically searched. Here, we concentrate on the first two, in our ongoing quest for W-R stars in progressively more distant galaxies. With $V - M_v \approx 24$–25, we need to reach an apparent limit $V \approx 21$–22 in order to detect all W-R stars of Population I except those suffering abnormally large extinction: This is expected to be a serious problem only in edge-on spirals as in our own Galaxy.

Specifically, one would like to detect and investigate W-R stars in external galaxies for the following reasons:

1. The total number of W-R stars in a galaxy can be expected to tell us something about the present efficiency of star formation at the massive end of the initial mass function, since W-R stars are believed to be a common but relatively short phase in the post–main-sequence evolution of massive O stars (cf. Conti 1976 and Garmany, Conti, and Chiosi 1982).

2. W-R stars are believed to be immediate precursors of Type II supernovae (cf. van den Heuvel and Heise 1972). Thus, with typical lifetimes of $\sim 2 \times 10^5$ yr (Vanbeveren and Packet 1979) for the W-R phase as massive He-burning stars (plus very short post–He-burning phases), there is a good chance that one W-R star from a total sample of 5000 will explode in the next 40 yr. If spiral and massive irregular galaxies each

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contain an average of ~100 W-R stars, it should be possible to find a few thousand W-R stars within the next few years, given the rapid development of efficient, low-noise, large panoramic detectors. If one can reach apparent continuum magnitude $B \approx 25$ (even less faint for strong-line objects), one should be able to detect most W-R stars in all ($\lesssim 30$: de Vaucouleurs 1978*b*) galaxies out to distance modulus ~29. Locating W-R stars now will increase our chances in the genetic tracing of some supernovae as they occur later.

3. By comparing the *number* of W-R stars with the number of red supergiants, one can test the result found by Maeder, Lequeux, and Azzopardi (1980) that the number ratio of red supergiants to W-R stars increases by two orders of magnitude in the Galaxy going from $R \approx 8$ to 12 kpc from the center. The corresponding ratio for the LMC corresponds to the outer regions of the Galaxy, while the SMC has an even larger ratio, in line with the decreasing trend in abundance of heavy elements in passing from the Galactic inner through outer disk, to the SMC.

4. With *spectral* information, one can expect statistically to be able to probe the metal content *within* as well as among spiral and irregular galaxies, where star formation is still proceeding. It has been known for some time that certain W-R subclasses tend to concentrate in different parts of the Galaxy (e.g., lack of WC9 at large R) and in the Magellanic Clouds (e.g., lack of WC6–9 stars entirely)—cf. Smith (1973)—probably as a result of variations in metallicity. Clues like this should aid in our understanding of why galaxies differ.

II. SEARCH METHOD

Basically there are two obvious approaches available to detect W-R stars in relatively large fields, by virtue of their generally intense emission lines. The more direct approach involves narrow-band imagery with an interference filter whose central wavelength coincides with the most intense emission feature in the easily accessible optical range. This occurs at $\lambda \approx 4670$ Å where strong lines of C III/C IV ≈ 4650 in WC, N III ≈ 4640 in WN, and He II 4685 in both, dominate. By blinking or numerical differencing techniques, such a narrow-band plate can be compared with either a narrow-band, off-line filter (cf. Wray and Corso 1972) or a wide-band filter centered on the same wavelength. The former method has the disadvantage of being sensitive to stars with extreme colors. The latter method is analogous to the photometric Hβ Balmer line (cf. Crawford and Mander 1966). In either case, W-R stars should appear brighter on the 4670 plate, except when the emission lines are too weak to make the on-line images appear significantly above the noise (0.1–0.2 mag on photographic plates). The image pairs must be taken in immediate succession, in order to diminish the probability of picking up variable stars, and to match the seeing (for ease in blinking).

The other approach involves low-dispersion objective spectroscopy, e.g. with a transmission grating prism (cf. Conti and Massey 1981). The main disadvantage here results from crowding of the necessarily elongated spectral images, especially in regions of high star density; from confusion by zero-order images; and from decreased signal-to-noise ratio on the integrated sky background compared to direct imagery. Spectral resolution at 1000 Å mm^{-1}, plate scale ~15″ mm^{-1} typical at the prime focus of large telescopes, and 1″ seeing would be ~70 Å. This is comparable to current narrow-band filter techniques. Nevertheless, objective spectra can provide additional information, and the two approaches can be considered complementary.

In this paper, we concentrate on the direct method, in which a narrow-band photographic plate centered at λ4670 Å is blinked with a wide band B plate (central wavelength ~4500 Å for IIa-O emulsion + Schott filter GG 385). Since the broad-band plate is not exactly centered at λ4670 (IIIa-J + GG 385 would be better but more time consuming, since one would have to match with the 4670 filter by using the relatively slow IIIa-J emulsion for it, too), very red stars ($B-V \gtrsim 1.5$) will appear up to ~0.3 mag brighter on the 4670 plate and must be eliminated by additional blinking of red-blue continuum plate pairs. Compared with the off-line narrow-band filter method, one gains significantly in observing time, because the required narrow-band filters are generally $\gtrsim 10$ times slower than the broad-band B filter.

In Figure 1 we show the transmission profile of our 4670 filter compared to the line profile of a WN star (see below). The central wavelength of the filter will shift ~7 Å for each 50° C change in ambient temperature; an f/4.2 converging beam (prime focus wide-field at CFHT) will be shifted by ~15 Å to the blue at its outer edge; and the relative radial velocities of Local Group galaxies will cause shifts up to ~5 Å. These are all relatively unimportant compared to the FWHM of 87 Å. Detection of quasars with strong emission shifted to λ4670 is not expected to influence our results.

We tested our method in the moderately rich fields of two galactic open clusters, each of which contains a well-known W-R star. They are NGC 6871, containing the WN 4.5 + O9.5 Ia star HD 190918, and Dolidze 7 containing the WC5 pec star ST 3 (cf. van der Hucht *et al.* 1981). The former is a weak-line W-R star of the nitrogen sequence, whose emission lines are considerably diluted by an unresolved, orbiting O type companion; the latter is a strong, broad-line W-R star of the carbon sequence with abnormally strong O VI lines at λλ3411, 3434 Å. Figure 2 shows a reproduction of direct photographs of Dol 7 in the 4670 and B bands taken on IIa-O emulsion with the f/8 camera of the 1.6 m telescope of the Mont Mégantic Observatory. Plates in V were also obtained in order to locate red stars. Similar photographs were secured for NGC 6871. Even

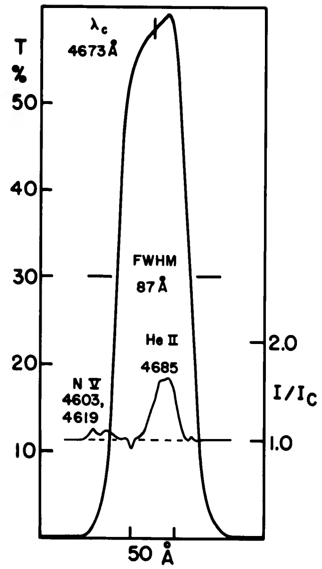

FIG. 1.—Transmission profile of our λ4670 filter (central wavelength 4673 Å at 23° C, FWHM 87 Å) compared to the line profile of the WN 4.5 + O9.5 Ia star HD 190918 from the atlas of Smith and Kuhi (1981). Manufactured by "Spectro-Film," the interference filter is 15 mm thick, with a clear aperture of 160 × 160 mm. Outside the intended bandpass, it is completely blocked from X-ray to IR wavelengths.

a casual inspection confirms the presence of the W-R star in Dol 7 which stands out relative to other cluster stars on the 4670 plate.

In Figure 3 we show the quantitative results for ST 3 in the form of iris reading differences, which correspond more directly than magnitudes with what one sees on the plates, versus magnitude. Clearly, ST 3 is well separated from normal stars, being ~ 0.8 mag ($\gtrsim 6\ \sigma$) brighter with the 4670 than the B filter. This is to be expected for a broad- and strong-line WC star with $W_e \approx 400$ Å (according to an anonymous referee) for the 4650 C III/C IV feature. The magnitude difference would be even greater if our narrow band filter was centered at λ4650.

The 4640–4686 emission feature of the WN binary HD 190918 is too weak ($W_e \approx 20$ Å: Smith and Kuhi 1981) to bring this star above the noise ($\sigma \approx \surd 2 \times 0.1$ mag per plate pair) in the 4670 filter. We conclude that we should detect a given W-R star only if its $W_e \gtrsim 50$ Å, corresponding to a 3σ excess of ~ 0.5 mag in the 4670 filter compared to non–emission-line stars. Since the only published quantitative determination suggests that the mean reddening in M31 is low ($\overline{A_v} \lesssim 1.1$: Beck and Gräve 1982, cf. § IVc), we do not expect to miss a large number of faint reddened W-R stars outside the bright central bulge.

III. OBSERVATIONS OF M31 AND NGC 6822

a) *Direct Photography*

We have photographed the Magellanic type irregular galaxy NGC 6822 at the f/9 Cassegrain focus (with the RGO electronographic camera) of the Wise Observatory telescope in 1979 May; at the f/8 Cassegrain focus of the Mégantic telescope in 1979 July; and at the f/4 prime focus of the Canada-France-Hawaii (CFH) telescope in 1980 September. With the 4670 filter, the electronographic camera at Wise Observatory reached

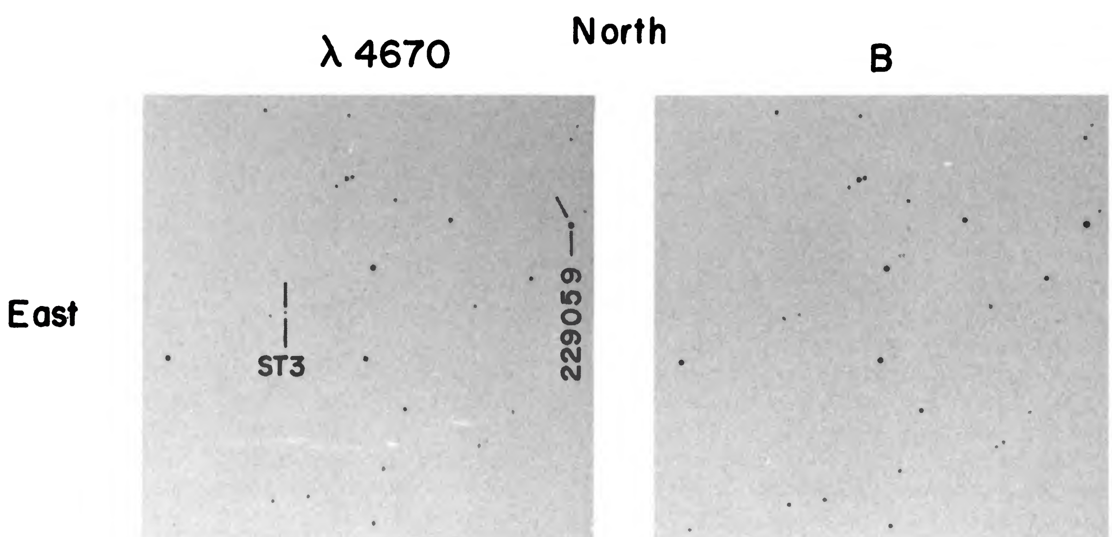

FIG. 2.—Reproductions of 4670 and B plates from Mont Mégantic Observatory of the open cluster Dol 7. The W-R star ST 3 ($B = 14.4$), 6′ from the early B supergiant HD 229059 ($B = 10.2$), is indicated. Both stars are heavily reddened with $B - V \approx 1.5$. The exposures were 50 minutes and 4 minutes, respectively, through partial clouds at 5″ seeing. A Pickering-Racine wedge produces secondary images with a 4 mag difference. The W-R star is close to the plate limit on the B plate, much like the W-R candidates in M31.

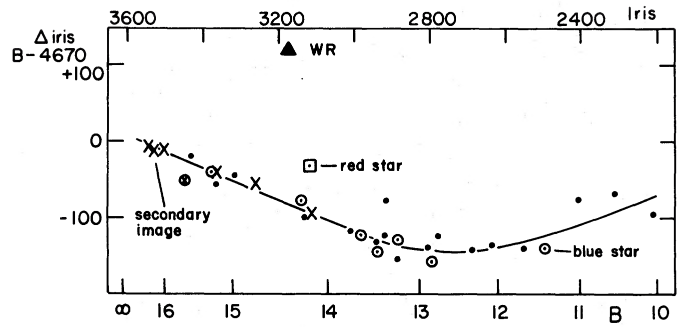

FIG. 3.—Difference in Cuffey iris reading vs. iris and vs. B magnitude for stars in the cluster Dol 7. Approximate magnitudes were obtained from photoelectrically measured stars within ~ 30′ around Dol 7 from the catalog of Blanco *et al.* (1968). Stars redder or bluer than the mean by ~ 0.5–1.0 mag in $B-V$ are indicated.

$B \approx 19$ in 2 hr in 2″ seeing. The Mégantic telescope can reach continuum mag $B \approx 19.5$ in 5 hr exposure on IIa-O direct in 2″–3″ seeing. The CFHT can reach $B \approx 21.5$ in 3 hr on IIa-O direct in 1″–2″ seeing. These limits are based on the visibility of the faintest photoelectric sequence stars on Kayser (1967) and would be even fainter for strong-line W-R stars. The fields for the three telescopes cover 20′, 43′, and 37′, respectively. This comfortably includes all of NGC 6822 in each case.

Blinking NGC 6822 revealed 19 candidates which were marginally brighter on the 4670 than the B plates. None was located in an H II region. However, after blinking B/V plate pairs, all of these appear to be red stars, although there are many blue stars which are not candidates. One might conclude that NGC 6822 has no W-R stars with $W_e \gtrsim 50$ Å down to $M_B \approx -3$, adopting an apparent distance modulus of 24.3 (van den Bergh and Humphreys 1979). However, this limit for W_e may be slightly too optimistic: Although no W-R stars were detected with $W_e < 50$ Å in M31, some non–W-R stars were "detected" because they stood out at λ4670 as much as some of the confirmed weaker line W-R stars (cf. § IV*b*). If these non–W-R stars are really *intrinsically* brighter on the 4670 plate for one reason or another, then the limit $W_e \approx 50$ Å would still apply. Otherwise, if due to the tail of a random error distribution, the limit of completeness for detection of WR stars would be raised to $W_e \approx 70$–100 Å. With low mean reddening for luminous stars in NGC 6822: $\bar{E}_{B-V} \approx 0.27$ according to Kayser (1967), it is unlikely that any of our candidates are heavily reddened W-R stars unless they are weak lined.

The giant Sb galaxy M31 was photographed using only the 3.6 m CFH telescope. Two 37′ fields have been studied so far, one centered on the nucleus, the other about 40′ SW of the nucleus along the major axis (cf. Fig. 4). The baked IIa-O plates were exposed 3 hr at λ4670 and 18 minutes in B. Since there are no available faint photoelectric standards in these fields, we assume that we reached the same limiting magnitude as in NGC 6822, i.e., $B \approx 21.5$ in the continuum. Observing conditions and techniques were identical for both galaxies.

From blinking the $4670/B$ plate pairs, we found ~ 200 candidate W-R stars in M31. We rated them from probability 1 (4670 much brighter than B) through 2 to 3 (marginal magnitude difference). Blinking B/V pairs led to the elimination of most of the numerous probability 3 stars as very red and thus probably non–W-R stars. We retained 21 candidates with a reasonable to excellent chance of being W-R stars (cf. Table 1). They are identified in Figures 4 and 5; the latter shows eight enlarged fields of the 4670 and B discovery plates.

In Figure 6 we show the degree to which the W-R candidates in M31 stand out in the 4670 filter. The magnitude scale is approximate since there are no faint standards in M31. We extrapolate linearly from the faintest standard; hence, the magnitudes are lower limits. We note that stars 4, 10, and 17 are in crowded regions and appear to stand out least in Figure 6, much like the non–W-R candidates (cf. next subsection for spectra). Among the other W-R candidates, the WN stars stand out less than the early WC stars but much like the narrow-line cooler WC subclasses. The $O-C$ scatter among the test stars (dots in Fig. 6) is ~ 0.14 mag at $B \sim 19$. Thus, our ability to detect W-R stars at this magnitude is as predicted in § II. Gradual deterioration sets in at fainter magnitudes.

One might suspect possible confusion with planetary nebulae (PN) whose nuclei show He II emission, or that emit nebular lines falling in the 4670 Å filter. However, none of the 95 PN found in the deep, off-center field of M31 surveyed by Ford and Jacoby (1978) was detected on our 4670/B plate pair, although we found two good W-R candidates in the same field they surveyed. Spectra obtained later confirm this.

b) *Spectrophotometry*

During three clear but generally nonphotometric nights in 1981 August and October we obtained intensi-

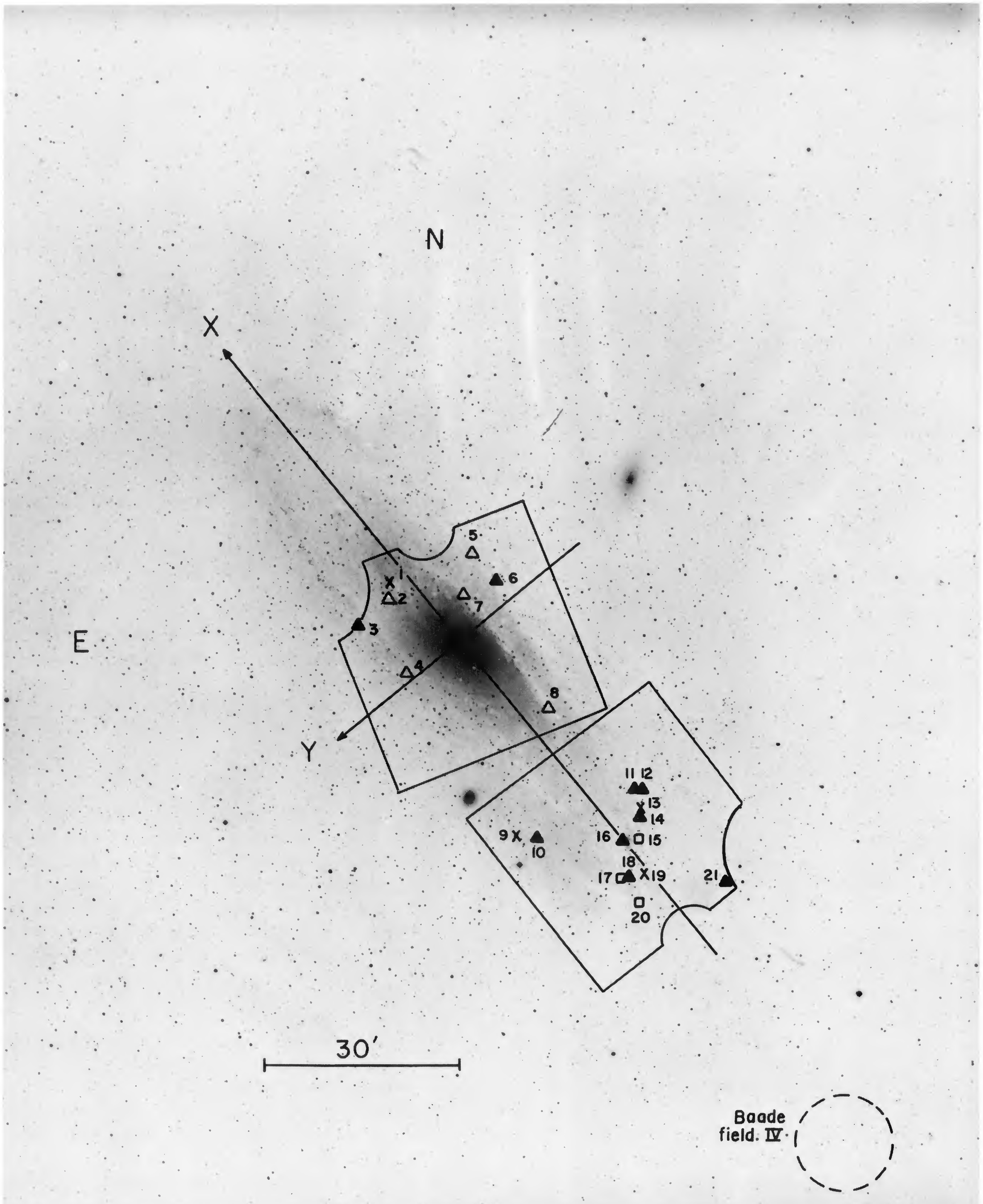

FIG. 4.—Overview chart (Schmidt *B* plate) of M31 showing the fields in which W-R stars were searched. Baade's field IV, 96′ from the nucleus, is shown for comparison. The irregular profile of the field edge is caused by filter defects. *X*, *Y* axes in the same sense that Baade and Arp (1964) used to locate H II regions in M31 are indicated. The axes are aligned with those of Sargent *et al.* (1977) in their study of globular clusters in M31. Key: □ WN6–7, △ WC7–9, ▲ WC4–6, X, non-W-R.

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TABLE 1

Wolf-Rayet Candidates in Two M31 Fields

No.	α^a 1950.0	δ^a 1950.0	B mag.	Rating[b]	Sp	λ ∿ 4670 emission FWHM Å	peak/cont. height	OB-assoc.	HII BA	HII AB	X kpc	Y/sin 12°3 kpc	R kpc	Remarks
1	$00^h\ 40^m\ 58.9^s$	+41° 09' 29"	>19.7	2	(non-WR)	-	-	2	-	-	(+ 2.6	+ 2.5	3.6)	1
2	40 57.2	41 06 38	>20.0	1	WC8+neb.	38	10	2	39	-	+ 2.2	+ 3.9	4.5	
3	41 21.9	41 02 56	>20.1	1-2	WC5-6	55	13	36:	35,36:	32:	+ 2.2	+ 9.2	9.5	2
4	40 46.6	40 55 38	>19.6	2	WC8.5+wk.neb.	32	1.6	-	6	38:	+ 0.2	+ 8.4	8.4	5
5	39 50.1	41 13 57	≳19.2	2	WC8	35	4.7	61	524:	-	+ 1.8	- 9.2	9.4	
6	39 30.2	41 09 14	≲20.0	1	WC6+wk.neb.?	57	30	63	510:	-	+ 0.7	- 9.2	9.2	
7	39 57.7	41 06 47	>20.1	1	WC8	39	35	-	511:	-	+ 1.0	- 4.6	4.7	
8	38 50.9	40 49 26	>19.7	1-2	WC7	56	12	19	-	-	- 3.2	- 3.5	4.7	
9	39 15.6	40 29 29	≳19.4	2-3	(non-WR)	-	-	84	-	-	(- 5.6	+10.6	12.0)	
10	39 00.5	40 28 50	≲18.6:	1	WC5-6+neb.	82	1.8:	76	293	44	- 6.1	+ 8.8	10.7	3, 8
11	37 39.0	40 36 06	≳19.2	1	WC5-6	82	3.2	132	457	59	- 6.7	- 6.0	9.0	
12	37 36.0	40 35 57	≲19.7	1	WC4-5+neb.!	96	7	132	458	59	- 6.8	- 6.7	9.5	
13	37 37.1	40 33 07	>20.1	1-2	(non-WR)	-	-	72	-	-	(- 7.2	- 5.3	8.9)	2, 3, 4
14	37 37.0	40 31 40	>19.5	1	WC5-6+wk.neb.?	69	40	72:	-	-	- 7.4	- 4.2	8.5	
15	37 39.6	40 28 26	>20.1	2-3	WN6-7	27	4.0	78	-	-	- 7.9	- 2.5	8.3	2, 7
16	37 51.2	40 28 05	>20.0	1	WC5-6	69	>50:	78	-	-	- 7.6	- 0.4	7.6	7
17	37 48.2	40 22 42	≳19.2	2-3	WN6-7+wk.neb.	33	1.8	✓	318:	-	- 8.5	+ 2.8	8.9	2, 3, 6
18	37 45.8	40 22 50	>20.2	1	WC5-6+wk.neb.	64	4.5	✓	-	-	- 8.6	+ 2.1	8.9	6
19	37 33.5	40 23 03	≳19.3	2	(non-WR)	-	-	99	-	-	(- 8.8	0.0	8.8)	2, 3
20	37 37.7	40 18 53	>19.8	1-2	WN6	31	10	80	-	-	- 9.4	+ 3.2	9.9	
21	36 27.9	41 21 48	>19.7	2	WC5-6	57	15	127	-	-	-10.4	- 7.7	12.9	

[a]Accurate to ± 1″–2″, not allowing for proper motion, since positions were measured for 1980.7 using galactic reference stars.

[b]Subjective probability of a real intrinsic magnitude difference on plates (1 = high, 3 = low).

Remarks.—(1) Recognized as possible red star before spectrum taken. (2) Recognized as possible (but unlikely) red star before spectrum taken. (3) Crowded. (4) Includes one red star in a crowded area. (5) Core of dense cluster? (6) Unnamed association between stars 79 and 80. (7) OB 78 = NGC 206, a rich association. (8) Spectrum has poor sky subtraction.

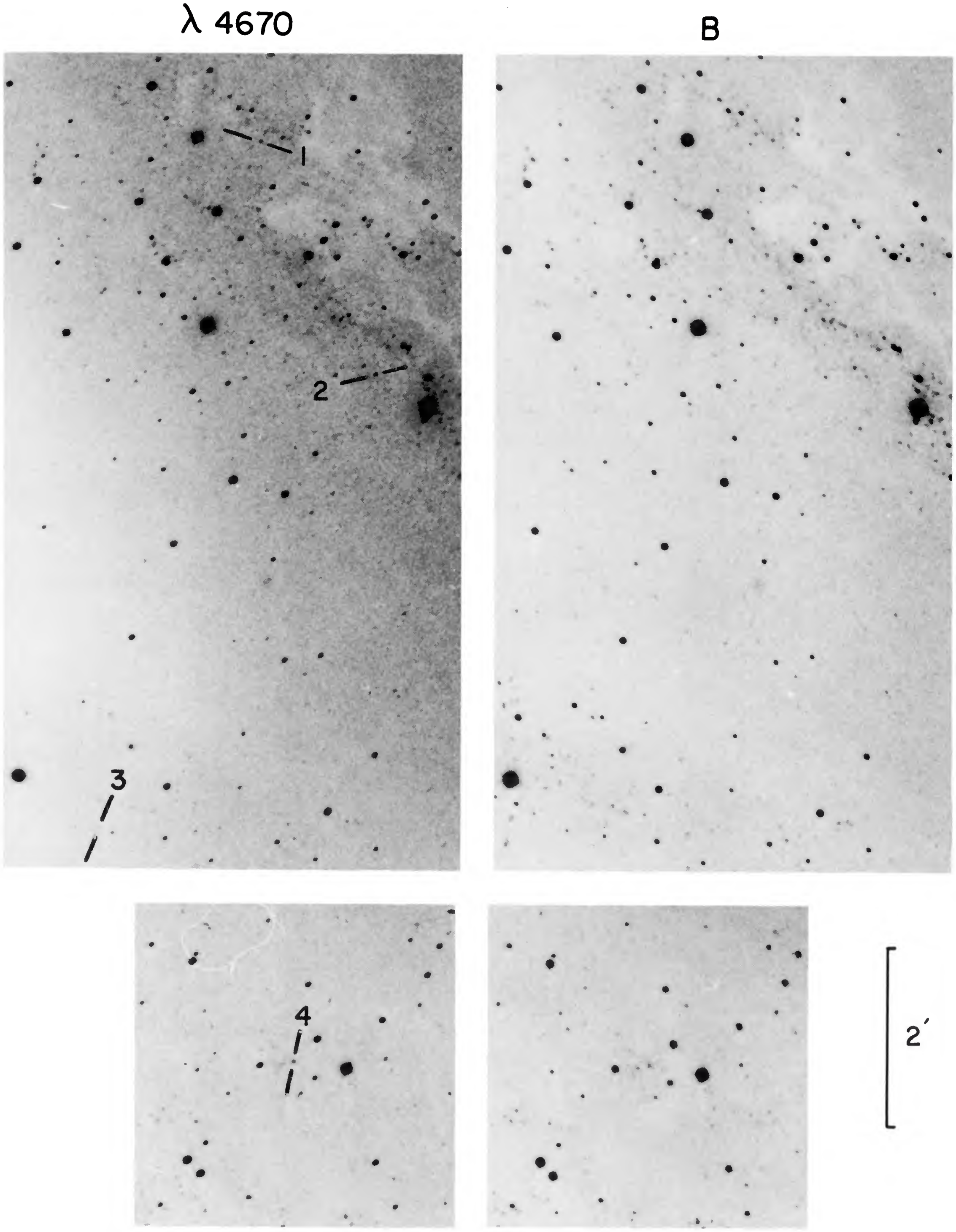

FIG. 5a

FIG. 5.—Identification charts for the 21 best W-R candidates in M31

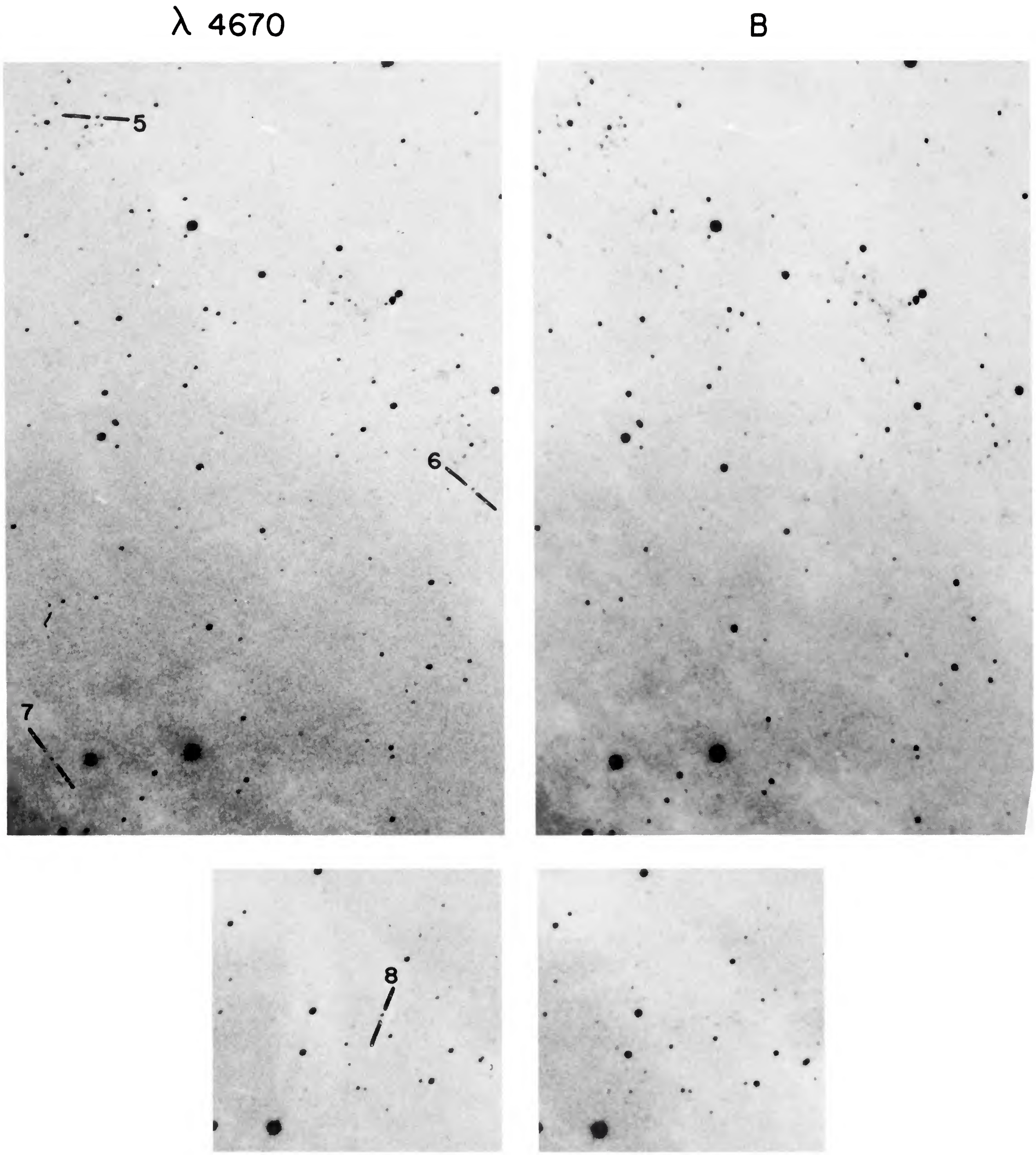

FIG. 5*b*

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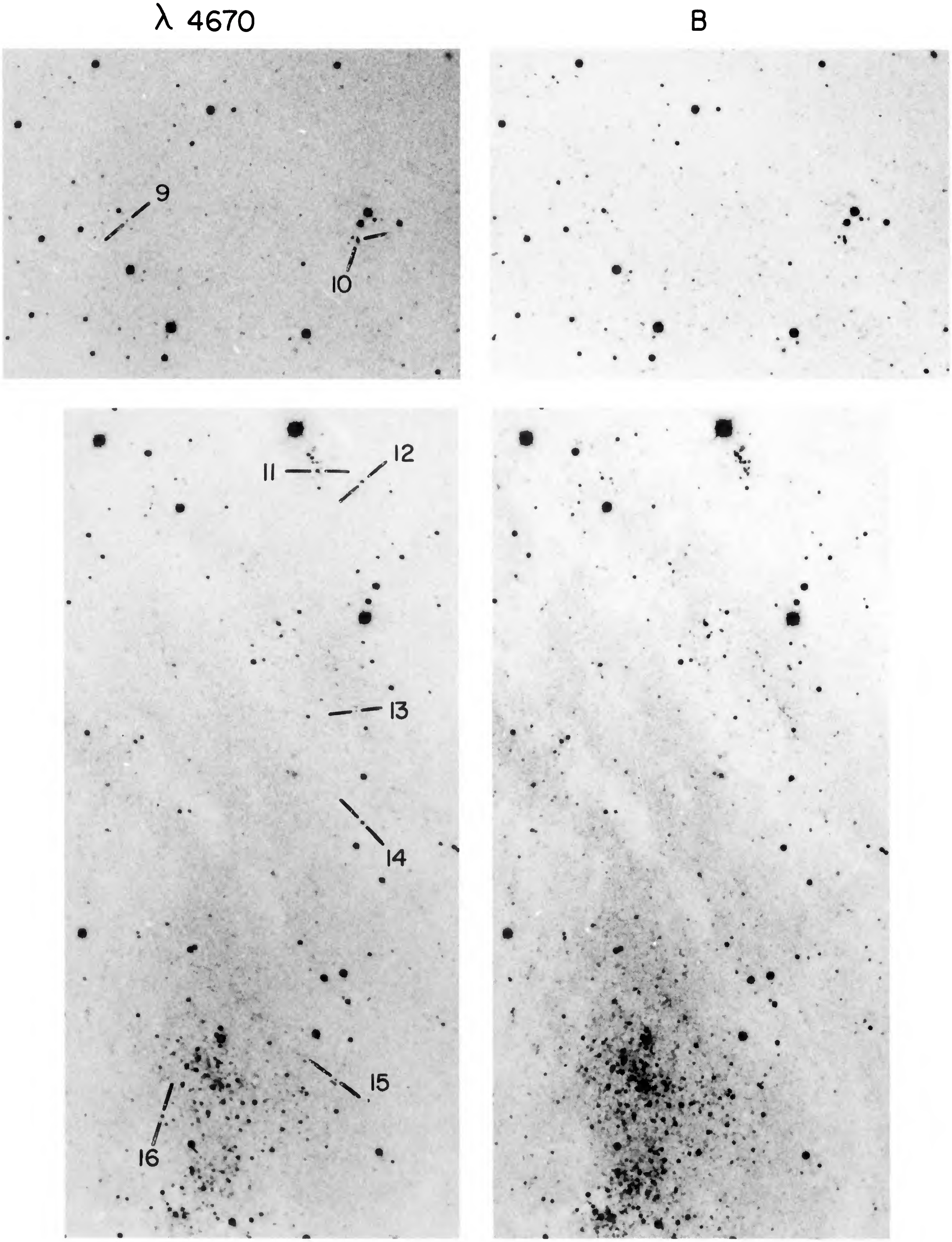

FIG. 5c

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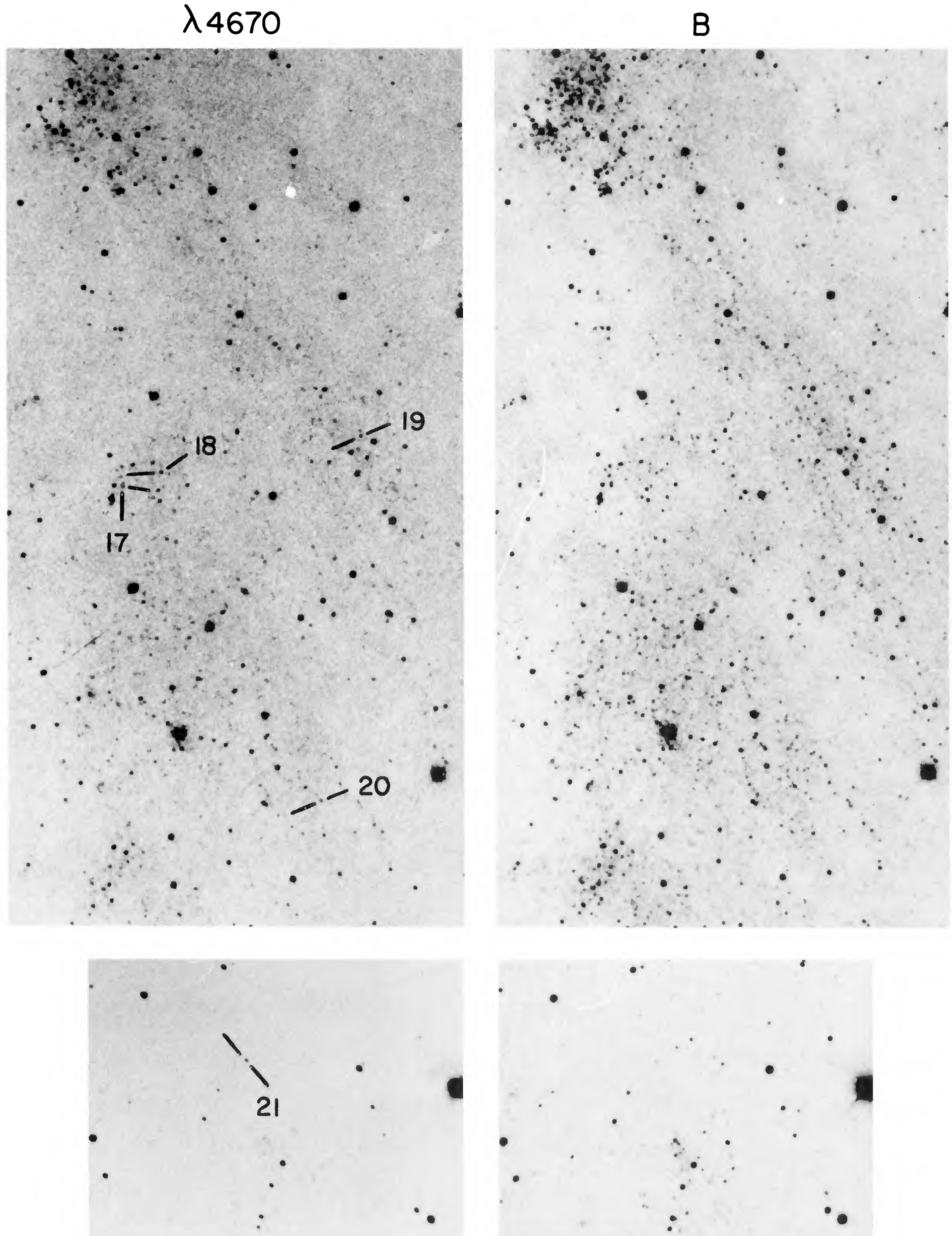

FIG. 5*d*

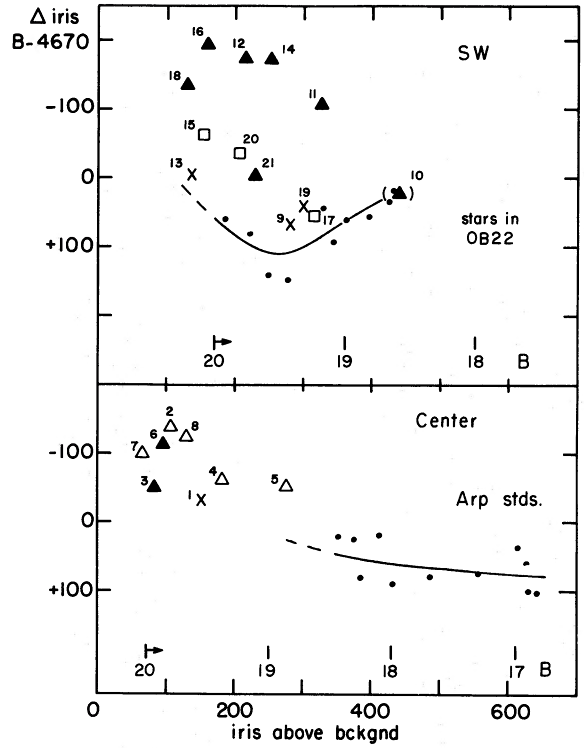

FIG. 6.—Difference in iris above the mean background around each star vs. iris in the two M31 fields. Approximate magnitudes were obtained from the photoelectric sequences of Arp (1956): These reach $B \approx 18.6$ in the central field and $B \approx 17.8$ in the SW field. W-R candidates are seen to stand out by up to ~ 1.5 mag from non–W-R (*points*) in either field. The standard deviation of the latter stars about a curved line as in Fig. 3 is ~ 0.14 mag. Symbols are as in Fig. 4 with the addition of the points which refer to probable non–W-R stars.

fied Reticon spectra in the range λλ3800–6800 Å for each of the 21 best candidates in M31 and one (rating 2–3) in NGC 6822, using the Multiple-Mirror Telescope on Mount Hopkins, Arizona. With the 300 l mm^{-1} grating, the instrumental profile has a FWHM of ~ 8 Å. We observed each star along with the sky alternating between twin diaphragms of size $\sim 2'' \times 2''$ and separated by $\sim 30''$. This was carried out long enough (usually 10–30 minutes per star) to show whether the spectrum is W-R or not; if so, then long enough to estimate the W-R spectral subclass. After dividing out the flat field source, normalizing to relative flux from observations of spectrophotometric standards, and convolving with the standard MMT Gaussian smoothing filter, we show the spectra in Figures 7 (WN), 8 (WC) and 9 (non–W-R).

Spectral subclasses based on the scheme of Smith (1968) and van der Hucht *et al.* (1981) are given in Table 1 for the W-R stars in M31: 17 stars are confirmed W-R, mostly WC, while the remaining four stars (+1 in NGC 6822) appear to be non–W-R. Among the latter, we draw attention to the possible detection of two (Galactic halo?) carbon stars: in M31, 19 and in NGC 6822, C9 (the latter number is from Kayser 1967), on the basis of the spectral atlas of cool stars by Keenan and McNeil (1976). In particular, we note the presence of the C_2 Swan band heads at λ5165 Å and 5635 Å, but absence of TiO at 6158 Å especially in M31, 19. The other three non–W-R spectra are noisy and difficult to classify. Object 9 is a relatively blue object with possible excess emission at ~ 4600 Å from an unknown source. In general it is not obvious why these five stars were brighter in the 4670 filter; a combination of effects may have contributed: very red continuum (although such stars should already have been eliminated), line-depressed continuum to either side of 4670 Å, and/or fortuitously large random magnitude difference or variability.

It is becoming apparent that some massive H II regions harbor a significant fraction of W-R stars among a population of massive stars (Conti and Massey 1981 in

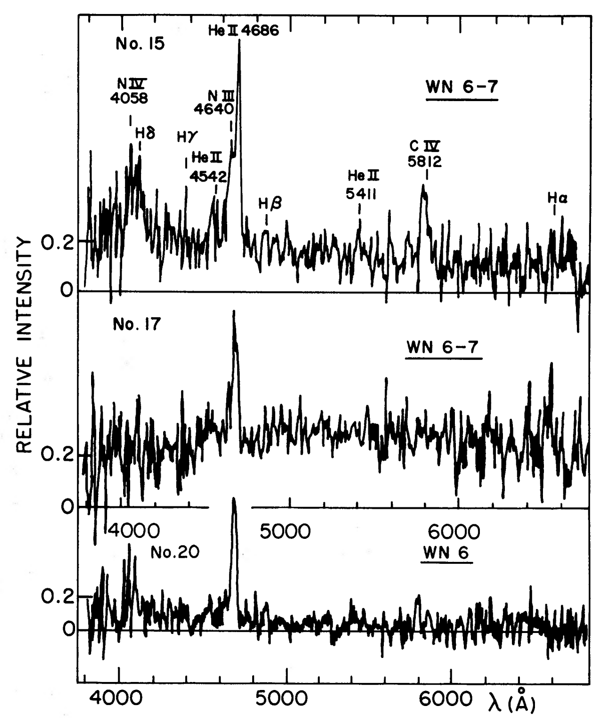

FIG. 7.—Reduced, intensified Reticon spectra of the three confirmed WN stars in M31. As in Figs. 8–11, we note that the night sky emissions of [O I] at λ5577 Å and 6300 Å did not always subtract out well, despite the symmetric mode of observation (star/sky channels switched every 5 minutes). Identification of the most prominent lines is given on the top spectrum. Since conditions were generally not photometric, we give only relative flux, although an approximate scale factor is 10^{-16} ergs s^{-1} cm^{-2} $Å^{-1}$ except for the spectra from August (indicated by an asterisk on the ordinate) for which the factor is 10^{-10} ergs s^{-1} cm^{-2} $Å^{-1}$; the difference arises from an unknown hardware glitch. Note that stars 18, 20, and 21 have slightly different wavelength scales.

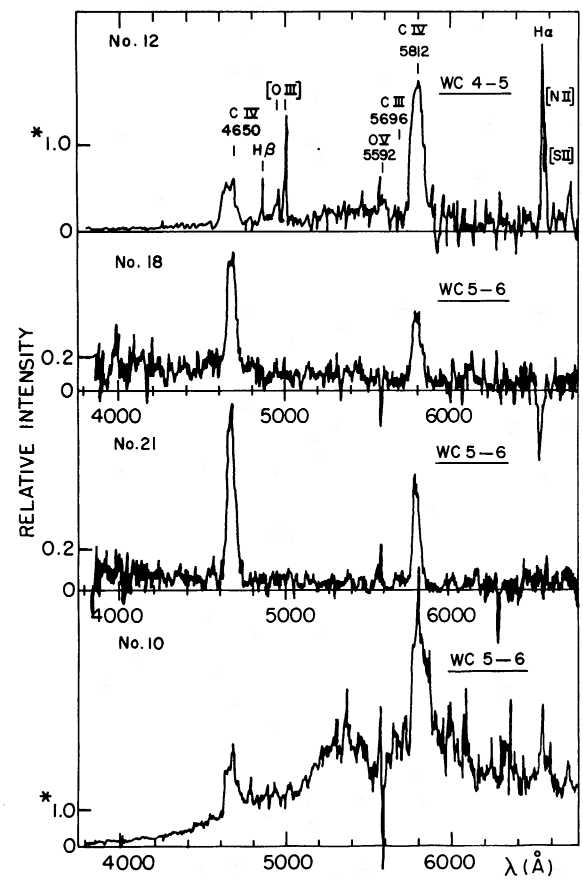

FIG. 8*a*

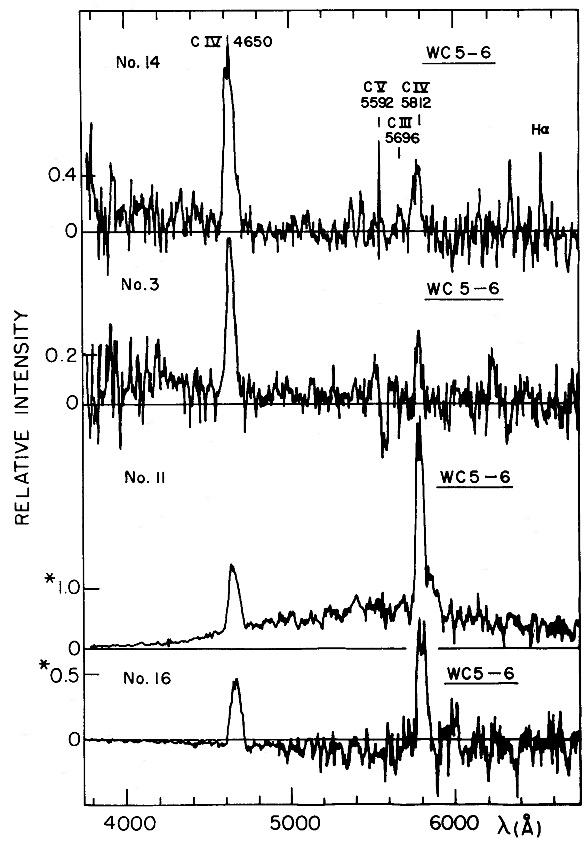

FIG. 8*b*

FIG. 8.—As in Fig. 7 but for the 14 WC stars found in M31. The spectra are sorted from hot to cool subclasses based mainly on the intensity ratio of C IV 5812 : C III 5696.

M33, and D'Odorico and Rosa 1982*b* in general). Possibly even a supermassive central object with a W-R-like spectrum as claimed to be the case for the core (R136) of 30 Dor in the LMC (Feitzinger *et al.* 1980; Cassinelli, Mathis, and Savage 1981; however, see Moffat and Seggewiss 1983) may be present. Therefore, we decided to check this in some of the exciting stars in the more prominent H II regions in M31 and NGC 6822. The spectra so obtained are presented in Figures 10 and 11, respectively. In these spectra, there is no hint of stellar 4686 or 4650 emission, indicating that these two galaxies probably do not possess H II regions which are sufficiently massive (cf. Spencer and Burke 1974) to lead to the formation of massive progenitors of W-R stars. Other published spectra of H II regions in M31 lead to the same conclusion (e.g. Blair, Kirshner, and Chevalier 1982).

IV. DISCUSSION

a) *Absolute Magnitudes*

Most of the W-R stars detected in M31 lie within a relatively tight range of magnitude ($19.2 \lesssim B \lesssim 21.5$). Adopting the true distance modulus 24.1 from de Vaucouleurs (1978*a*), mean optical extinction $\bar{A}_v \lesssim 1.1$ obtained directly from Population I objects and independently deduced from radio data (cf. Beck and Gräve 1982)—corresponding to $A_B \lesssim 1.5$—we find $-4.1 \gtrsim \bar{M}_B \gtrsim -6.4$ or $-3.7 \gtrsim \bar{M}_v \gtrsim -6.1$. (see discussion in § IV*b* concerning heavily obscured W-R stars). This is compatible with similar stars in the Galaxy and the LMC (Smith 1973; van der Hucht *et al.* 1981) for which M_v ranges from -3.9 to -5:

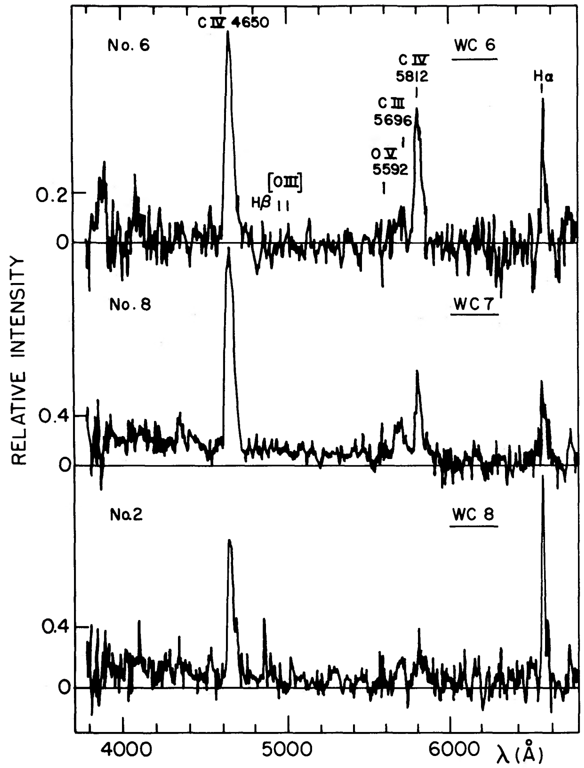

FIG. 8*c*

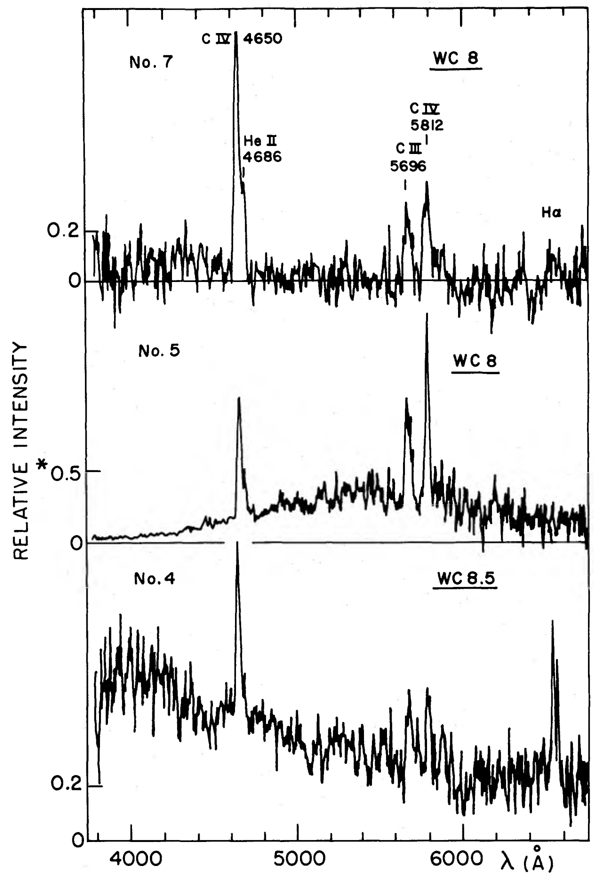

FIG. 8*d*

b) *Completeness*

In Table 1 we list the separations in kiloparsecs of the W-R stars from the center of M31 along the major axis (X) and minor axis (Y), allowing for a tilt of 12°.3 (cf. Hodge and Kennicutt 1982). A distance for M31 of 650 kpc was assumed (de Vaucouleurs 1978*a*). Along the minor axis our survey plates extend out to a true distance of ~ 14.5 kpc, although the most distant W-R star is found 9.2 kpc along this axis. We therefore deduce that there are very few if any (moderate- or strong-line) W-R stars beyond $R \sim 10$ kpc. Though our survey only reached ~ 11 kpc on the *major* axis (SW), we probably missed very few W-R stars by failing to extend the search further out along this axis. We conclude that we have searched ~ two-thirds of the area in M31 in which W-R stars can be expected to occur with only the NE section of the main body left to be surveyed.[5]

[5]This area as well as Baade's field IV ($Y = 0$, $X = -18.5$ kpc) are being studied presently using image-tube plates from CFHT.

It could be argued that we are failing to detect many W-R stars in M31 because of its low inclination and claimed high obscuration (cf. Humphreys 1979). The direct observation of Population I Cepheids and H II regions (cf. Beck and Gräve 1982) yields a mean optical extinction $A_v \lesssim 1.1$ mag, which is not adequate to hide a significant number of W-R stars. The red continua of stars 5, 10, and 11 appear at first to show signs of high reddening. However, in the case of stars 10 and 11, this could be the result of crowding by intrinsically red stars; star 5 appears isolated and may indeed be reddened more than average. In any case, these stars are all among the brightest found, making it unlikely that they are seriously affected by interstellar extinction.

How does the detected number of W-R stars compare with the number of OB stars in M31? We estimate the number ratio of W-R to luminous stars in the prominent spiral arms of M31 to be ~ 1 : 100 on the basis of star counts. Within the Galaxy, one of the 54 stars in the catalog of luminous stars ($M_v \lesssim -3$) in the Southern Milky Way (Stephenson and Sanduleak 1971) is W-R.

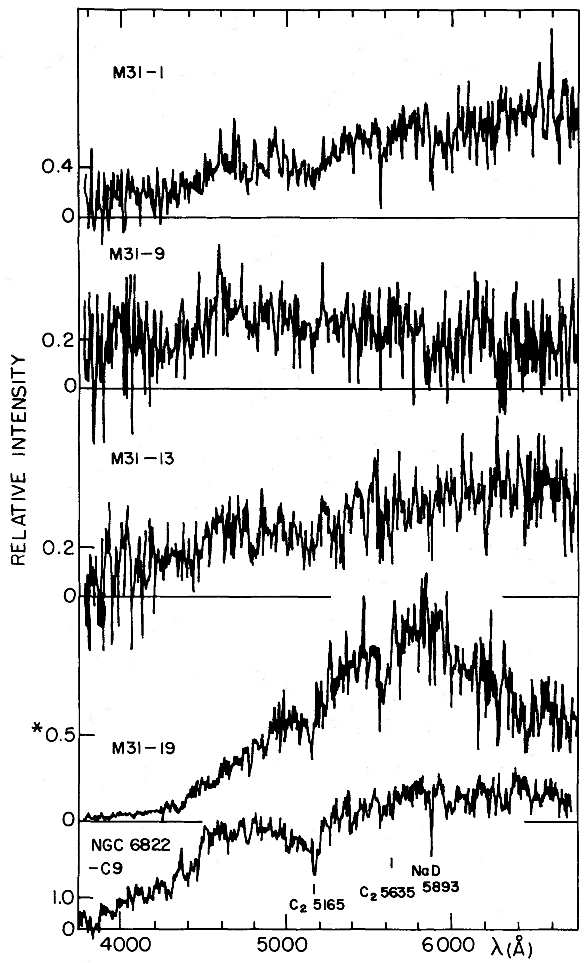

FIG. 9

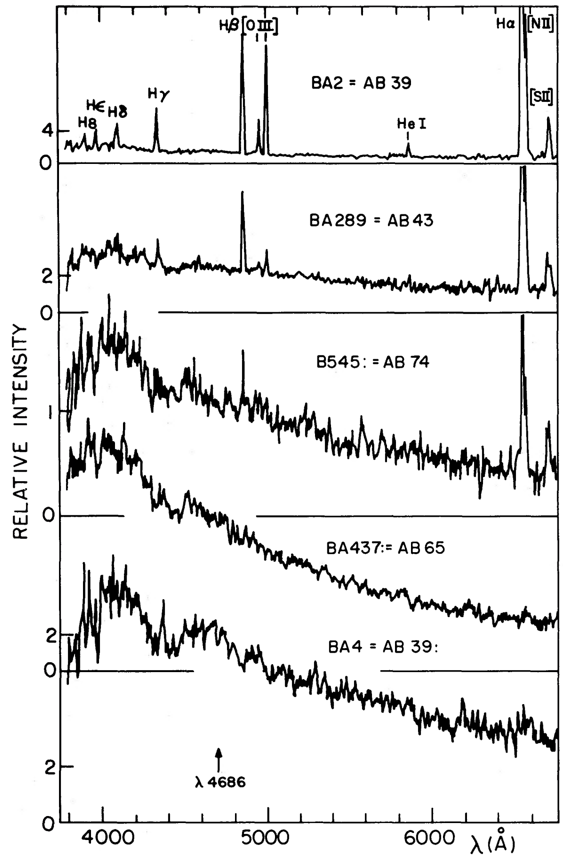

FIG. 10

FIG. 9.—As in Fig. 7 but for the five non–W-R stars (four in M31, one in NGC 6822). The last two may be carbon stars.

FIG. 10.—As in Fig. 7 but for the five brightest knots or stars in five prominent H II regions of M31. BA and AB numbers are from Baade and Arp (1964) and Arp and Brueckel (1973), respectively.

The observed ratios of W-R to OB stars are similar in both galaxies. This suggests that the initial mass functions in M31 and the Galaxy are rather similar, in agreement with the conclusions of Lequeux (1979) (see, however, Garmany, Conti, and Chiosi 1982).

How does our inability to detect weak-line W-R stars affect the numbers observed? To approach this question, we show in Figure 12 a plot of the FWHM of the 4650 Å C III/C IV feature versus subclass for the WC stars in M31. The general trend in M31 follows that for galactic WC stars (Smith 1968); however, the cooler (WC7–9) galactic stars appear to have narrower lines on the average than corresponding stars detected so far in M31. One could argue that this is due to selection, since we have probably not detected any narrow line stars with $W_e \lesssim 50$ Å in M31. These are more likely to be the WC7–9 stars, whose emission lines tend to have lower equivalent widths on the average, as indicated by the product of line-height and line-width in Table 1. For the broader, generally stronger line WC4–6 stars with typically $W_e \gg 50$ Å we can be reasonably confident that our survey is complete in the area studied. Therefore, in comparison to the Galaxy we have the number ratio:

$$\left(\frac{N_{\rm M31}}{N_{\rm Gal}}\right)_{\rm WC4-6} \approx \frac{9\times3/2}{34\times4.5} = 0.09 .$$

Here we have taken the number of galactic stars from van der Hucht *et al.* (1981) and an approximate completeness factor 4.5 based on the overall galactic distribution given by Hidayat, Supelli, and van der Hucht (1982). For the cooler WC subclasses:

$$\left(\frac{N_{\rm M31}}{N_{\rm Gal}}\right)_{\rm WC7-9} \approx \frac{5\times3/2}{36\times4.5} = 0.05 .$$

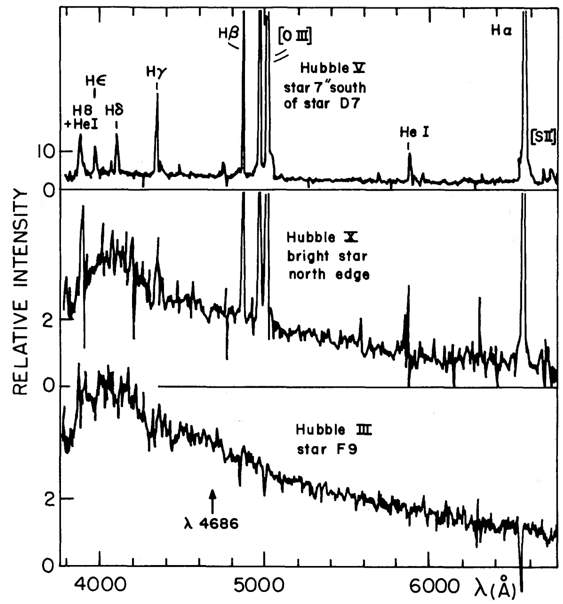

FIG. 11.—As in Fig. 7 but for the brightest stars (knots?) in each of the three brightest H II regions (Hubble 1925) in NGC 6822. Stars F9 and D7 are from Kayser (1967).

Not surprisingly, this ratio is lower than for the hotter WC stars, but only by a factor $\lesssim 2$. If M31 and the Galaxy do not *drastically* differ in their relative numbers of various WC subclasses, the present survey of WC stars in M31 would be $\gtrsim 75\%$ complete in the two-thirds of the surface of the main body surveyed. If the WN stars in M31 have W_e's similar to Galactic WNs, they will be less complete than the WC7–9 stars. We can be fairly confident that NGC 6822 contains no WC stars and at least no strong-line WN stars at the present limit of detection.

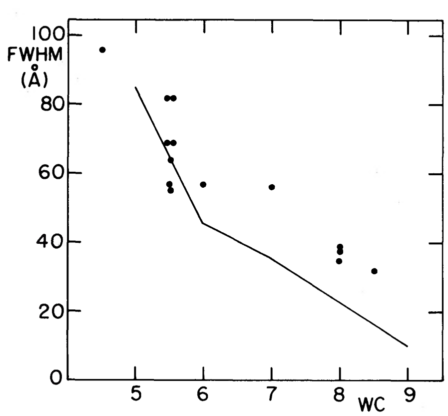

FIG. 12.—Line width (FWHM) vs. spectral subclass for the 14 WC stars in M31 (*points*) compared to the mean for galactic WC stars (Smith 1968).

c) Total Number of W-R Stars among Local Group Spirals and Irregulars

How do the observed total numbers of W-R stars in the Local Group spirals and irregulars compare with the numbers expected on the basis of counts of massive stars in general? Lequeux (1979) has compared the rates of formation of massive stars ($M \gtrsim 10\ M_\odot$) in these galaxies. From Lequeux's estimate of the ratio of the number of massive stars to neutral hydrogen mass ($N_\star/M_{\rm H}$) and $M_{\rm H}/M_{\rm tot}$, we can find $N_\star$. With the assumption that the number of W-R stars is proportional to $N_\star$ (as discussed above); that the total number of W-R stars in the Galaxy is ~ 720 (van den Heuvel 1976); and that $M_{\rm H}$ for the Galaxy is $\sim 10^{10}\ M_\odot$, we derive the expected number of W-R stars in each of the seven Local Group spirals and irregulars. They are listed in Table 2 for each galaxy in order of decreasing degree of evolution according to Lequeux (1979). To within about a factor of 2, both columns agree rather well. The largest discrepancy occurs for the LMC, where the giant emission nebula, 30 Doradus, appears to be exceptionally active in forming very massive stars (the progenitors of W-R stars) and perhaps inducing massive star formation in other parts of the LMC as well (cf. Feitzinger 1980).

Although M31 is 2–3 times as massive as the Galaxy (Faber and Gallagher 1979), the present rate of star formation, as reflected in the number of moderate- and strong-line W-R stars, appears to be lower in M31 by about an order of magnitude. This reinforces similar conclusions based on the number of OB associations (van den Bergh 1964) and counts of luminous (i.e., massive) stars (Lequeux 1979).

d) Correlation with Clusters, Associations, and H II *Regions*

No W-R emission features were found in the most prominent H II regions in M31 (cf. Figs. 10 and 11). On the other hand, the spectra of about half the W-R stars discovered in M31 show nebular lines (cf. Table 1). There is no obvious preference for the nitrogen or the carbon sequence (the number of stars with nebular lines to the total is seven of 14 for WC, one of three for WN). From Table 1, we also see that all but two (both are late WC) of the 17 W-R stars lie in the direction of OB associations from the catalog of van den Bergh (1964). Their assumed membership implies ages of $\sim 20 \times 10^6$ years, although sequential star formation would permit considerable spread (Elmegreen and Lada 1977). Such ages are compatible with W-R stars being young but evolved massive stars.

Also in Table 1, the relative height of the 4640–4686 emission feature above the continuum is less than 2 for W-R stars which are located in crowded regions or in dense clusters (stars 4, 10, 17: two WC, one WN). Pre-

TABLE 2

COMPARISON OF THE TOTAL NUMBER OF W-R STARS PREDICTED AND OBSERVED IN LOCAL GROUP SPIRALS AND IRREGULARS

Galaxy	Type[a]	Predicted	Observed	References
M31	Sb I–II	< 43	$\gtrsim 1.5\times17\approx26$	1
Galaxy	Sbc	(720)	159×4.5:	2,3
M33	Sc II–III	36	68	4,5,6
NGC 6822 ...	Ir IV–V	2	0	1
LMC	Ir III–IV	14	100	7,8
IC 1613.......	Ir V	0.4	1	9
SMC	Ir IV/IV–V	4	8	10

[a] van den Bergh 1979.

REFERENCES.—(1) Present work. (2) van den Heuvel 1976. (3) van der Hucht *et al.* 1981. (4) Wray and Corso 1972. (5) Corso 1975. (6) Conti and Massey 1981. (7) Azzopardi and Breysacher 1980. (8) Breysacher 1981. (9) D'Odorico and Rosa 1982*a*. (10) Azzopardi and Breysacher 1979.

sumably, the emission in these cases is suppressed by increased continuum contamination from other stars falling in the 2″ slit. For all other W-R stars in M31, the emission-to-continuum ratio is greater than 3, and there is no obvious association with dense clusters. Some of these stars have remarkably strong emission, with ratios ranging up to ~ 50; in some cases this may be the result of poor sky subtraction. Nothing can be inferred from the present spectra about possible duplicity of W-R stars in M31.

e) *Metallicity*

The number ratio of W-R stars to red supergiants and hence metallicity (cf. Maeder, Lequeux, and Azzopardi 1980) cannot yet be estimated for M31 due to the lack of a red survey. Only the stellar content of the outlying Baade field IV has been studied in any detail so far (Humphreys 1980).

The possibility that the metallicity in M31 is *higher* than that in the Galaxy is supported by several independent lines of evidence:

1. The stellar content in Baade's field IV at $R \sim 18.5$ kpc (Humphreys 1979) matches well our own Galaxy at $R = R_\odot = 9$ kpc. Therefore, since metallicity increases toward the center of M31 (Blair, Kirshner, and Chevalier 1982), Z can easily be larger at $R \approx 9$ kpc in M31 than at the same galactocentric distance in the Galaxy.

2. Blair, Kirshner, and Chevalier (1982) find the abundance ratio [O/H] to be higher in M31 than in our Galaxy at the same distance $R \approx 9$ kpc, by a factor $\gtrsim 2$. This effect is somewhat offset by [N/H] which is in fact slightly lower in M31.

3. Van den Bergh (1979) notes that the mean metallicity of a galaxy is approximately proportional to the square root of its total mass. Since $M_{\rm M31}/M_{\rm Gal} \approx 2$–3 (Faber and Gallagher 1979) and $Z_{\rm Gal}$ ($R = 9$ kpc) ≈ 0.03, one would predict $Z_{\rm M31}$ ($R = 9$ kpc) ≈ 0.04–0.05 on this basis.

We conclude that the value of Z in M31 is 50%–100% larger than Z in the Galaxy at the same intermediate galactocentric distance.

In Figure 13, we show the metallicity Z (from Peimbert and Torres-Peimbert 1974, 1976 for the solar vicinity of the Galaxy and for the Magellanic Clouds) as a function of the WC/WN number ratio (1:7 for the SMC—Azzopardi and Breysacher 1979; 18:80 = 0.22 for the LMC—Breysacher 1981; 1.60 for the solar neighborhood based on surface *density*—Firmani 1982). By extrapolation, we predict a WC/WN number ratio of ~ 3 at $R \sim 9$ kpc in M31. For the same approximate range in galactocentric distance in M31 as in the Galaxy, i.e., $R \approx 7$–11 kpc, the observed WC/WN ratio for M31 is 10:3. If our present estimates of the numbers of WC and WN stars are affected by nondetection of weak-line (mainly WN stars), it appears to be in such a way that the observed number ratio WC/WN is fairly close to the expected value (cf. Fig. 13).

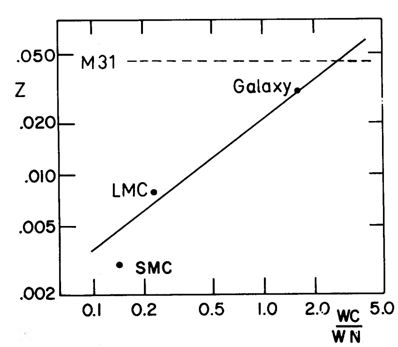

FIG. 13.—Logarithmic plot of metallicity vs. the number ratio of WC to WN stars in the three Local Group galaxies surveyed previously. A straight line is forced through the three points, giving low weight to the SMC which contains $\gtrsim 10$ times fewer W-R stars than the LMC. The Z-values for M31 and the Galaxy refer to a distance of ~ 9 kpc from their centers.

In NGC 6822, we can only say that the lack of moderate- to strong-line WR stars compared to a large proportion of luminous red stars (Kayser 1967; Humphreys 1980) is compatible with low metallicity, as found in the outer regions of the Galaxy and in the Magellanic Clouds (Maeder, Lequeux, and Azzopardi 1980).

f) Overall Distribution in M31

In Figure 14, we show how the number of W-R stars varies with galactocentric distance in M31. As noted earlier, except for the nondetection of some weak-line W-R stars, our search is probably two-thirds complete *in area* out to $R \approx 14.5$ kpc, increasing inward to 100% at $R \approx 4$. Within $R \sim 3$ kpc, the bright bulge of M31 will progressively hinder detection of W-R stars, although the surface area is low there compared to the outer regions. Hence, the clear peak in the numbers (and number density) of all W-R subclasses at $R \approx 8$–10 kpc is coincident with the ring of active star formation at $R \approx 7$–12 kpc, indicated by continuous radio emission, neutral hydrogen, ionized hydrogen, OB associations, open star clusters, UV emission, and X-ray sources (cf. Beck and Gräve 1982). This ringlike structure is reminiscent of that in our own Galaxy (Gordon and Burton 1976).

Figure 14 also demonstrates that cooler WC7–9 stars tend to be located nearer to the center of M31 ($\bar{R} \approx 6.3 \pm 1.1$ kpc) than the hotter WC4–6 stars ($\bar{R} \approx 9.5 \pm 0.5$ kpc). It is unlikely that selection effects are operating for various subclasses at different galactocentric radii. In a relative sense, the situation in M31 is very similar to that in our own Galaxy (cf. Hidayat, Supelli, and van der Hucht 1982). The three WN stars detected in M31, of intermediate subclass, are located ($\bar{R} \approx 9.0 \pm 0.5$ kpc) close to the WC4–6 group in the ring of active star formation. It is likely that these trends are a consequence of radial metallicity variations. Such variations are directly observed to occur in M31 (Blair, Kirshner, and Chevalier 1982). In regions of high Z, W-R stars appear to be able to transform from WN to WC at higher masses (WC7–8) than in regions of lower Z, where WN stars evolve more slowly (and are thus more frequent, as in the Magellanic Clouds) to lower mass WC4–6 stars (cf. Moffat 1981, 1982). This may happen as a result of Z-dependent mass loss rates.

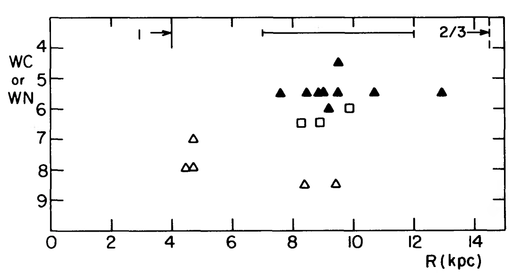

FIG. 14.—Distribution of various W-R subclasses with distance from the center of M31 (cf. Table 1). Symbols are as in Fig. 4. Vertical lines indicate areal limits of completeness of the search: ~100% to $R = 4$ kpc; 70% along the minor axis to 14.5 kpc. The horizontal bar corresponds to the observed ring of intense radio continuum emission, where star formation is proceeding most vigorously.

The situation in M33 appears to be quite different. Based on Wampler's (1982) spectroscopic observations of W-R stars in M33, there appears to be no correlation of WC subclass with radial distance. This is also in line with the fact that star formation occurs vigorously throughout M33 unlike the ring of activity in M31 or in the Galaxy.

V. CONCLUSIONS

While M31 is 2–3 times as massive as the Galaxy, its star formation rate is down by about a factor of 10. The present investigation shows this to be reflected in the total number of W-R stars observed, especially for the strong-line WC4–6 subclasses, whose detection probability is close to 100%. It appears that late-type spirals and irregulars of high luminosity are as highly efficient in forming W-R stars as they are in forming massive stars in general.

Despite the low total yield in M31 and NGC 6822, we have enlarged our bank of potential supernova precursors. This is especially true for the easily detected, hot WC stars. These may be the least massive, final W-R stage in the evolution of massive stars just before a supernova explosion (cf. Moffat 1981, 1982; Maeder and Lequeux 1982). Clearly, one should concentrate future efforts on luminous late-type spirals and irregulars in the quest for presupernova W-R stars.

The relative frequency of different W-R subclasses and its variation with galactocentric distance found in M31 is compatible with evidence that massive early-type spirals like M31 are metal richer (a) than galaxies of lower mass and (b) toward their centers. Presumably such galaxies produced the bulk of their present high metallicity in previous stages of more vigorous star formation. A remaining important step is to increase the sample of galaxies searched for W-R stars to include galaxies of high and low luminosity for each morphological type. To do this means going beyond the Local Group to fainter, more distant galaxies. One consolation is that such galaxies will be smaller in angular size and will fit better than M31 on present small size two-dimensional digital detectors.

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