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WOLF-RAYET STARS IN THE ANDROMEDA GALAXY

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ABSTRACT

We have completed a survey of M31 for strong-line Wolf-Rayet (W-R) stars, confirming the trends found previously, that (1) M31 is at present about an order of magnitude less active in star formation than the Galaxy, as reflected in the total number of W-R stars, assumed to have evolved from massive progenitors; (2) the number ratio of late to early WC stars, WCL/WCE, varies systematically with galactocentric radius as in the Galaxy, possibly a consequence of the metallicity gradient in the disk; and (3) most W-R stars lie in the prominent ring of active star formation at $R = 7$–12 kpc from the center of M31.

Subject headings: galaxies: individual (M31) — galaxies: stellar content — stars: Wolf-Rayet

I. INTRODUCTION

The specific goals of this paper are the following:

1) To complete our previous photographic survey for Wolf-Rayet (W-R) stars in M31 (Moffat and Shara 1983, hereafter MS);

2) To check our previous detection rate in a region of high W-R star density using a narrower filter that better discriminates weaker-line stars;

3) To check our previous efficiency of visual blinking on photographic plates, using PDS scanning techniques.

The overall aim is outlined in MS; briefly, it is to learn more about W-R stars in general from their spatial and spectral distribution in galaxies, and to learn more about the galaxies themselves in which these W-R stars lie.

II. OBSERVATIONS

Most of the northeast section of M31 which remains to be surveyed for W-R stars (see MS) was photographed in four 20′ diameter fields defined by the one-stage image-tube camera at the f/4.2 prime focus of the 3.6 m CFH (Canada-France-Hawaii) telescope, in 1981 September. As in MS, a FWHM 87 Å interference filter centered at $\lambda_c = 4670$ Å was used to discriminate the strongest emission feature seen at this wavelength in all W-R stars: N III λ4640 in WN stars, C III/IV λ4650 in WC stars, and He II λ4686 in both. For a reference continuum we used a FWHM 98 Å filter at $\lambda_c = 4450$ Å (instead of the broad-band B filter of MS). With baked IIIa-J emulsion we reached slightly fainter in similar seeing and in a shorter time than we did with the direct IIaO detection method of MS. In addition to the four fields described above, a fifth field was observed. This field was centered close to the position of Baade's Field IV, 20 kpc southwest from the nucleus of M31 where the most remote (on an angular scale) stellar associations are seen (van den Bergh 1964).

All plate pairs were exposed in immediate succession in order to optimize the matching process for the visual blinking of the plates as well as to reduce the effects of variable stars. The fields are indicated schematically in Figure 1. In one of the fields (IT6), the 4450 Å plate was out of focus so that direct plates in U and V (a good B plate not being available) from the same telescope but at a different epoch were used as a reference (kindly made available by B. Madore).

For our most promising W-R candidates we began in 1981 to obtain spectra at the Multiple Mirror Telescope using the intensified Reticon detector, with the same parameters as in MS. In 1983 January we obtained an image-tube plate pair using a new pair of filters of a test field (IT2 in Fig. 1) within our previous direct southwest field. This test field was chosen to be centered on OB 78 (van den Bergh 1964) = NGC 206, the brightest stellar association in M31 (both in the visible—as any published chart of M31 will show—and in the UV; see Bohlin 1985), around which the highest concentration of W-R stars was found to lie (see MS). The new narrow filter has a central wavelength of 4686 Å and a FWHM of 37 Å in the f/4.2 beam. The new broad-band reference filter has a FWHM of 330 Å but is centered at nearly the same wavelength (4710 Å). Baked IIIa-J plates were used as with the other image-tube fields. The seeing was again $\sim 1\farcs5$, and the plate pair reached slightly fainter ($B > 21.5$) than did our previous direct pair (see MS).

Finally, CCD images of dimensions $\sim 3' \times 5'$ centered on NGC 206 were obtained at Kitt Peak National Observatory by H. Ford, using filters with central wavelengths and bandpasses (FWHM) of ~4500, 1000 (B); 4670, 90; and 4686, 35 Å, respectively. The images reach magnitude $B \approx 21.5$ with signal-to-noise ratio ~5 for non–emission-line stars.

III. DETECTION LIMITATIONS AND COMPLETENESS OF THE SURVEY

Blinking the five new image-tube plate pairs in the northeast section and in Baade's Field IV of M31 led to the discovery of W-R candidates that are brighter in the 4670 filter than in the 4450 filter. The number detected ranges from three candidates

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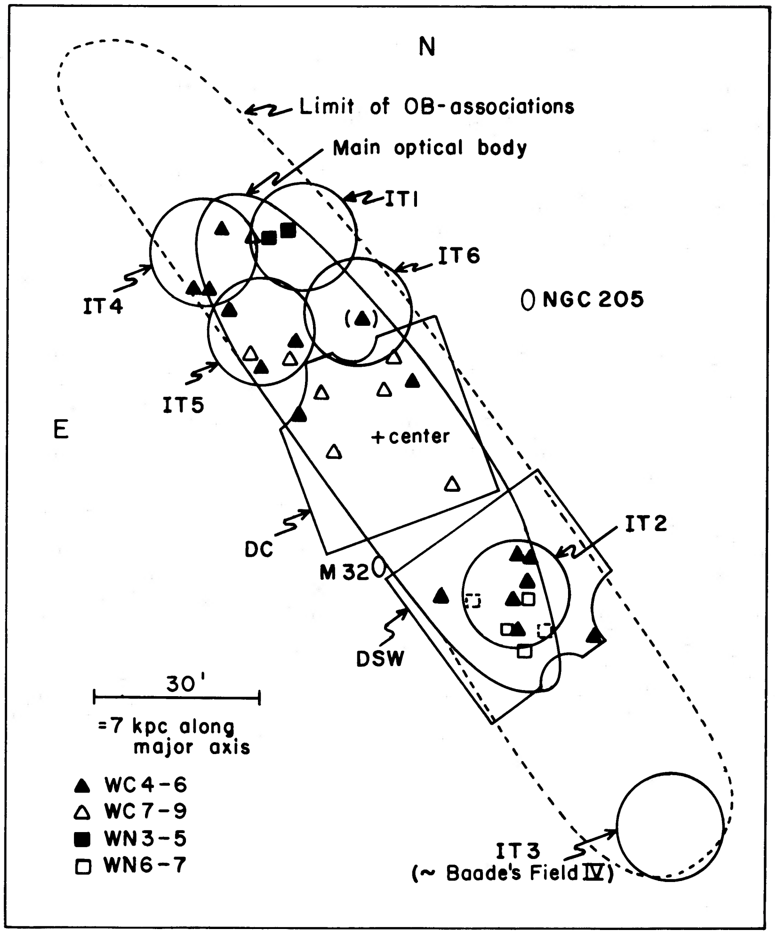


FIG. 1.—Schematic of M31 showing: (1) outline of main optical body from which most of the light is emitted; (2) limit of star formation defined by the most remote OB associations, (3) areas searched for W-R stars using direct photography (see MS) and image tube; and (4) all spectroscopically confirmed W-R candidates found to date, with the addition of the two high-rating candidates in field IT2 (*dashed symbol*).

in IT3 to 50 in IT1. However, whether they really are W-R stars or not, depends on several limiting factors: (1) mismatch of the central wavelengths of the on- and off-line filters; (2) interstellar reddening; and (3) mismatch of the on-line filter bandpass relative to the emission-line widths. These factors are discussed here, along with the final estimated limits in magnitudes and line strength actually encountered.

Since the two filters have different central wavelengths (4670 vs. 4450 Å), extremely red stars (intrinsically red or interstellar reddened) could blink like W-R stars—more strongly in the 4670 filter than in the 4450 filter (see MS). This could be aggravated by the complex nature of the spectra of red stars, as strategically placed absorption lines and troughs help the surrounding continuum to mimic emission. Thus, we also inspected U and V plates and compared them to our 4450 plates in order to eliminate red stars ($B-V \gtrsim 1$).

Red stars comprised the majority of the candidates. Could these include some reddened W-R stars, with $E_{B-V} > 1$, i.e., $A_V > 3$ or $A_B > 4$? With $B_o - M_B =$ 24.1 for M31 (de Vaucouleurs 1978), our continuum limit $B = 21.5$ would correspond to $M_B < -6.6$, and this would imply that we had not found the majority of W-R stars, which have $M_V \approx M_B \approx -4.5$. This is probably not the case, however, because the mean extinction for stars in the disk is unlikely to be this high: Beck and Graeve (1982) estimate for the ring of active star formation a mean extinction integrated through the disk of $\langle A_V \rangle < 1.1$, which reduces to a mean of $\langle A_V \rangle < 0.55$ for stars distributed at random in the disk, so that most W-R stars should appear blue and have $B < 21$ (see below). Our own Galaxy yields $\langle A_V \rangle = 0.7$ through half the disk at the solar distance at an angle $b = 12\overset{\circ}{.}3$.[4] Nevertheless, in the vicinities of large H II regions, A_V may be locally significantly higher than in the rest of the disk, and our survey may be less complete in such regions.

The new pair of filters used in IT2 can be expected to be almost impervious to red stars (same λ_c) and to allow better discrimination of most W-R stars (filter width better matched to mean emission-line width). This is illustrated in Figure 2, where we plot the expected magnitude difference Δm between narrow- and wide-band images of W-R stars compared to that of non–emission-line stars as a function of equivalent width of

[4] In our own Galaxy one has $E_{B-V} = 0.06 \csc(b) - 0.06$ due to extinction in half the disk, i.e., $A_V = 3.2E_{B-V} = 0.19 \csc(b) - 0.19 = 0.7$ at the solar distance for $b = 12\overset{\circ}{.}3$, the inclination of M31. In fact, $A_V = 0.7$ ($A_B = 0.9$) is probably an upper limit for the mean extinction of stars in the disk of M31, which has used up proportionately more of its gas and dust to form stars than has the Galaxy. Hiromoto *et al.* (1983) have published near-IR profiles of the disk of M31. After dividing their derived values for the total A_V by 2, the resulting estimate of the mean absorption for disk stars would range from $\langle A_V \rangle = 0.26 \pm 0.06$ in the inner regions up to a maximum of 1.2 ± 0.5 at $R \approx 10$ kpc.

the emission line. This is assumed to fall entirely within an ideal filter, with a rectangular profile and FWHM = F_N for the narrow-band filter and F_W for the broad-band filter. Then

$$\begin{aligned}\Delta m &= -2.5 \log [(F_N + W_e)/(F_W + W_e)] \\ &\quad -[-2.5 \log (F_N/F_W)] \\ &= -2.5 \log [(1 + W_e/F_N)/(1 + W_e/F_W)] .\end{aligned}$$

In reality, broad emission lines will spill out beyond the narrow bandpass and $|\Delta m|$ will be smaller than in Figure 2. When considering detection limits, this can be neglected for weak-line (and therefore generally narrow-line) W-R stars for which the magnitude difference is then reliable. We thus find that with a 3 σ level of detection near the plate limit of $\Delta m = -0.5$ mag, the new pair of filters will enable us to detect stars with W_e down to ~ 25 Å compared with only ~ 60 Å for the previous pair. Thus, if the W-R stars in M31 are like those in the Galaxy and the LMC (see W_e's of Conti, Leep, and Perry 1983), we can expect to find the large majority of them down to a limit of $W_e = 25$ Å, providing we reach to faint enough stars. ($B = 21.5$ in the continuum yields $M_B = -3.5$ for $B_o - M_B = 24.1$ and $\langle A_B \rangle = 0.9$; intrinsically faint, single W-R stars of subclass WC and WNE tend to have larger equivalent widths and can thus be seen in the emission-line filter to fainter apparent magnitudes.) According to Conti *et al.* (1983), 98% of the observed WN 2.5–6 stars and 54% of the WN 7–8 stars in the Galaxy and the LMC have W_e (He II λ4686) > 25 Å. The WN 7–8 stars comprise 31% of the total sample of WN stars. In a given volume, this fraction is decreased to ~ 5%, since WN 7–8 stars are intrinsically ~ 2 mag brighter on average. Even W_e (He II λ4686) > 60 Å includes 59% of the WN 2.5–6 stars and 7% (30% including N III λ4640 as does our previous wider filter) of the WN 7–8 stars. On this basis, our previous survey (MS) should have detected ~ 50% of the WN stars in the surveyed areas, if WN stars in M31 are similar to their counterparts in the Galaxy and in the LMC. WC stars generally have much stronger emission at 4650 Å than do WN stars, and we expect our survey to be complete for WC stars in M31 at a high level; only the weaker line, WC 9 stars as well as a few WC stars with bright OB companions like γ^2 Vel or θ Mus in the Galaxy, might be expected to be somewhat incomplete.

In their recent paper on massive stars in M31, Massey, Armandroff, and Conti (1986) have questioned the completeness of the detection of W-R stars in M31 by MS. In particular, they have located W-R candidates in their narrow-band survey, which they claim MS should have easily detected. This claim is incorrect, however, for the following reasons:

1. The association OB 69 was *not* included in the MS survey. It happens to lie in the narrow wedge between the two direct-image fields.

2. The star OB 78–WR 3 has W_e (C IV λ4650) ≈ 65 Å from their spectrum. This is sufficiently close to MS's estimated completeness limit of detection of $W_e \approx 50$ Å, or possibly even

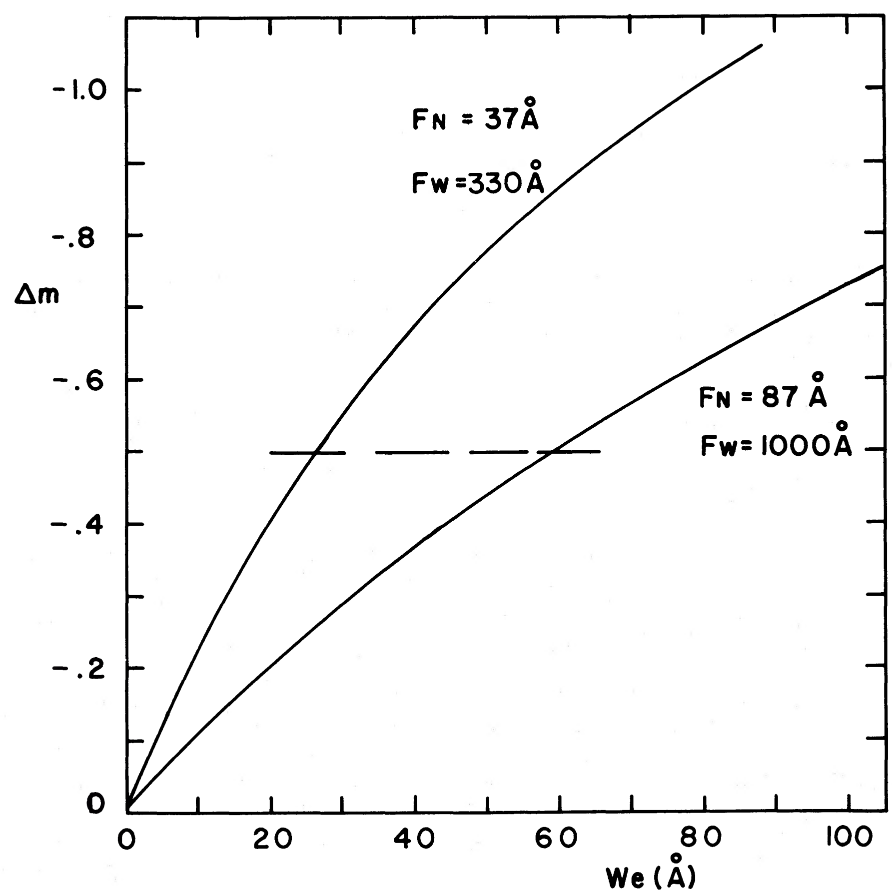


FIG. 2.—Expected magnitude difference between narrow and wide band images of W-R stars, compared to non–emission-line (and non–absorption-line) stars, assuming all the W-R emission of equivalent width W_e falls within box-shaped filters of widths F_N and F_W, respectively.

TABLE 1

W-R CANDIDATES IN THE NEW IT FIELDS OF M31

NUMBER	COORDINATES (1950.0) RA	Decl	RATING	SPECTRAL CLASS	EMISSION		OB	X	Y^*	R
IT1-38.........	00^{h}41^{m}52^s.7	+41°35′38″	1	WN 5+neb!	62	8:	54	7.7	−4.2	9.8
-40.........	00 41 35.7	+41 37 47	2	WN 4–5+neb	31	4.2	...	7.6	−8.1	11.1
-48.........	00 42 08.5	+41 37 30	1	WC 8.5+neb!	32	11	...	8.2	−2.7	8.6
IT2-[a]										
IT3-[b]										
IT4-01.........	00 42 39.0	+41 37 27	1	WC 5–6+w.neb	45	30:	...	9.0	0.8	9.0
-13.........	00 42 52.0	+41 25 38	1	WC 5+vw.neb	70	8	...	7.5	9.0	11.7
-14.........	00 43 06.1	+41 26 17	1	WC 6+vw.neb	51	20	...	7.9	10.4	13.1
IT5-01.........	00 42 26.4	+41 21 51	1	WC 6	55	13	48	6.4	7.9	10.2
-02.........	00 42 07.0	+41 12 42	1	WC 7	38	2.3	41	4.6	9.9	10.9
-03.........	00 41 59.4	+41 11 12	1	(WC 4–5)	75:	7	41:	4.2	9.6	10.5
-04.........	00 42 10.7	+41 14 40	1–2	...	...	...	42	5.0	9.4	10.6
-06.........	00 42 28.7	+41 21 16	2	...	...	...	48	6.4	8.4	10.6
-07.........	00 42 29.2	+41 21 10	2	...	...	...	48	6.3	8.4	10.5
-10.........	00 42 16.2	+41 14 30	1–2	...	...	...	42	5.1	10.1	11.3
-15.........	00 41 27.7	+41 13 16	1	WC 7	56	18	...	3.8	4.4	5.8
-19.........	00 41 25.4	+41 16 27	1	WC 6+neb!	66	10	10	4.2	2.2	4.7
IT6-01.........	00 40 18.2	+41 20 40	1–2	(WC E+neb?)	90:	0.5	59	3.4	−8.9	9.5

NOTES.—Rating is from visual blink or PDS comparison: 1 = high, 3 = low. Table includes only stars that are not very red. Marginal, nonred candidates of rating ≥2–3 are not included (one star in each of IT1 and IT4, and five less-certain stars in IT6). Stars with spectral classes in parentheses were observed in one aperture only, due to clouds. IT6-01 was found with a high rating on 4670 vs. the *B* chart of the Palomar Observatory Sky Survey, later found to be a red (W-R?) star. Eight additional candidates of moderate rating (~2) in IT6 are not identified due to the lack of a blue continuum plate in this field. The OB association numbers and inclination of M31 are from van den Bergh 1964. X, Y (= Y^* sin 12°.3) are projected coordinates (kpc) along the major and minor axes, respectively. (X increases toward the northeast, Y toward the southeast—see MS.); $R^2 = X^2 + Y^{*2}$. A distance of 650 kpc is assumed (de Vaucouleurs 1978). Emission includes two entries for the 4670 emission feature: FWHM (Å) and the ratio of peak to continuum, respectively. Colons imply less certain values.

[a] Test field; see Table 2.

[b] Baade's Field IV; no candidate.

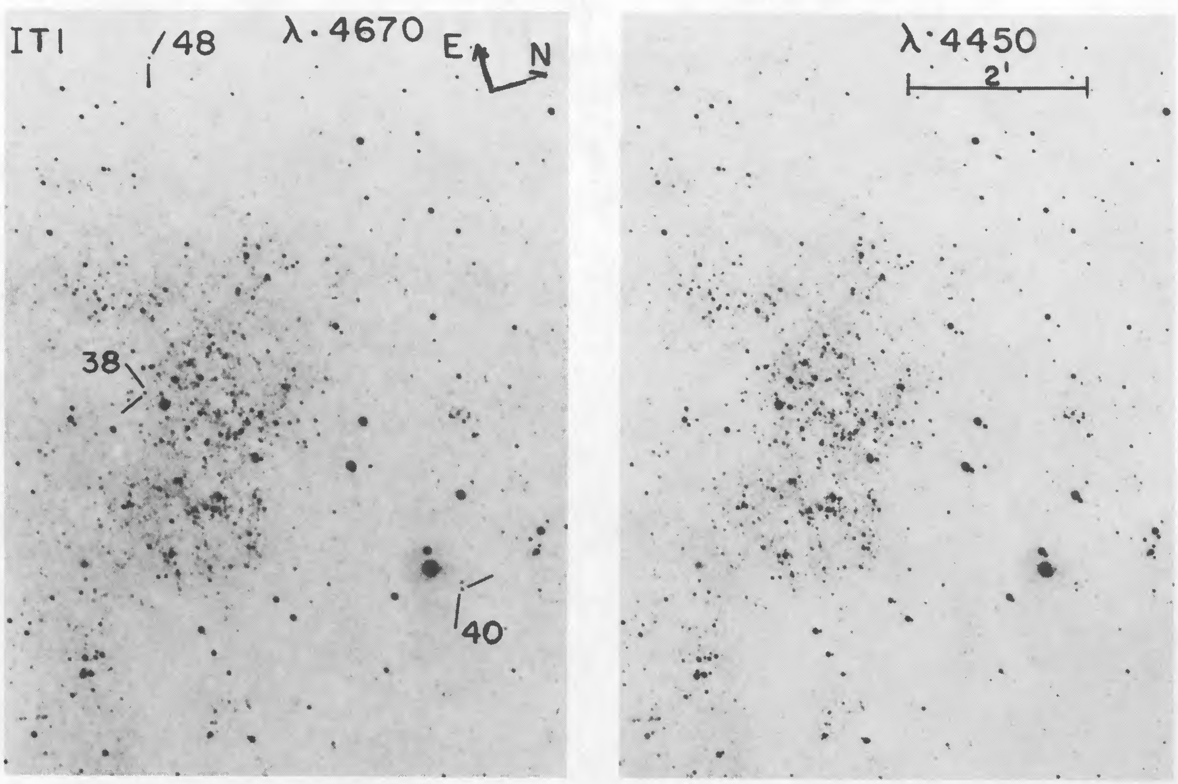


FIG. 3.—Identification charts for stars listed in Table 1. Both on- and off-line filter (λ4670 and λ4450, respectively) images, if available, are shown for comparison. The scale is given on the first figure pair and is the same for all. Candidates in (*a*) refer to the new image tube field IT1, (*b*) to IT4, (*c*) to IT5 (northeast), (*d*) to IT5 (south and west), and (*e*) to IT6.

1987ApJ...320..266M

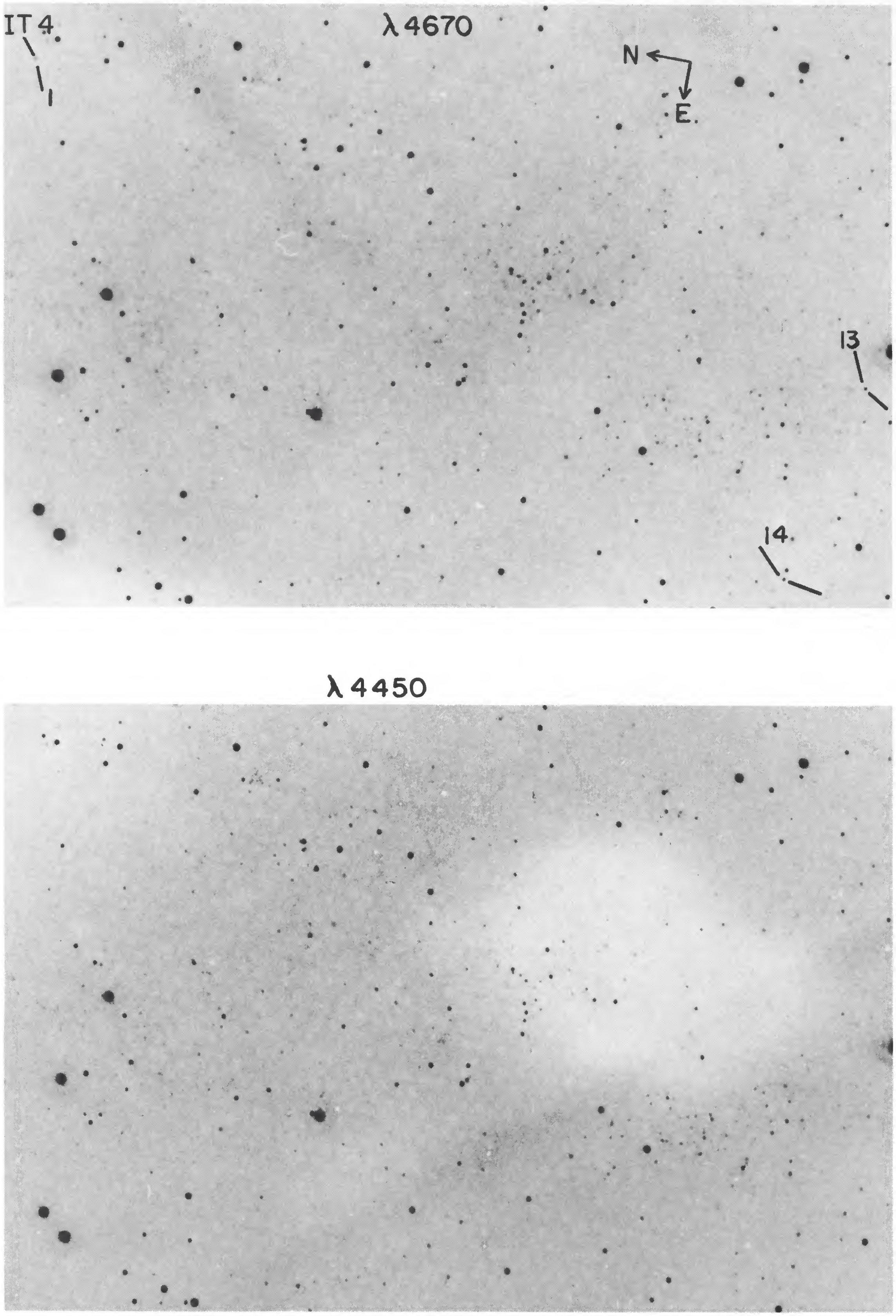


FIG. 3b

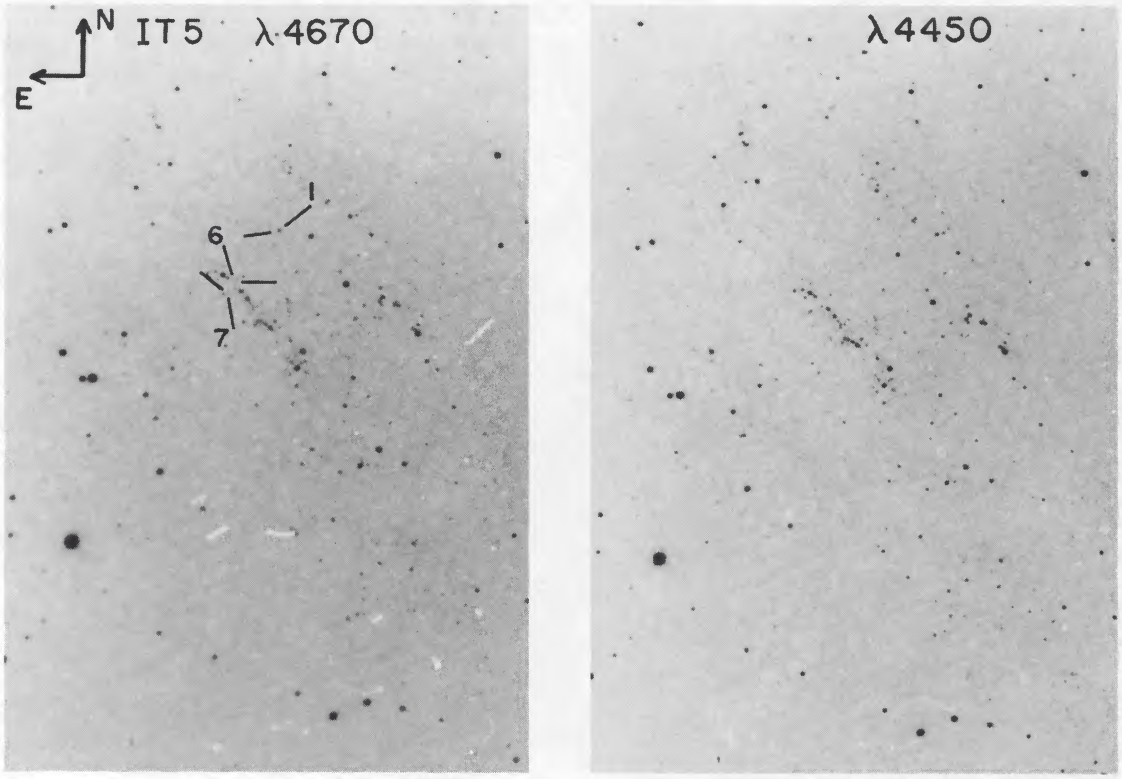


FIG. 3c

70–100 Å (see MS), that one need not be surprised that it was missed.

3. This is even more so for OB 78–WR 2, which has W_e (He II λ4686) $\sim$ 30 Å. This is well below MS's survey limit.

4. We did not (MS) and do not claim to be complete in the *total* W-R population of M31, nor in the ratio of WC to WN types; only for the strong-line WC stars are we near completeness. However, we do not expect our detection bias to operate differently in different parts of M31, so that trends *can* be studied even based on incomplete data, e.g., the relative number of WCL to WCE stars as a function of galactocentric radius.

IV. RESULTS

a) Survey of the Northeast Section

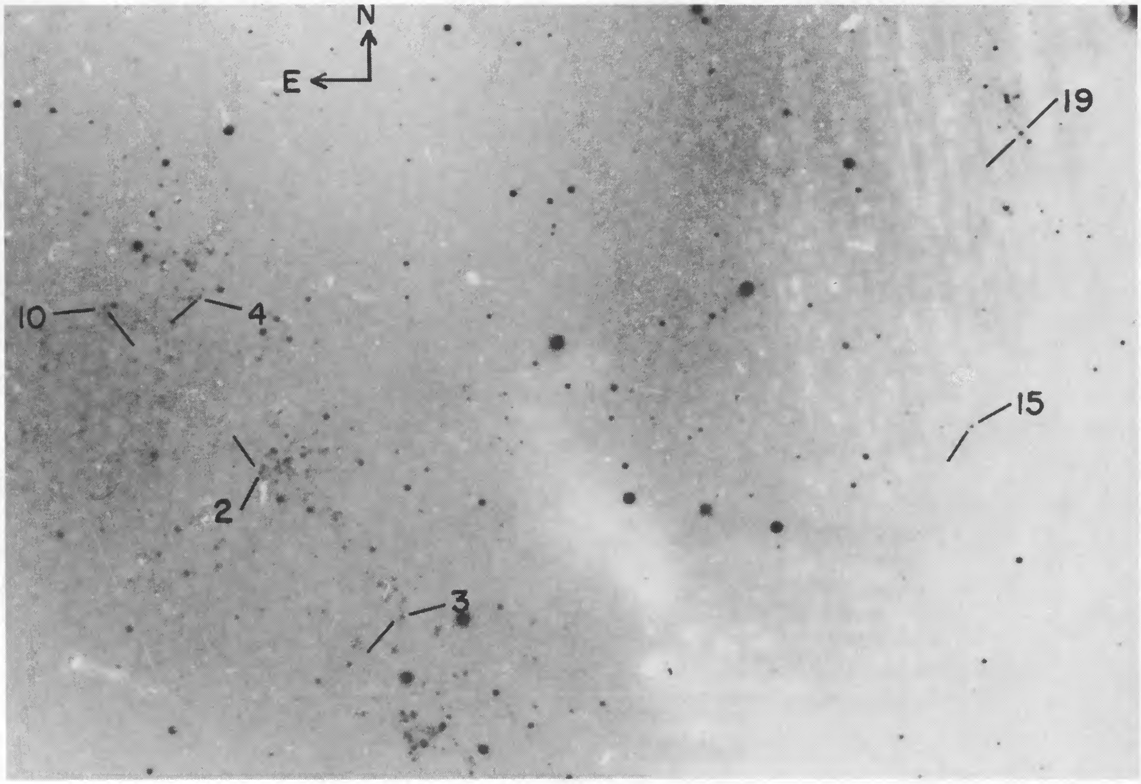
With image-tube fields IT1, 4, 5, 6 the main optical body of M31 has now been $\sim$90% covered in a search for W-R stars. Since few W-R stars were found in the regions surveyed beyond the main body (see Fig. 1), we expect not to have missed many W-R stars (to within our limits of detection) in all of the area beyond the main body. This is confirmed by the result of finding no W-R stars in Baade's Field IV (IT3). In the Galaxy, the space density of W-R stars similarly falls off in galactocentric radius R significantly more rapidly than it does for OB stars beyond $R = 10$ kpc (Conti *et al.* 1983; Meylan and Maeder 1983).

A list of new W-R candidates in the new northeast fields is presented in Table 1. They are identified in Figure 3. Spectra obtained for most of the best candidates are shown in Figures 4 and 5.

b) Test Field with Narrower Filter and Image Tube

Figure 6 shows our new image-tube plate pair of field IT2 using the new filters. All stars listed in Table 2 are identified here. These include all stars found in our previous survey (MS) of this region (five WC, two WN, and two non–W-R) with the addition of four new nonred candidates, two of high rating (Nos. 23, 29) and two of relatively low rating (Nos. 25, 30). The rating is based on four independent modes of search: (1) visual blinking of the image-tube plates; (2) PDS scanning and differencing of the scaled photographic density (see § IV*c* below) for the image-tube plate pair; (3) the rating of MS from blinking the direct plates; and (4) PDS scanning of the direct plate pair.

As expected, the two previously detected WN 6–7 stars (Nos. 15, 17) increased their detection rating on the new narrower line filter image-tube plates, while the five WC stars, especially those with broad lines, decreased slightly, but are still strong. Also, as expected, neither of two confirmed non–W-R red stars was detected on the new image-tube plates. The two new good candidates (Nos. 23, 29) were missed by visual blinking but were found by subsequent independent PDS scanning of the direct plates. If these two stars are W-R, they are probably of the WN sequence, since their rating has increased going from the direct to the image-tube plate pair. Until spectra of the four new candidates are obtained, we conclude that our 87 Å wide filter blink survey of M31 for W-R stars of all types is $\sim$64%–77% (7/11–7/9) complete within the limits $W_e \gtrsim 25$ Å and $B \lesssim 21.5$ ($M_B \lesssim -3.5$). Our survey for WC stars should be close to 100% complete, except possibly for the weaker line WC 9 stars and WC + OB binaries, but our completeness for WN stars may be as low as 33%–50% (2/6–2/4) complete. If the completeness rate for all W-R sub-



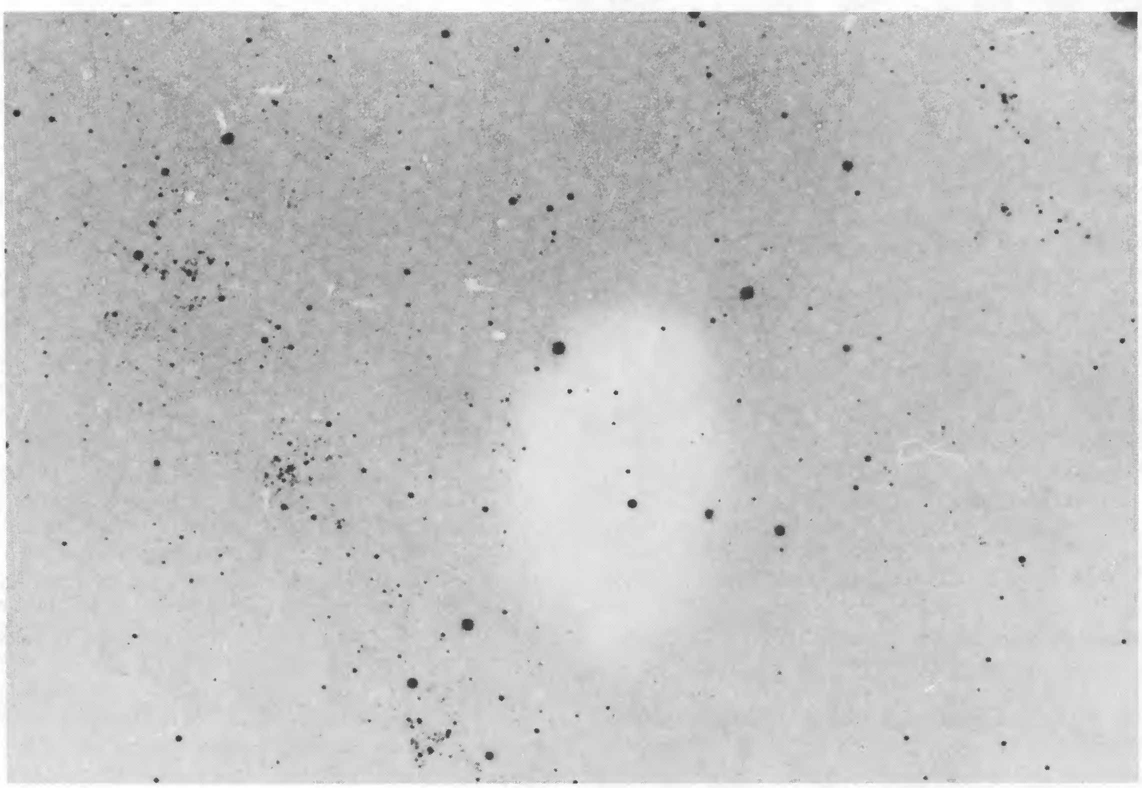


FIG. 3*d*

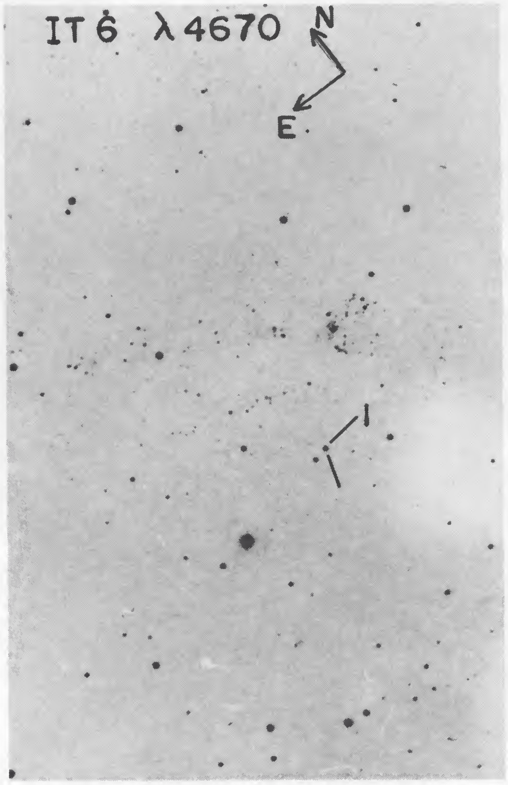


FIG. 3e

types was much less than 64%–77%, we would have expected to find many more new candidates with the new narrower band filter.

c) *Reassessment of the Direct Southwest Field Plates*

The direct southwest field plate pair of MS was searched for W-R stars using visual blinking techniques. We have now PDS scanned these plates and examined them digitally section by section (~ 1 cm $\times$ 1 cm)[5] by comparing pixel by pixel the photographic density of the narrow and wide plates. (This was not done for the direct central field due to the large range in background density encountered there.) Stars for which the photographic density on the narrow image exceeded the normalized photographic density on the wide image by $\gtrsim 3\ \sigma$ were considered as initial candidates whose weight depended on the actual magnitude difference. A total of 127 such candidates was found, compared with a total of 75 found by MS in their visual blink search. Only 33 candidates were found to overlap between the two completely independent searches. After elimination of red stars we note that:

1. All previously found, spectroscopically confirmed W-R stars (Nos. 10–12, 14–18, 20–21; see MS) were revealed with ease (rating ≤ 2) in the PDS search.

2. Among the three spectroscopically confirmed, intrinsically red, non–W-R stars (Nos. 9, 13, 19) only No. 13 was found to be brighter in the emission line filter but with a relatively low rating (2–3).

[5] In order to minimize the effects of variation in sensitivity and image distortion.

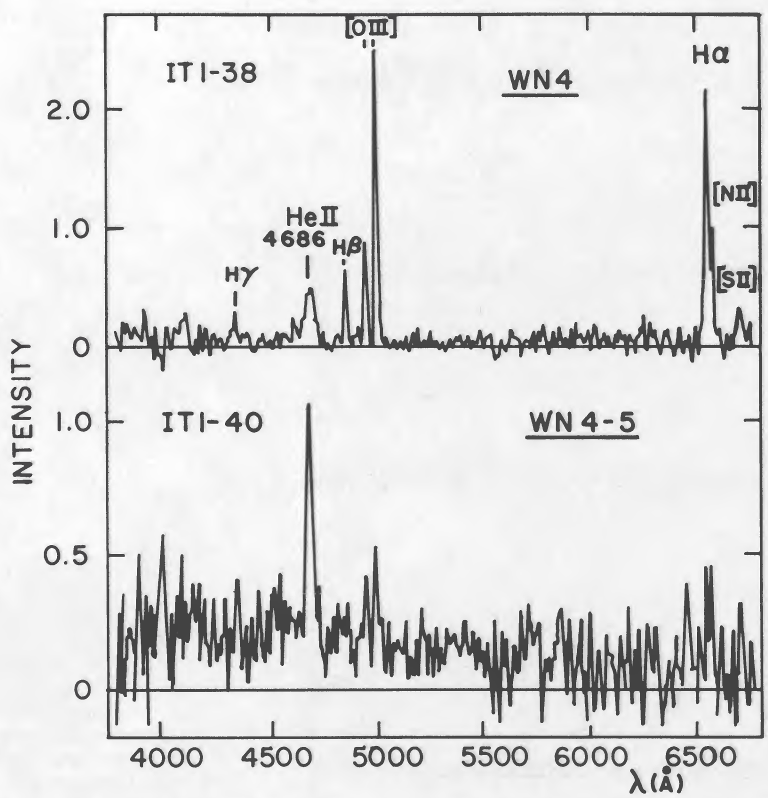


FIG. 4.—Reduced, intensified Reticon spectra of two confirmed WN stars in northeast section of M31 (as in Fig. 7 of MS). Intensity is in approximate units of 10^{-16} ergs s^{-1} cm^{-2} Å^{-1}.

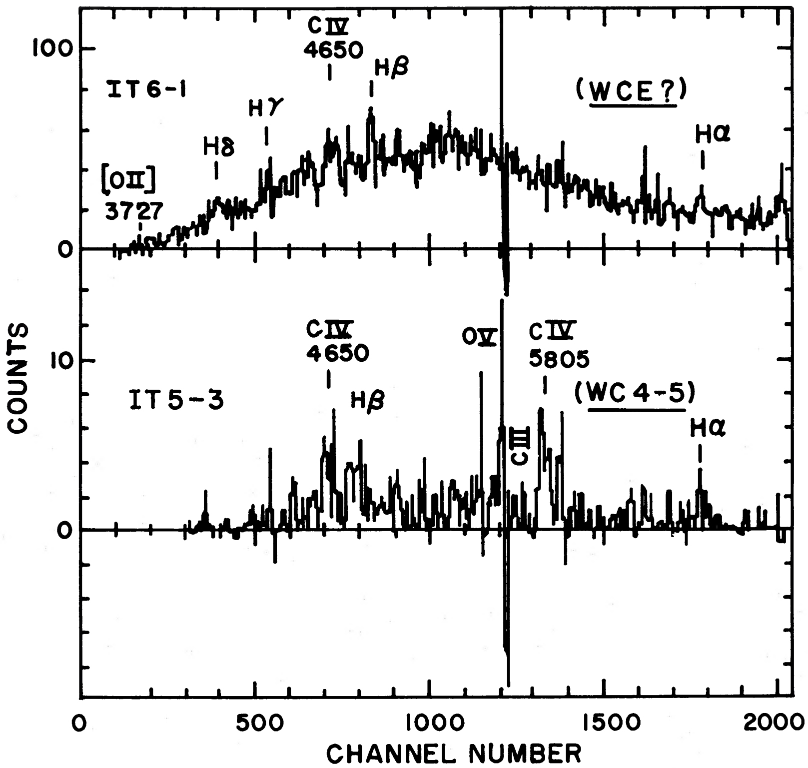


FIG. 5a

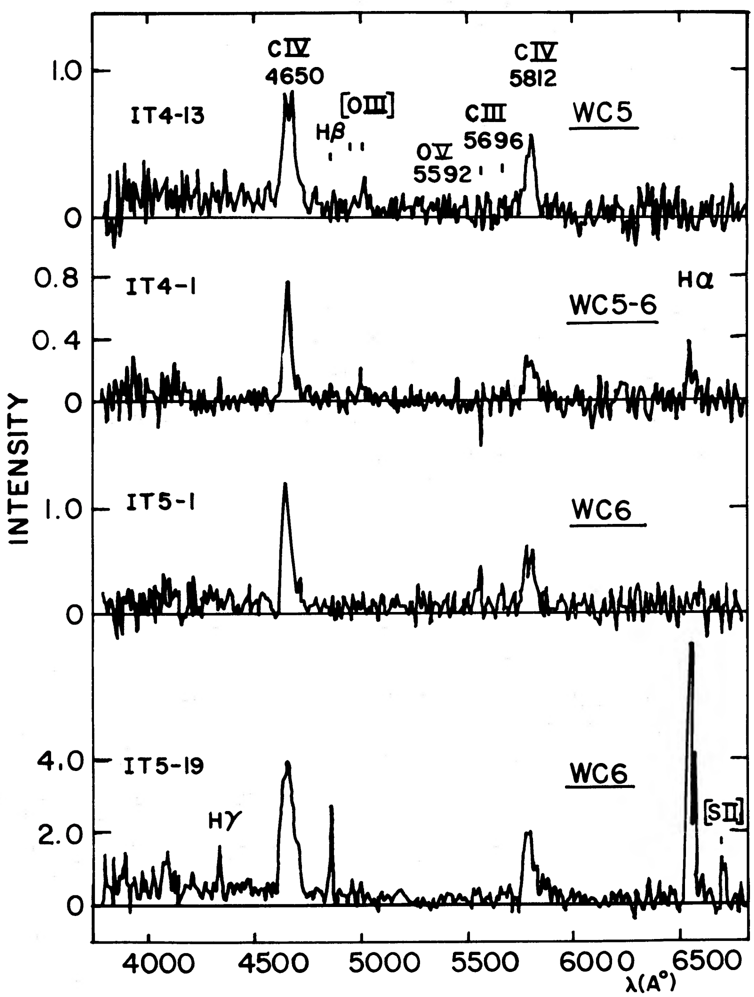


FIG. 5b

FIG. 5.—As in Fig. 4, but for the 10 newly discovered WC stars in northeast section of M31. Spectra are sorted from hot to cool subclasses from (*a*) to (*b*) to (*c*). In (*a*) the spectra refer to raw counts since they were prematurely terminated by clouds with the W-R stars having been observed in only one aperture.

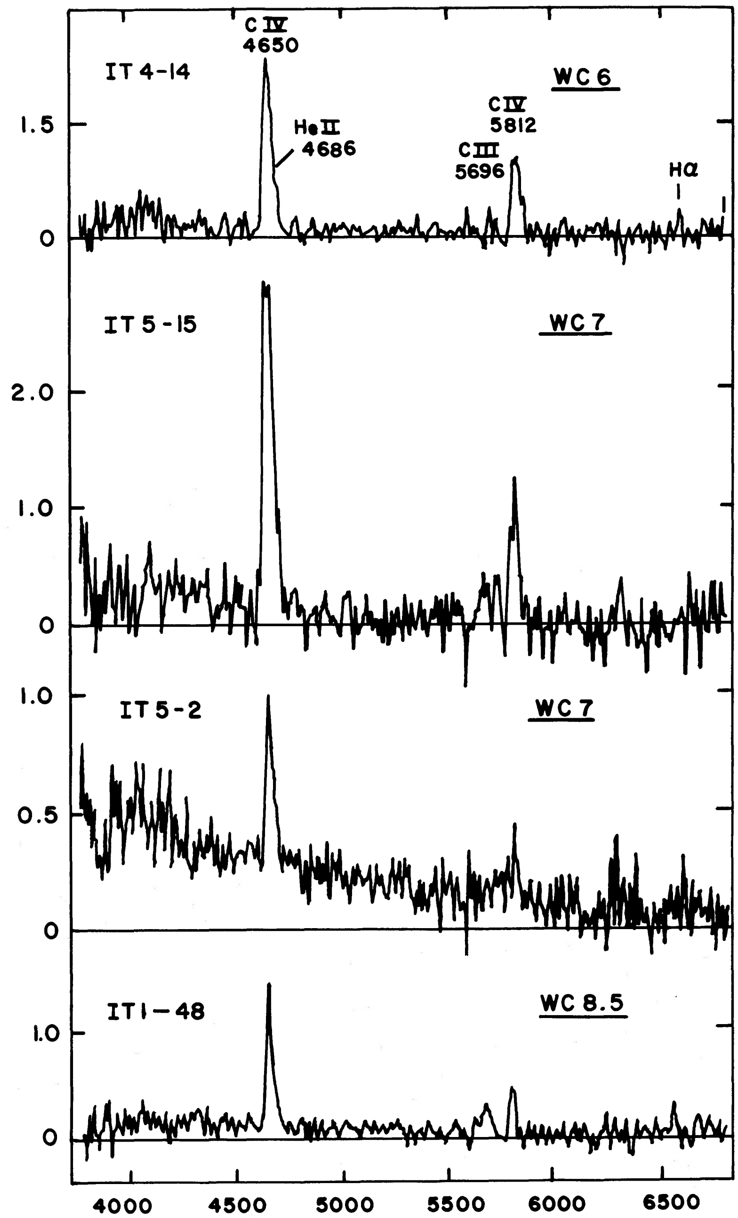


FIG. 5c

TABLE 2

W-R CANDIDATES IN THE TEST FIELD (IT2) CENTERED ON NGC 206

Number	Spectral Class	MS	IT	PDS (direct)	X	Y^*	R
11.........	WC 5–6	1	1–2	1	−6.7	−6.0	9.0
12.........	WC 4–5+neb!	1	2	1	−6.8	−6.7	9.5
13.........	(non–W-R)	1–2	4	2–3	...	...	...
14.........	WC 5–6+w.neb?	1	1	1	−7.4	−4.2	8.5
15.........	WN 6–7	2–3	1–2	1–2	−7.9	−2.5	8.3
16.........	WC 5–6	1	1	1	−7.6	−0.4	7.6
17.........	WN 6–7+w.neb	2–3	2	1–2	−8.5	+2.8	8.9
18.........	WC 5–6+w.neb	1	1–2	1	−8.6	+2.1	8.9
19.........	(non–W-R)	2	4	4	...	...	...
23.........	...	2–3	1	1	−6.5	+4.8	8.1
25.........	...	3	~2	4	−7.5	−2.0	7.8
29.........	...	3	1–2	2	−8.8	−1.6	8.9
30.........	...	3	~2	4	−8.7	+3.9	9.5

NOTES.—Stars are included only if not very red. Nos. 11–19 are from MS. New candidates 23–30 had already been discovered independently but had not been published by MS. X, Y^*, R are as in Table 1. " IT " refers to image tube; the IT ratings are a mean of visual blinking and PDS analysis.

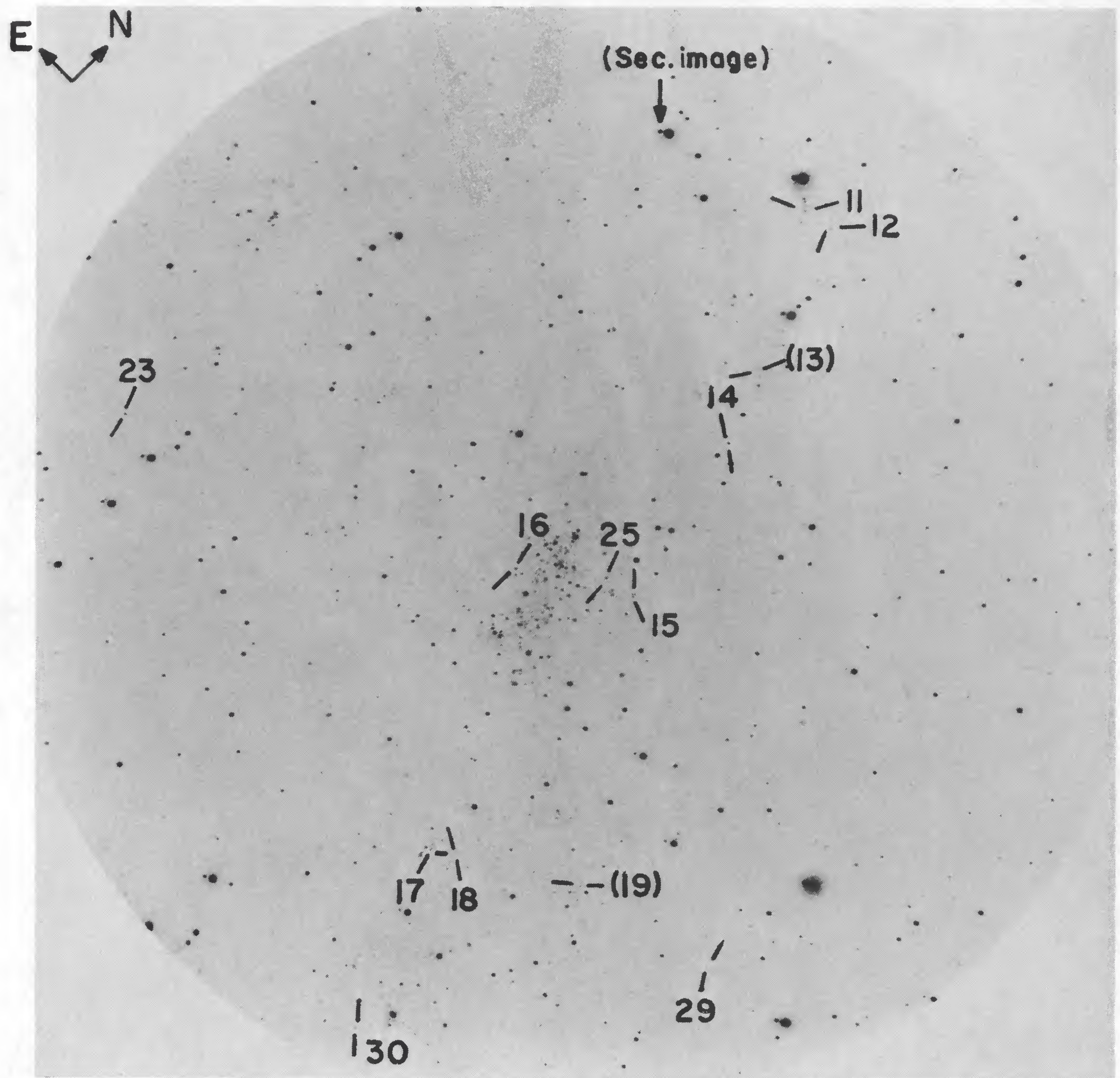


FIG. 6a

FIG. 6.—Identification of W-R candidates in Table 2 from (a) narrow-band (FWHM = 37 Å) filter at $\lambda_c = 4686$ Å and (b) broad-band (FWHM = 330 Å) filter at $\lambda_c = 4710$ Å. Faint secondary image to east of all bright stars in (a) is due to a glitch in telescope tracking. Image-tube field has diameter of $\sim 20'$.

3. Among the new image-tube candidates (Table 2), only Nos. 23 and 29 were found with any certainty.

4. Only one other new, convincing candidate was found (nonred and rating ≤ 2). It is located 472″ west and 29″ south of WR 20, near the edge of the field, where its reality was put into doubt during the original blink survey.

d) *CCD Check for W-R Stars in NGC 206*

Recently, Massey and Armandroff (1986) have surveyed NGC 206 and several other associations in M31 for W-R stars using a CCD detector and appropriate on- and off-line filters. They found a total of eight W-R candidates in and around NGC 206. We have checked these candidates and searched for new ones on our CCD images of the same field (see Fig. 7).

We have blinked our CCD 4686/35–*B* image pair by visual inspection on a video display. This revealed only three candidates: the spectroscopically confirmed stars WR 15 and WR 16, and the new candidate A, with ratings 1, 2, and 2–3, respectively. Star A is very red and is therefore probably not a W-R star; it was also picked up on the IT test field survey and rejected because of its red color.

Blinking of our 4670/90–*B* image pair revealed nine candidates: WR 15 and WR 16 with rating 1, star E (1–2), stars A and C (2), stars B and G (2–3), and stars D and F (3). Stars A and F can be eliminated because they are very red.

The only candidates which show up consistently in all searches are the two confirmed W-R stars WR 15 and WR 16. Among the Massey/Armandroff candidates, two are identical with WR 15 and WR 16, one (star E) shows up on our 4670/90–*B* pair only, while one (their No. 8) is below our limit of detectability. The rest (Massey/Armandroff Nos. 1, 2, 6, and 7) do not show up as W-R candidates at all, although they were visible, on our new CCD survey.

Nor do four of our new nonred candidates (B, C, D, and G) show up as W-R candidates in Massey/Armandroff's search. Most likely, we are dealing with the tail end of an error distribution, so that few, if any, of these once only candidates are likely to be true W-R stars.

We conclude that our previous visual survey is already quite complete at the levels mentioned in § IV*b* above. This applies to all of M31 now covered with the 87 Å filter. Note that all good candidates and subsequently spectroscopically confirmed

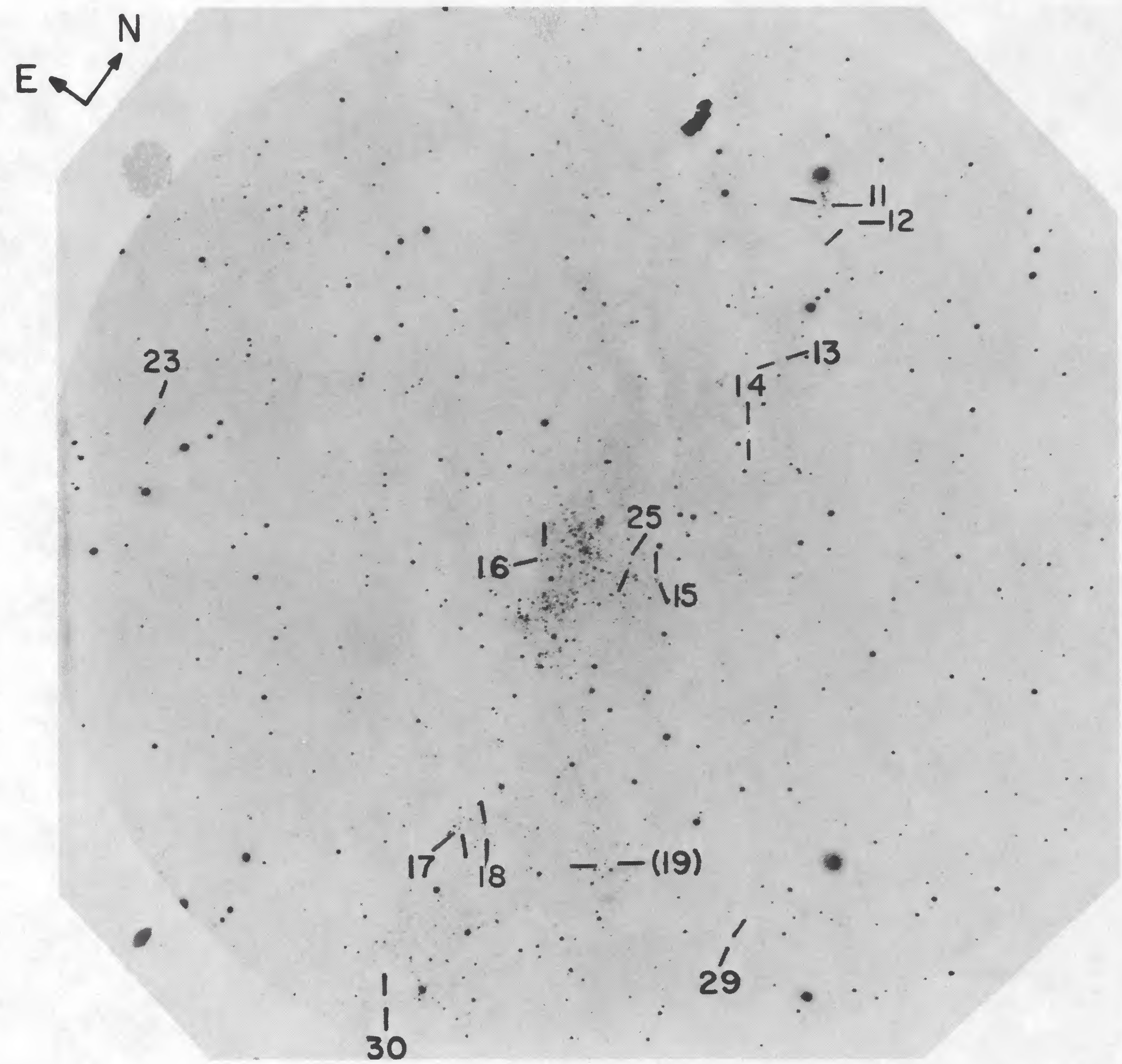


FIG. 6*b*

W-R stars are nonred, while the spectra of a few strong but red candidates are those of intrinsically red, non–W-R (foreground?) stars.

V. CONCLUSIONS

About 90% of the main body of M31 has been thoroughly searched for W-R stars to $B \approx 21.5$ ($M_B \approx -3.5$) to a level of $W_e(4670) \gtrsim 60$ Å. Our principal conclusions on the basis of this work can be summarized as follows:

1. We confirm our previous finding (MS) of the relatively low number of W-R stars compared to the Galaxy. This agrees with recent *IRAS* observations which show that the present star formation rate in M31 is very low compared to the Galaxy's (Habing *et al.* 1984). In particular, the fraction of more easily discoverable WCE stars, which generally exhibit relatively strong emission lines, is down by an order of magnitude compared with that of the Galaxy (see MS). A quantitative estimate of the relative number of W-R stars in M31 versus that in the Galaxy can be made as follows:

a) We restrict ourselves to all Galactic WN stars of W_e(He II λ4686) $\gtrsim 60$ Å, corresponding to our limit in M31. Conti *et al.* (1983) show that there are at least 28 such WN stars known in the Galaxy.

b) We assume that all the 70 observed Galactic WC stars have $W_e(\lambda4670) \geq 60$ Å. This is entirely reasonable in view of the spectroscopic WC study of Torres, Conti, and Massey (1986), who find that ~90% of their sample of 60 measured Galactic WC stars have W_e(C IV λ5806) ≥ 60 Å; the C IV/III λ4650 feature is expected to be as strong or stronger.

c) We adopt an incompleteness factor of 4.5 for the ratio of the total number to the observed number of W-R stars in the Galaxy (see Hidayat, Supelli, and van der Hucht 1982).

d) We assume that our survey, which now includes 29 spectroscopically confirmed W-R stars, is nearly complete in M31 for $W_e(\lambda4670) \gtrsim 60$ Å in 90% of the main body where all the W-R stars probably lie.

Thus, we find

$$N(\text{Gal W-R})/N(\text{M31 W-R}) = (28 + 70) \times 4.5/(29/0.90) \approx 14 ,$$

for $W_e \gtrsim 60$ Å. This ratio is an upper limit since it includes only the W-R stars in M31 which have spectroscopic confirmation. Adding the 10 good (rating ≥ 2) M31 candidates which still lack spectroscopic confirmation (four stars in IT5; star E near NGC 206; stars 23, 25, 29, and 30 in IT2;

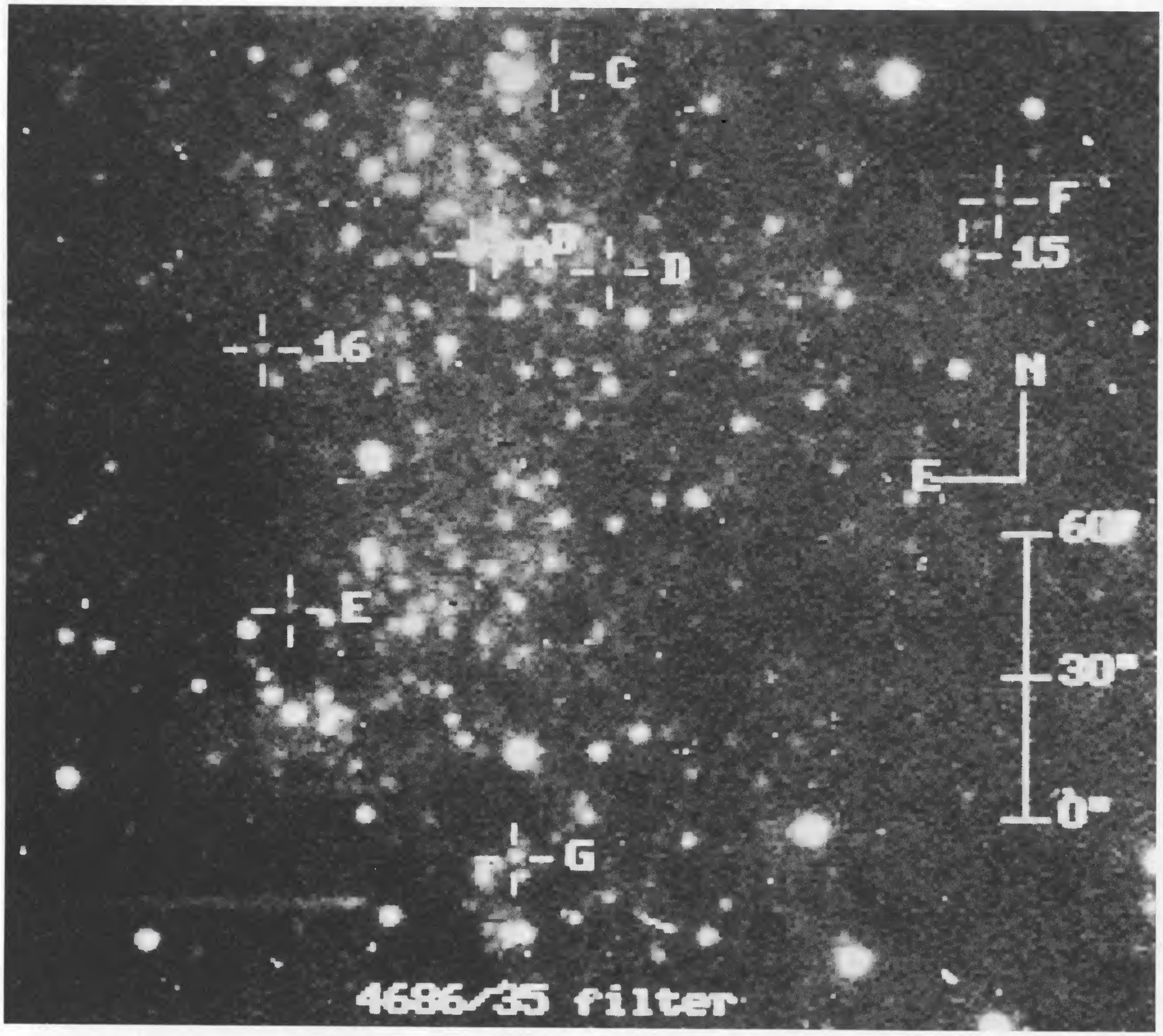


FIG. 7*a*

FIG. 7.—CCD images of association NGC 206 in M31. The nine W-R candidates are identified. (*a*) 4686/35 filter; (*b*) 4670/90 filter; (*c*) *B* filter.

and the new candidate near WR 20), one finds a ratio of 10 instead of 15. Thus, it is safe to say that M31 contains an order of magnitude fewer W-R stars than the Galaxy.

2. Most of the W-R stars in M31 are located in the $R = 7$–12 kpc ring of active star formation. This is revealed in Figure 8 where we show the two-dimensional projected distribution of the spectroscopically confirmed W-R stars superposed on the 11 cm radio continuum map of Beck and Graeve (1982) and the 60 μm *IRAS* map of Habing *et al.* (1984). The concidence of W-R stars with the radio and IR features is striking. Figure 9 shows a radial one-dimensional plot of the same stars. As in the Galaxy, there are few if any W-R stars located beyond the main optical body of M31, which extends out to $R \approx 13$ kpc.

3. If the results of our new narrower filter search in the field IT2 are typical of the frequencies of WN and WC stars in M31, then we conclude that the WC/WN number ratio is ~ 1 in the M31 star-forming ring. This is comparable to the WC/WN number ratio in the inner part of the Galaxy.

4. As one approaches the center of M31 the relative proportion of late-type WC stars increases, just as is observed in our Galaxy (see Fig. 9 and MS). We are attracted to the simple hypothesis that this effect is a consequence of a gradient in metallicity (see Meylan and Maeder 1983), but recent work on IC 1613 and NGC 6822 (Armandroff and Massey 1985) shows that the issue is by no means settled.

Future W-R searches will benefit from high–quantum-efficiency, high signal-to-noise CCDs, as these detectors overcome the problems of readout noise and limited field size. As an illustration we note our own high S/N CCD results (Moffat, Seggewiss, and Shara 1985) for the central cluster ($\phi \approx 2'$) of the 30 Dor nebula in which all W-R and strong-line Of stars have been detected down to $|\Delta m| \sim 0.05$ mag using the same new filter pair as here in IT2. This implies reliable detection of W-R and Of stars down to $W_e \approx 2$ Å with S/N ≈ 30 on each image.

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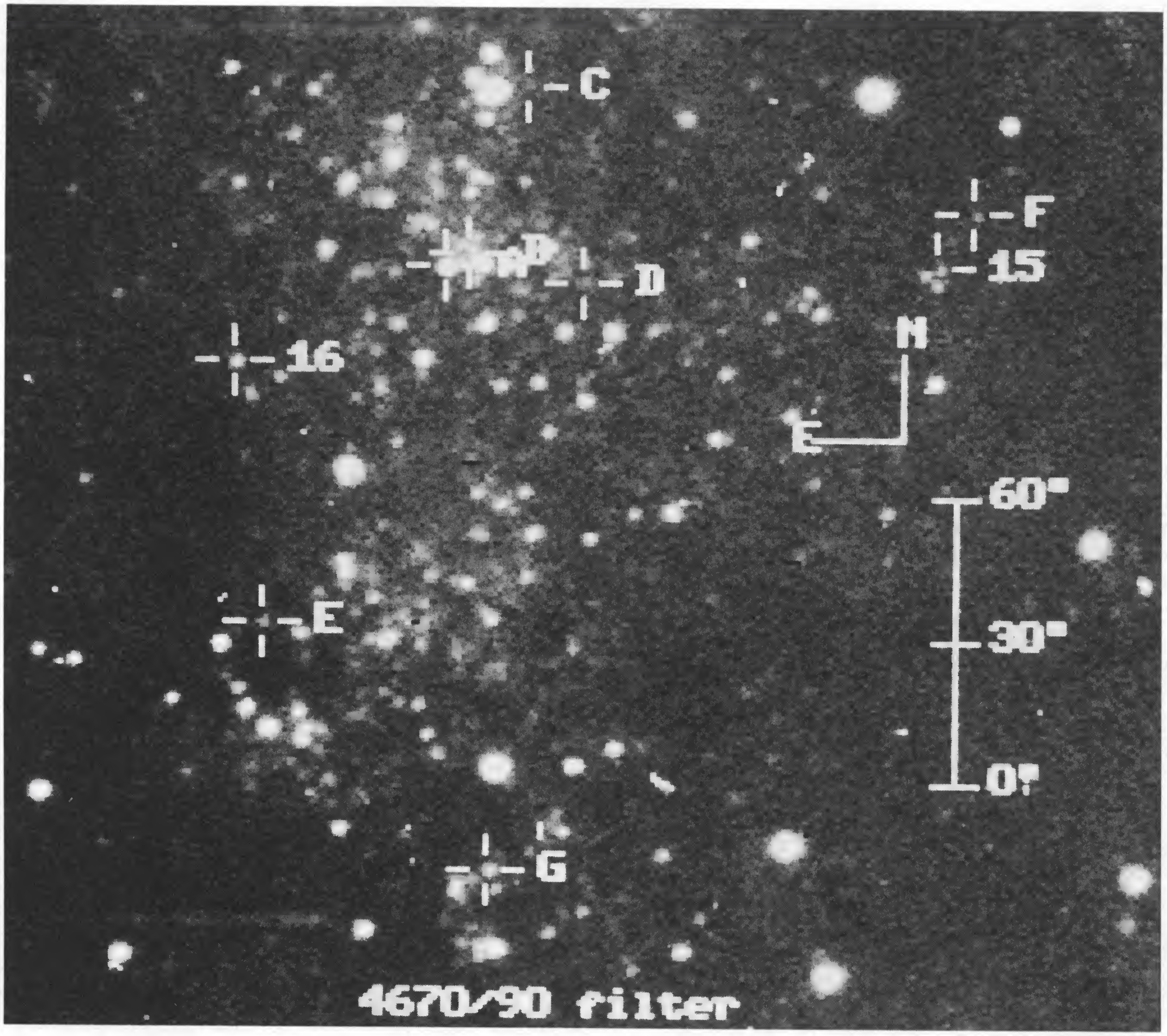

FIG. 7b

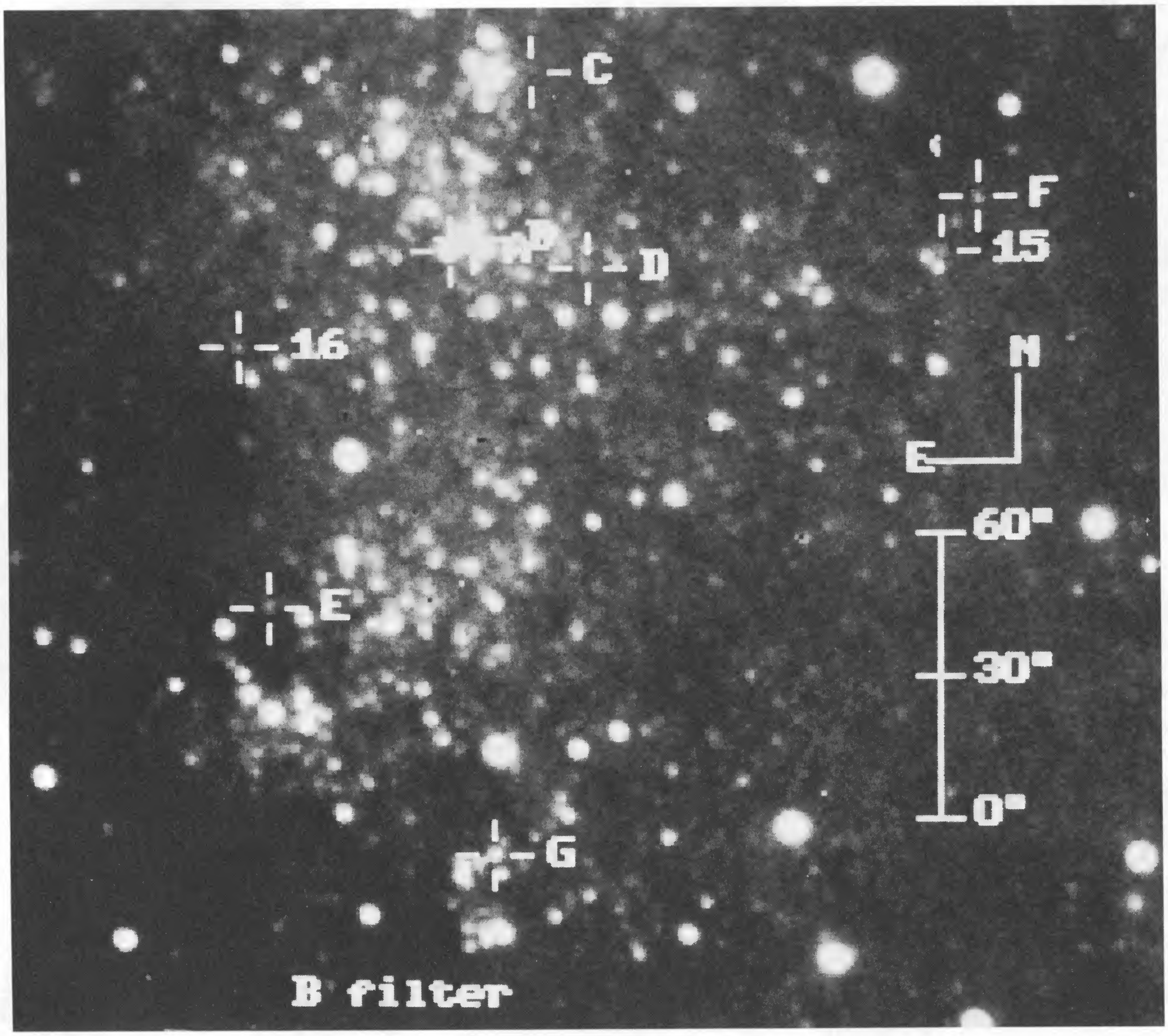

FIG. 7c

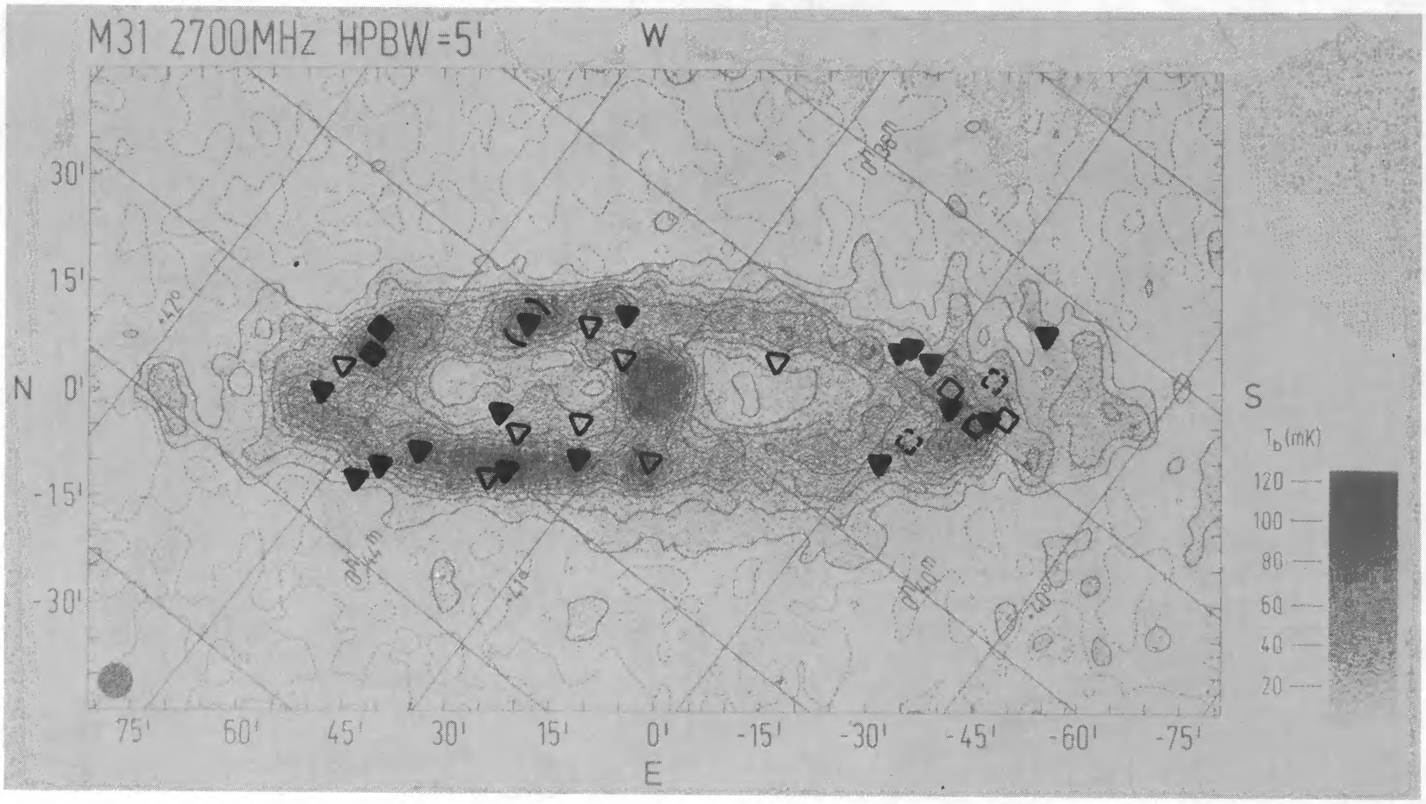

FIG. 8a

60 µm IRAS

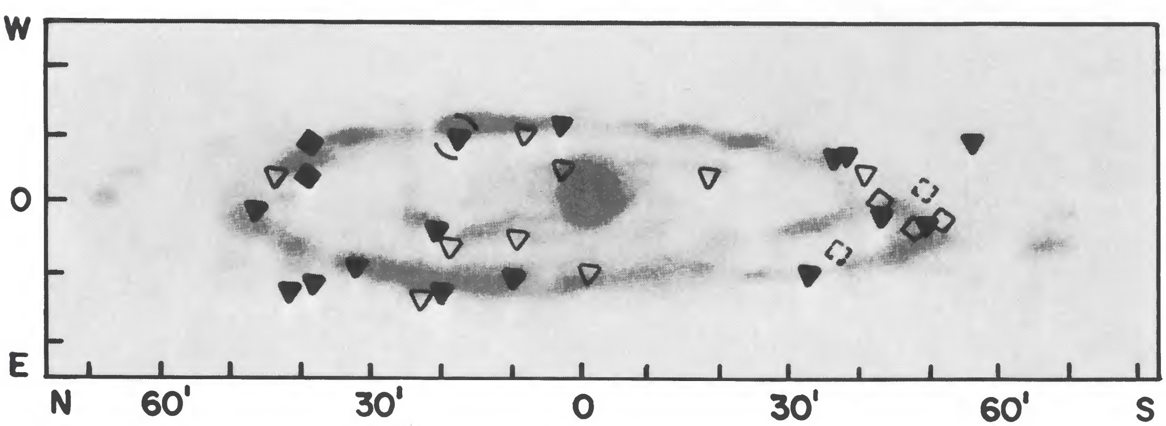

FIG. 8b

FIG. 8.—(*a*) Radio continuum map ($\lambda = 11$ cm) of M31 from Beck and Graeve (1982) on which are superposed all spectroscopically confirmed W-R stars found to date, with addition of two new high priority candidates in new narrow filter field IT2. Symbols are as in Fig. 1. (*b*) Same as (*a*), but for 60 μm *IRAS* map of M31 (Habing *et al.* 1984). (*a*) and (*b*) are reprinted courtesy of R. Beck and Springer Verlag, and H. Habing, respectively.

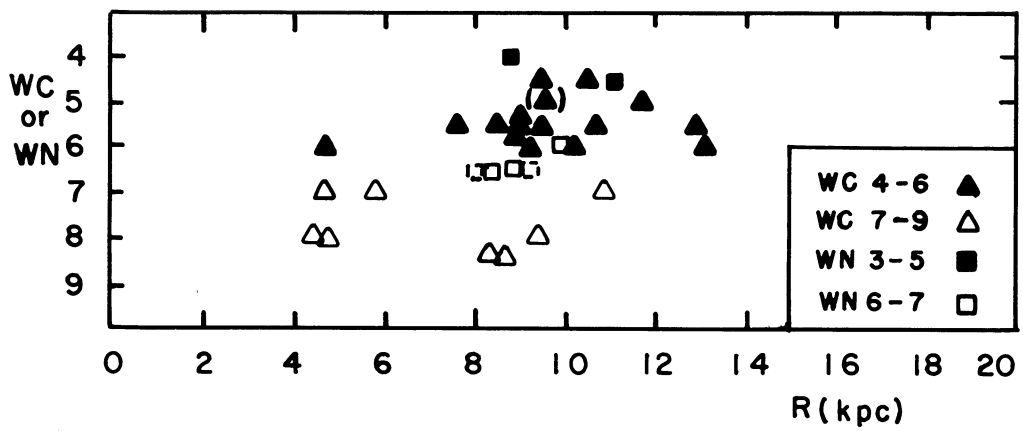

FIG. 9.—Distribution of various W-R subtypes, as in Fig. 6, as a function of galactocentric radius in M31

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