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THE WOLF-RAYET STAR POPULATION IN THE MOST MASSIVE GIANT H II REGIONS OF M33

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ABSTRACT

We have obtained narrow-band images of NGC 604, NGC 595, and NGC 592, the most massive giant H II regions (GHRs) in M33, in order to study their Wolf-Rayet content. These images reveal the presence of nine candidates in NGC 604 (seven WN, two WC), 10 in NGC 595 (nine WN, one WC), and two in NGC 592 (two WN). Precise positions and estimated magnitudes are given for the candidates, half of which have so far been confirmed spectroscopically as genuine W-R stars. The flux in the emission lines of all candidates is comparable to that of normal Galactic W-R stars of similar subtype. A few of the putative "superluminous W-R stars" are shown to be close visual double or multiple stars; their newly estimated luminosities are now more compatible with those of normal W-R stars. NGC 595 seems to be overabundant in W-R stars for its mass compared to other GHRs, while NGC 604 is normal. Factors influencing the W-R/O number ratio in GHRs are discussed: metallicity and age appear to be the most important.

Subject headings: galaxies: individual (M33) — galaxies: stellar content — nebulae: H II regions — stars: evolution — stars: Wolf-Rayet

I. INTRODUCTION

Wolf-Rayet (W-R) stars are thought to be the highly evolved descendants of the most massive ($M_i \gtrsim 30$–$40\ M_\odot$: see Conti *et al.* 1983; Humphreys, Nichols, and Massey 1985) O-type stars. For that reason and because their strong emission lines make them easy to detect, even in crowded regions, they are considered as good tracers of extreme Population I stars. The total number of W-R stars relative to the total mass of the parent population, such as a galaxy or an association, is expected to reflect the present efficiency of star formation at the massive end of the initial mass function (IMF). In M31 for instance, it is well established (although surveys are not complete; see Moffat and Shara 1983, 1987) that the number of W-R stars per unit mass is lower than in M33 or our own Galaxy, indicating a relatively low present global star formation rate in M31 (Smith 1988).

Three methods are primarily used to search for W-R stars in other galaxies: (*a*) serendipitous spectroscopy of selected stars or associations, which can lead to the discovery of a few W-R stars but which is tedious and can lead to erroneous conclusions; (*b*) low-dispersion objective prism surveys, which are not appropriate in crowded regions; and (*c*) interference filter imaging with photographic plates in extended regions or CCDs in smaller areas. A review of surveys for W-R stars in Local Group galaxies is presented by Azzopardi, Lequeux, and Maeder (1988).

Giant H II regions (GHRs) appear to be the most intense sites of star formation known, and they offer the unique opportunity to study massive stars at their birthplace. They are distinguished from their more normal counterparts on the basis of their large size (50 pc or more across), high Balmer-line luminosities (indicative of a large number of OB ionizing stars), and high-velocity kinematics (Roy, Arsenault, and Joncas 1986).

With regard to the important role that W-R stars play in the evolution of massive stars and the influence that they may have on the kinematics and "ecology" of their environment (i.e., the return of processed material, momentum, and energy via their strong winds and their eventual explosion as supernovae; see Abbott 1982 and Van Buren and McCray 1988), a study of GHRs without a parallel search for W-R stars would be incomplete. Moreover, the understanding of the relations between W-R stars and their parent GHR would provide clues to the understanding of some starburst galaxies in which strong W-R spectral characteristics are observed (Kunth and Schild 1986).

The W-R content of the largest GHR in the Local Group, 30 Dor, is well established (Moffat *et al.* 1987). The central object, R136a, once believed to be a supermassive object (Schmidt-Kaler and Feitzinger 1981; Savage *et al.* 1983), is now considered as a tight cluster (Weigelt and Baier 1985; Walker and O'Donoghue 1984) containing four to five WN stars (Moffat, Seggewiss, and Shara 1985, hereafter MSS). The W-R population of 30 Dor, as well as of the Galactic GHR NGC 3603 (MSS), is completely dominated by WN stars.

Apart from 30 Dor in the LMC, the most massive GHR in the Local Group, namely NGC 604 and NGC 595, are located in M33. With about $10^6\ M_\odot$ of H II (Viallefond and Goss 1986), NGC 604 is an order of magnitude more massive and more luminous ($M_B \sim -11.7$; Hunter and Gallagher 1985) than any known H II region in our own Galaxy. The radio continuum flux from this object, which is 90% thermal (Israel 1975), is believed to be generated by the equivalent of ~ 100 O6 stars (Israel and van der Kruit 1974). D'Odorico and Rosa (1981*a*) were the first to discover W-R stars in NGC 604: spec-

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troscopy of the brightest knots revealed the presence of W-R characteristics in most of them. This led these authors to conclude that an unusually large number (~ 50) of W-R stars was present in that nebula. Independently, Conti and Massey (1981, hereafter CM) confirmed the presence of W-R spectra in three of the brightest objects in NGC 604. Assuming that these objects were single stars, they concluded that some W-R stars in GHRs were, like R136, superluminous and hence supermassive. Both studies were made with a relatively large (5″) aperture, leading to considerable confusion e.g., light contamination by nearby stars, imprecise location of W-R candidates) in such a crowded region.

NGC 595 has received much less attention than NGC 604. It is less massive ($M_{\rm H\,II} \sim 2 \times 10^5$ $M_\odot$: Viallefond and Goss 1986; total mass of OB stars ~ 7000 $M_\odot$ compared to $\sim 15{,}000$ $M_\odot$ for NGC 604: Kennicutt 1984) and less luminous ($M_B \sim -11.2$: Hunter and Gallagher 1985) than NGC 604, but located closer to the center of M33. CM have discovered three W-R stars in NGC 595. However, as we now know (see §§ III), two of them were erroneously identified with bright "stars" just a few arcseconds away, which again led these authors to propose that one was seeing superluminous (thus supermassive) W-R stars. A photographic survey (finding charts in Massey *et al.* 1987; spectroscopy in Massey and Conti 1983, hereafter MC) was able to detect two more W-R stars. Armandroff and Massey (1985) used NGC 595 as a test object for a CCD survey of W-R stars in NGC 6822 and IC 1613 and found yet three more candidates.

NGC 592 is the smallest of the GHR studies here. It is about 15 times less massive than NGC 604 (Kennicutt 1984), and its visually brightest stars (HS 71 and 59A in Humphreys and Sandage 1980, hereafter HS) are in fact field Galactic stars seen in projection. CM have detected spectroscopically a W-R star in NGC 592: it was identified with a bright star nearby and considered as supermassive.

Although the presence of W-R stars is now well established in these three regions, some uncertainties remain. The purpose of the present study is (*a*) to locate precisely the W-R stars already discovered, (*b*) to detect new W-R candidates, and (*c*) to make a global assessment of the W-R population in NGC 604, NGC 595, and NGC 592.

II. OBSERVATIONS

CCD images were obtained with an RCA chip (512 × 320 pixels) attached to the Cassegrain focus of the Observatoire du Mont Mégantic 1.6 m telescope. With a scale of 0″.48 pixel^{-1} and a seeing between 1″.2 and 1″.5, the images were always oversampled. The set of filters, described in Table 1, is very similar to the set used by Armandroff and Massey (1985) and chosen to optimize the detection of W-R stars. The broad-band reference continuum filter used to decrease the overall exposure time by MSS was discarded in this work for two reasons: (*a*) it includes, at its edge, the strong nebular Hβ line; and (*b*) although the W-R emission lines are diluted in this filter, they still contribute in a nonnegligible way to the flux (0.2 mag for the narrow-line WNL stars and up to 1.5 mag for some WC stars). We have observed a few Galactic W-R stars with these filters in order to check their capability of sorting out W-R stars and to discriminate between WN and WC stars. The results are presented in Table 2. The equivalent widths (EW) found with our filters (supposing that the transmission curve was a square box and that all the line was included in the filter) agree reasonably well with the spectrophotometric studies (see Table 2 for references) for WN7–8 stars. However, we systematically underestimate the EW of WNE and WC stars because in those cases our filters are narrower than the lines themselves. The journal of the GHRs observations is presented in Table 3.

The images were processed as follows: the first step was to correct mismatches in image structure between the frames due to seeing, guiding, and focus differences. This was done using the algorithm CLEAN (in AIPS) and only for NGC 604. In this case, all the images were individually deconvolved using the bright 15th mag star 1′.5 south of the nebula as point spread function (PSF) and reconvolved with a 1″.3 FWHM Gaussian profile. The original images all had 1″.2–1″.4 FWHM, and we have not tried to increase the resolution. For NGC 595, this procedure was not used because the only star in the field bright enough to be used as PSF (1′.5 north of the nebula) has a faint companion which prevented proper deconvolution. In both cases, the best images in the same filter were co-added (after matching in X and Y by a translation) to increase the S/N ratio. In the case of NGC 592, only one good pair of images was obtained (in the continuum and 4686 filters), and no deconvolution was performed. The net emission-line image was then obtained by subtracting the continuum image from the emission-line image, after scaling in such a way that bright (non–W-R) stars outside the nebula disappeared. In the case of NGC 595, the subtraction of the continuum image from the on-line 4686 Å image was straightforward and the mismatches in image structure were not apparent after subtraction. However, because the quality of the on-line 4650 Å image was not as good as the quality of the continuum image (FWHM $\sim$ 1″.5 compared to ~ 1″.3), the latter was convolved with a Gaussian profile before subtraction. The fact that the continuum filter is not centered at the same wavelength as the emission-line filters may cause very red stars ($B-V \geq 1.0$) to appear as holes in the net image. In fact, observations of a few associations in M33 show that for non W-R stars, Δ(Emission − Continuum) $\sim 0.1(B-V)$. This difference should not cause problems for the majority of the bright stars in the GHRs, which are intrinsically blue.

Short-exposure (5 minute) spectrograms of a few stars in NGC 604 were obtained with a 1″ slit at the coudé focus of the CFHT 3.6 m telescope with grating 6 and the RCA2 CCD as detector (3.7 Å pixel^{-1}), just before twilight on 1988 June 15 and 16.

TABLE 1

FILTERS

Filter	λ_c (Å)	FWHM (Å)	Purpose
Continuum	4780	65	Reference continuum
4686	4689	35	He II λ4686 in WN
4650	4647	29	N III λ4640 in WN, C III/IV λ4650 in WC

TABLE 2

GALACTIC WOLF-RAYET STARS

Spectral Class[a]	WR[a]	Continuum − 4686[b]	Continuum − 4650[b]	W_{4686}(CCD)[c]	W_{4686}(Sp.)[c]	$W_{4640/50}$(CCD)[c]	$W_{4640/50}$(Sp.)[c]
WN8	123	0.77	0.98	36	32	43	46
	124	0.84	0.97	41	37	41	47
	130	0.75	0.70	35	45	26	38
	147	0.60	0.49	26	31	17	23
WN7	131	0.65	0.59	29	39	21	18
	158	0.59	0.45	25	31	15	20
WN6	141	1.46	0.61	100	230	22	51
	149	1.70	0.65	132	200	23	49
	153	1.04	0.50	56	48	17	13
WN4	128	1.23	0.30	74	110	9	25
	129	1.59	0.46	117	186	15	18
WN3	152	1.16	0.40	68	110	13	31
WC9	121	0.76	1.10	35	...	51 (86)	123
WC8	135	1.25	2.20	75	...	230 (305)	537
WC6	5	2.01	2.89	186	...	388 (574)	1120
	132	1.75	2.88	141	...	388 (529)	1260
	154	1.82	3.02	151	...	435 (586)	933
WC5	4	2.00	2.97	186	...	415 (601)	1230
	143	1.51	1.98	105	...	151 (256)	457
	150	2.48	2.93	309	...	406 (715)	1070
WC4	146	1.31	1.54	81	...	91 (172)	372

[a] From van der Hucht *et al.* 1988.

[b] Magnitude differences in the continuum filter minus the 4686 filter and the 4650 filter.

[c] Equivalent widths in Å deduced from the CCD data and observed in the spectroscopic data (Conti and Massey 1989) for the 4686 and 4640/50 spectral features. In the case of WC stars, the C III/IV line is blended with He II 4686, and the spectroscopic value refers to the total blend. Accordingly, we indicate the total equivalent width deduced from both filters with the CCD in parentheses.

III. DISCUSSION OF THE IMAGES

a) NGC 604

The continuum, on-line, and net emission images of NGC 604 are displayed in Figure 1. Details on the candidates are presented in Table 4. These images confirm that many of the bright knots in this nebula contain W-R stars.

Stars 1 and 2 were considered until now together as a single W-R star (CM11). The flux in each emission-line filter suggests that star 1 is a WC star and that star 2 is a WN star. This is confirmed by the spectra (not photometrically calibrated) displayed in Figure 2. Star 1 shows the C III/IV λ4650 and C IV λ5802/12 lines with no sign of C III λ5696, indicating a WCE classification, whereas star 2 displays He II λ4686. In their first paper, CM classified CM11 as WC on the basis of the wide C III/IV λ4650 line (see their Fig. 2*c*) but changed their classification later because "additional spectral coverage has shown that it has no C IV λ5812" (MC). We suggest that their first spectrogram included light from both stars (1 and 2), whereas the second time they obtained a spectrum of the visually brighter one, star 2. It is moreover obvious from the shape of star 2 (Fig. 1) that this object is indeed multiple. It could then be a tight cluster containing one WN star.

The area around stars 3, 4, and 5 was also known to harbor

TABLE 3

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Region	Filter	Image	Date (1987)	Exposure Time (s)	FWHM
NGC 592............	Continuum	N592b1	Nov 28	2000	1″3
	4686	N592c1	Nov 28	3000	1.3
NGC 595............	Continuum	N595b1	Oct 26	2000	1.4
	Continuum	N595b2	Nov 27	1800	1.2
	4686	N595c1	Oct 26	3000	1.4
	4686	N595c2	Nov 27	3000	1.2
	4650	N595d2	Nov 27	3000	1.4
	4650	N595d3	Aug 31	3000	1.6
	4650	N595d6	Nov 14	2400	1.5
NGC 604............	Continuum	N604b1	Sep 27	1500	1.4
	Continuum	N604b3	Nov 27	1500	1.4
	Continuum	N604b5	Nov 28	1200	1.2
	4686	N604c1	Sep 27	3000	1.4
	4686	N604c3	Nov 27	3000	1.4
	4686	N604c4	Nov 28	2500	1.3
	4650	N604d1	Sep 27	3000	1.4
	4650	N604d3	Nov 27	3000	1.4
	4650	N604d4	Nov 28	2500	1.3

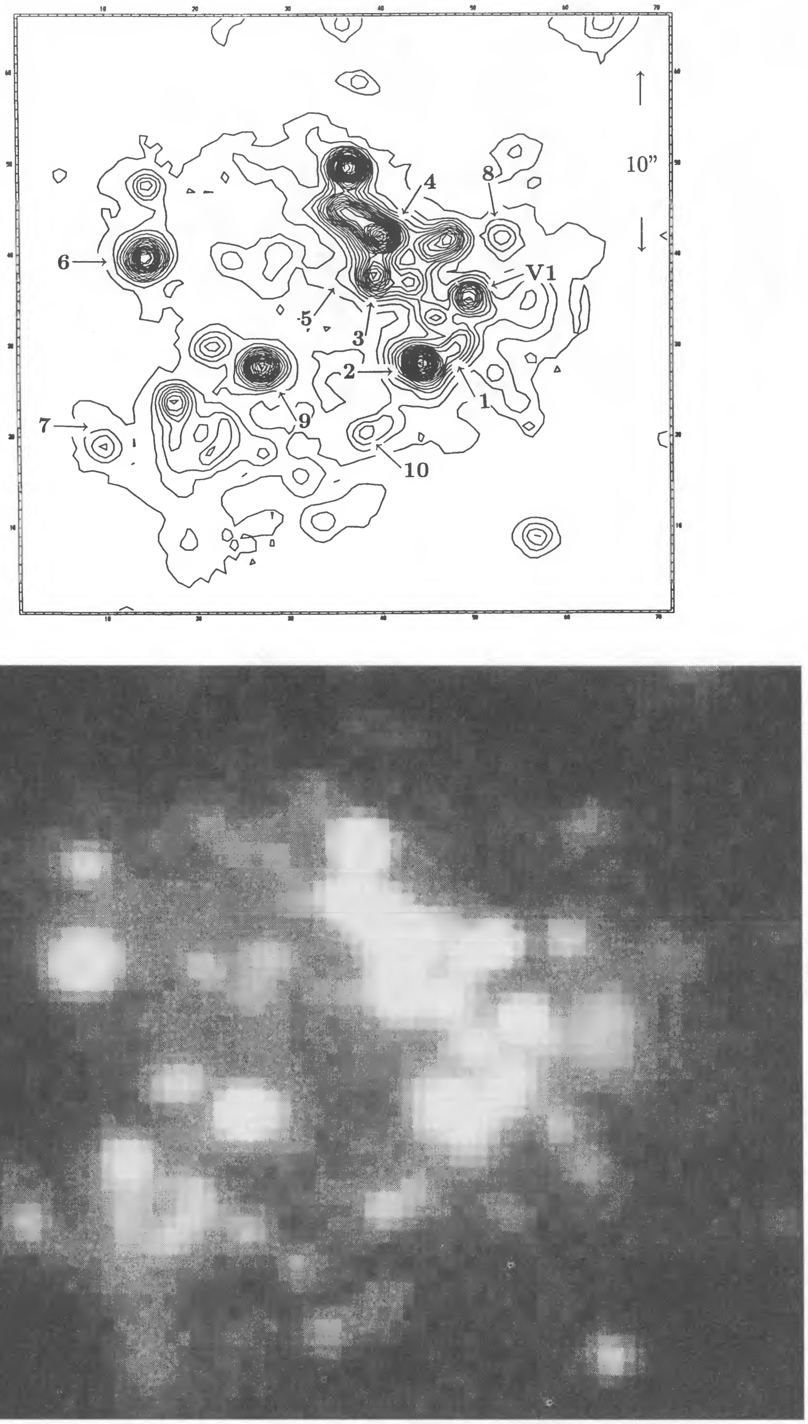
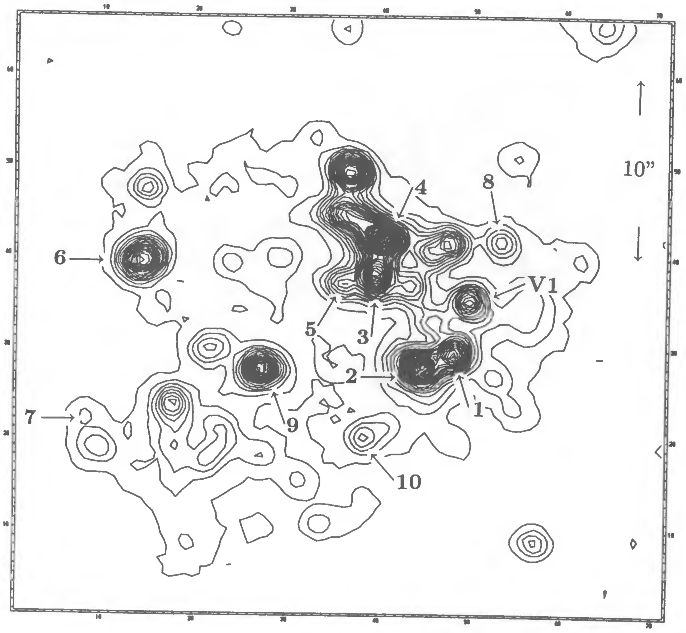


FIG. 1*a*

FIG. 1.—Images and corresponding (linearly scaled) isophotes of NGC 604 (north is at the top, east to the left): (*a*) continuum (4780 Å); (*b*) on-line 4686 Å; (*c*) on-line 4650 Å; (*d*) net 4686 Å; (*e*) net 4650 Å.

W-R stars (CM12; star E in D'Odorico, Rosa, and Wampler 1983; position 4 in D'Odorico and Rosa 1981*a*) with mixed WN/WC spectra. Actually, two WN stars (stars 3 and 4) and one WC star (star 5) show up distinctly, a spectrogram of star 4 is displayed in Figure 2, showing a moderately strong He II λ4686 line. Unfortunately, the spectrum does not go blue enough to show the N III λ4641 line, but the relative flux of the two narrow-band images suggests a WN6 classification.

The spectrum of star 6 (CM13) is shown by CM (their Fig. 2*b*). Although it is one of the brightest objects in NGC 604 ($M_{4780} \sim -8.2$), the flux in its emission lines is not abnormal compared to Galactic WNL stars (see below). Rosa and Solf



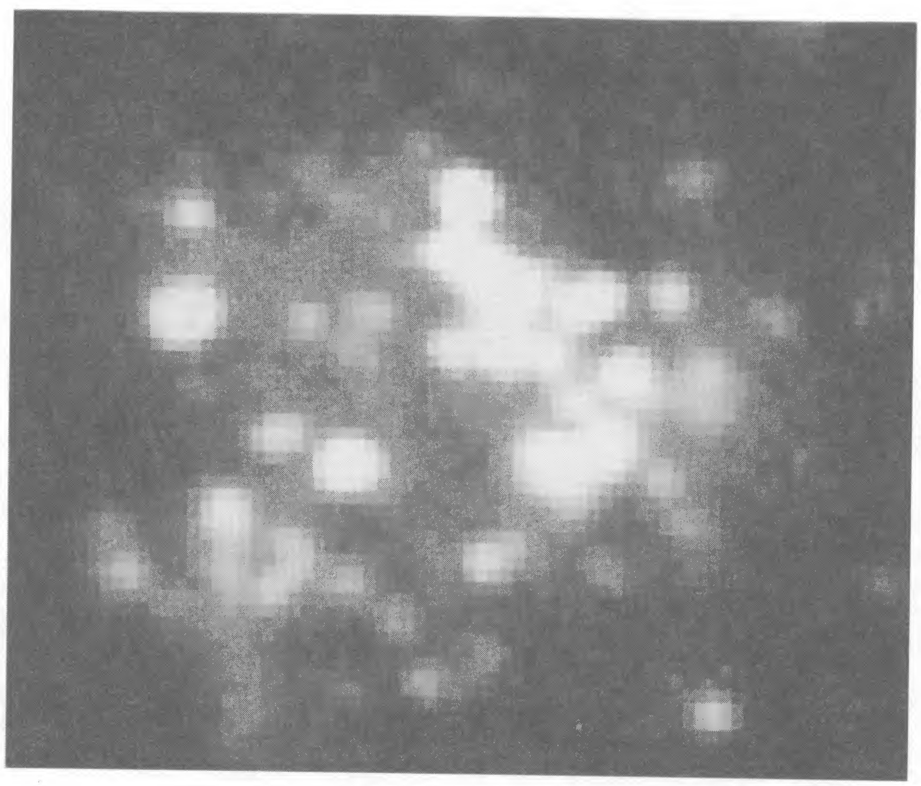


FIG. 1*b*

(1984) and Clayton (1988) mention the presence of a large expanding gas bubble surrounding this object. The energy input necessary to blow this bubble can be easily supplied by a single W-R star (Clayton 1988). The same can be said about another, larger bubble around stars 3, 4, and 5 (CM12). The presence of three W-R stars can account for the energy in this bubble (Clayton 1988).

Stars 7, 8, and 10 are new candidates. The weakness of their net emission-line flux suggests some caution until a good spectrogram confirms their W-R status. Star 7 is rather faint ($M_{4780} \sim -4.7$), but the EWs of its emission lines are large according to the filters, indicating a WNE classification. Conversely, stars 8 and 10 are bright, but their emission-line flux is rather weak, suggesting an Of/WNL classification.

The star indicated as V1 was found to be 0.8 mag fainter than usual in one of our continuum images (N604b3). One hour later, it was ~0.4 mag fainter in the N604c3 image than in the other 4686 images. It came back to its " normal " bright-

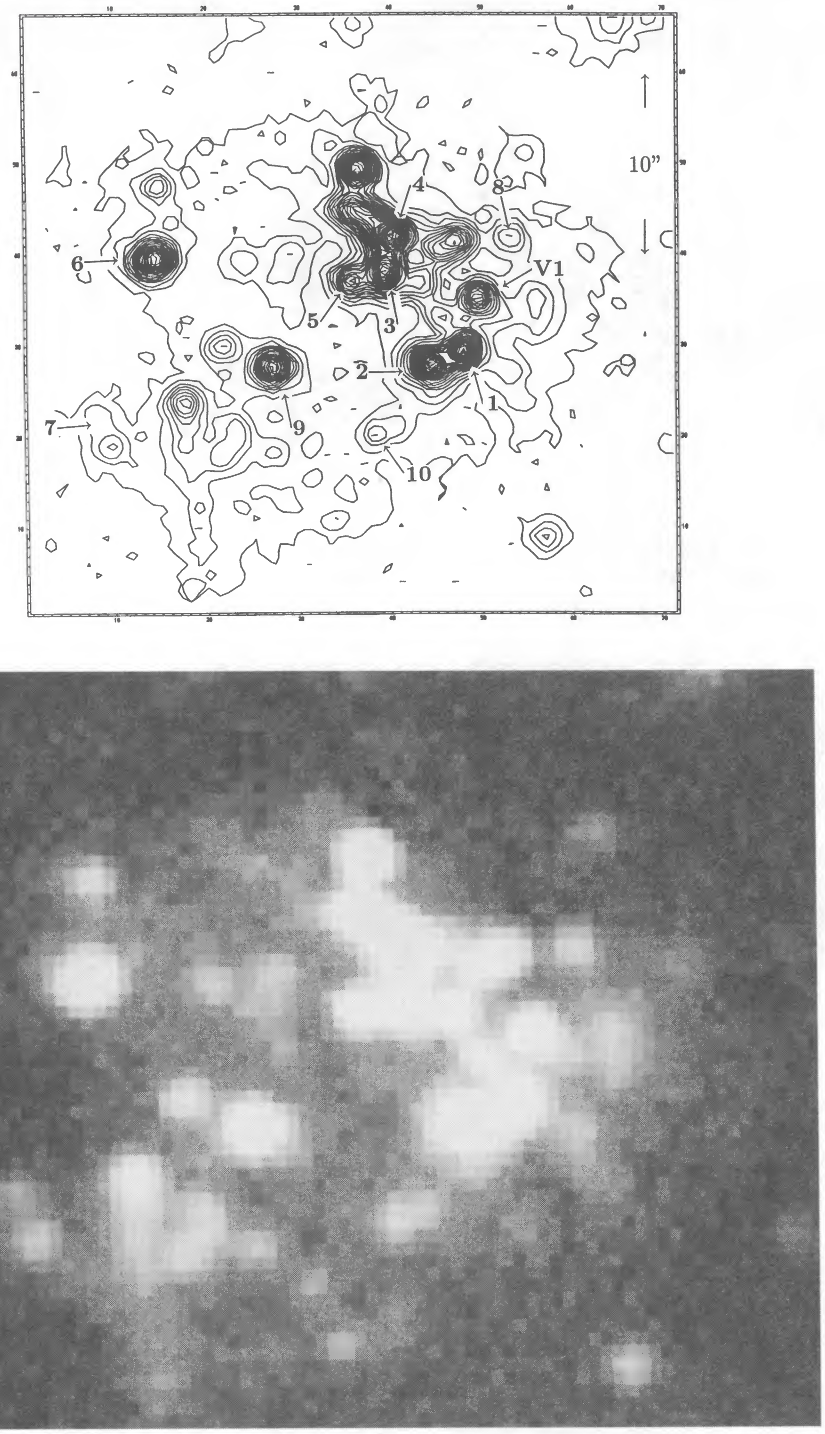


FIG. 1c

ness another hour later (image N604d3). This variability is probably the reason that it appears bright in the net 4650 image; it is probably not a W-R star. Long-term monitoring of this star might prove interesting.

Star 9 (identified in the direct images before subtraction) has been previously identified as a W-R star by D'Odorico and Rosa (1981*b*), D'Odorico, Rosa, and Wampler (1983) and Diaz *et al.* (1987) (region B in all papers). However, it does not appear in our net emission-line images. Careful examination of its spectrum (Fig. 2) shows a narrow emission line, but centered at 4659 Å, just outside our 4686 filter and within the limits of our 4650 filter. The spectrum displayed by D'Odorico, Rosa, and Wampler (their Fig. 6) also suggests a similar shift. If this line is the He II 4686 line, its position corresponds to a radial velocity in excess of 1000 km s^{-1}, which is difficult to explain. It could also be the [Fe III] 4658 line, which is sometimes seen

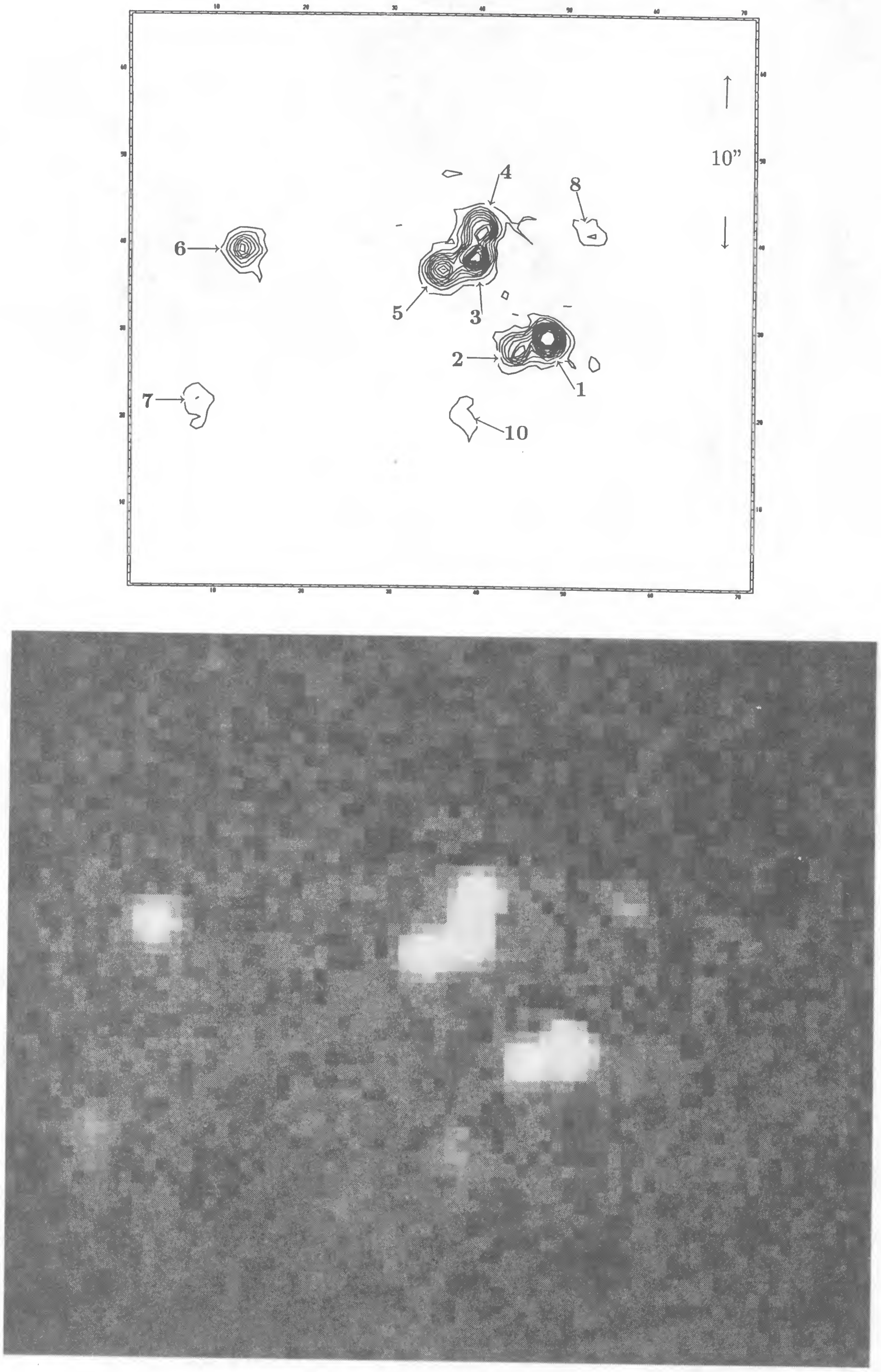


FIG. 1*d*

in LBVs. A good spectrogram of this star is needed to clarify this point. In the following discussion we consider this star as a confirmed W-R star.

An estimate of the magnitude of each candidate obtained with DAOPHOT (Stetson 1987) is presented in Table 4. For this, we have used the individual continuum (4780 Å) images and we have taken stars from Humphreys and Sandage (1980) outside the nebula as reference. The m_{4780} magnitude of these stars was interpolated from their B and V magnitudes. The errors on the magnitudes may be as large as 0.2 mag because of the severe crowding and the variable background. We have adopted a true distance modulus of 24.3 for M33 (Madore *et al.* 1985) and a constant extinction across the whole nebula, as suggested by Diaz *et al.* (1987) and converted to the 4780 filter ($A_{4780} = 0.9$) using their average value for $C_{H\beta}$. The excellent image (FWHM = 0\".6) obtained by Debray (1990) shows that

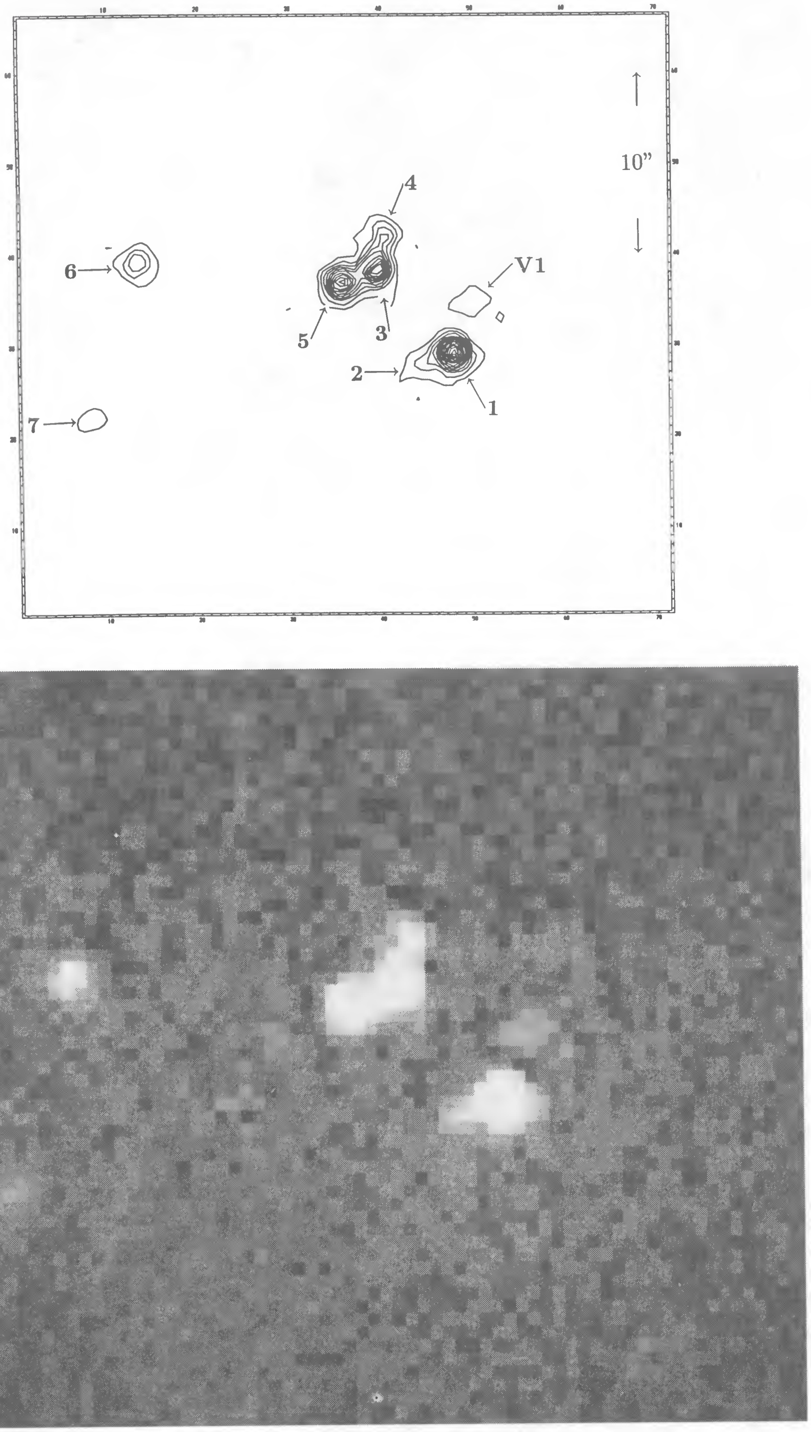


FIG. 1*e*

stars 2, 3, and 6 are resolved into multiple components. This reduces the absolute magnitude of these W-R stars to about −7.5.

We also present in Table 4 the magnitude differences for detected stars (some of which may still be multiple) between the continuum and emission-line filters, as well as the equivalent widths inferred from them. In Figure 3, we show the net emission line flux (within our filters) of Galactic W-R stars, scaled to the distance of M33 (725 kpc). The distances and absolute magnitudes of these stars were taken from van der Hucht *et al.* (1988). As mentioned previously, because our filters are narrower than the lines in WC stars, we underestimate their flux

TABLE 4

Wolf-Rayet Stars in NGC 604

Star	m_{4780}	M_{4780}	Continuum − 4686	W_{4686}	Continuum − 4650	$W_{4640/50}$	Spectral Class	Remarks[a]
1...........	17.8	−7.4	1.1	61	1.3	67	WCE	CM11(MC74) east
2...........	16.7	−8.5	0.2	7	0.1	3	WN	DR3, CM11(MC74) west
3...........	17.3	−7.9	0.5	20	0.5	17	WNL	CM12(CM75) east
4...........	16.6	−8.6	0.3	11	0.2	6	WN	DR4?
5...........	19.6	−5.6	1.2	71	2.0	155	WC?	CM12(MC75) west
6...........	17.0	−8.2	0.2	7	0.1	3	WN	DR1, CM13(MC76), region C in DRb, DRW, D87
7...........	20.5	−4.7	1.0	53	1.2	59	WN?	New candidate
8...........	18.7	−6.5	0.4	16	0.1	3	WN?	New candidate
9...........	17.1	−8.1	...	...	...	...	WN	Region B in DRb, DRW, D87, not detected as W-R here
10...........	18.8	−6.4	0.3	11	...	...	WN?	New candidate

Notes.—Definitions as in Table 2.

[a] CM = Conti and Massey 1981, MC = Massey and Conti 1983, DR = D'Odorico and Rosa 1981*b*, DRW = D'Odorico, Rosa, and Wampler 1983, D87 = Diaz *et al.* 1987. Note that some objects, especially the brighter ones, may still not refer to single stars. This also applies to Tables 5 and 6. Hence, the absolute magnitudes must be taken as bright upper limits.

by about a factor of 2 depending on the subtype. We display in Figure 3 the net emission-line flux of the W-R candidates in NGC 604, as well as in NGC 595.

b) NGC 595

The images of NGC 595 are displayed in Figure 4, and details on the W-R candidates are presented in Table 5. The "4780" magnitude was determined with DAOPHOT on the individual continuum images from comparison with five stars observed by HS, namely 62A, 62B, HS164, HS166 and HS168. The absorption was found to be highly variable and relatively large in NGC 595 (Viallefond, Donas, and Goss 1983) and we have used approximate values based on their Figure 5. We also present in Table 5 the magnitude difference between the continuum and emission-line filters, as well as the equivalent widths of the emission lines as registered by the filters.

In addition to the five spectroscopically confirmed W-R stars, we have detected four unconfirmed candidates, two of them (stars 4 and 5) being very bright and standing out clearly. Armandroff and Massey (1985) have also detected these last two (their stars 3 and 4), but no spectroscopy has been published so far.[2] Lequeux, Meyssonier, and Azzopardi (1987) have mentioned these two objects in their objective prism survey, but classify them as luminous blue variables (LBV), not as W-R stars. Some LBVs show He II λ4686 in emission and/or [Fe II] λ4658 (which falls in our 4650 filter), but these lines are never as strong as He II λ4686 or 4650 emission in genuine W-R stars, as seen here.

Stars 3, 6, and 8 were also known before and spectroscopically confirmed, star 3 being the only WC star in NGC 595. Star 6 (MC28) is strong in the 4686 filter but quite weak in the 4650 filter, indicating a WNE classification (see the spectrum in MC), although Massey, Conti, and Armandroff (1987)

[2] A recent paper by Armandroff and Massey (1990) confirms that stars 4, 5, and 7 are WNL.

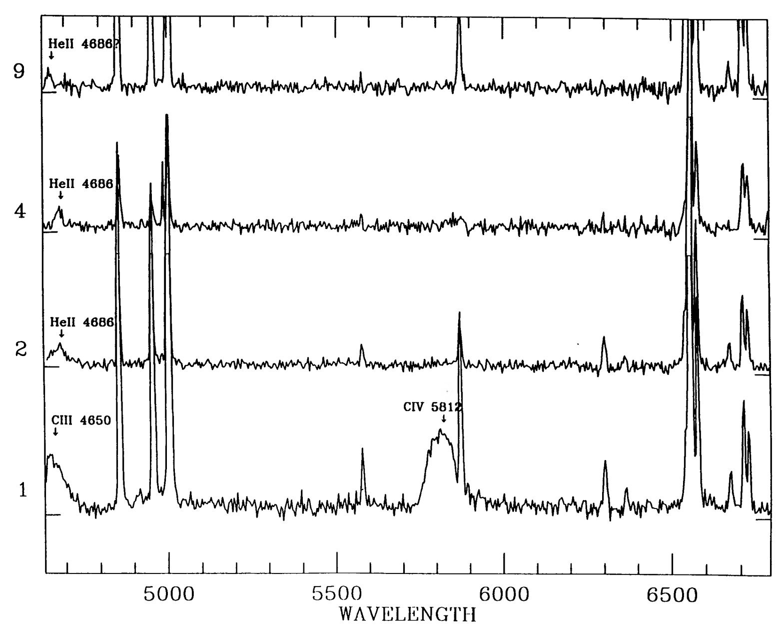


Fig. 2.—Snapshot spectrograms of four W-R stars in NGC 604. Intensity has been normalized to the continuum. Numbers on the left refer to the W-R star numbers, as in Table 4.

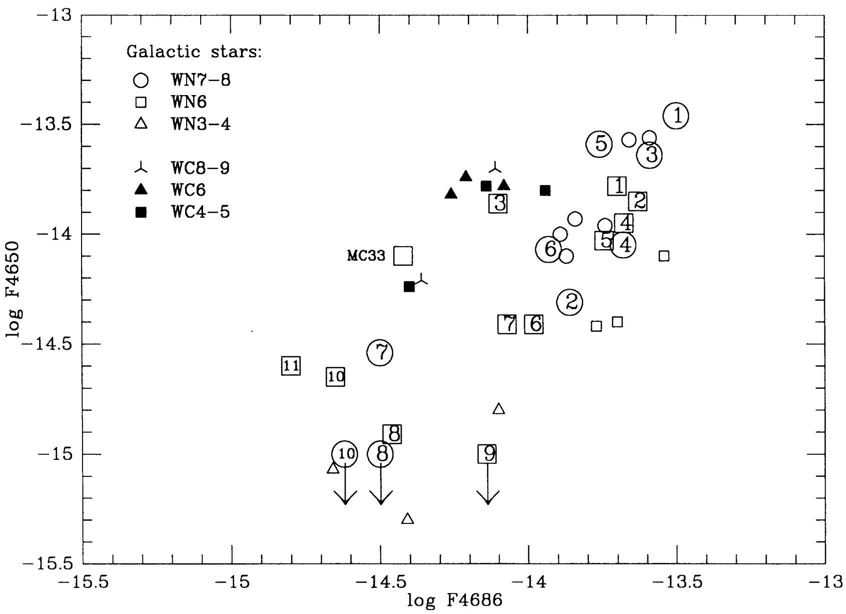


FIG. 3.—Net flux (in units of ergs cm^{-2} s^{-1}) in the 4650 Å filter vs. net flux in the 4686 Å for Galactic W-R stars (shifted to 725 kpc) and M33 W-R candidates (corrected for absorption). The number inside circles (NGC 604) and squares (NGC 595) refer to the candidate numbers, as in Tables 4 and 5. Arrows indicate upper limits on the flux. The flux was assumed to be 5.3×10^{-9} ergs cm^{-2} s^{-1} $Å^{-1}$ at 4780 Å for a zeroth mag star (Heber *et al.* 1984). We have also assumed that our filters have square-shaped transmission profiles.

classify it as WNL. The WC star MC 33 stands out clearly in our net emission images (not shown here). It is located $\sim 1'$ from the core of the nebula ($\sim 30''$ from the edge), i.e., 100–200 pc from the core, in projection. Supposing that it was formed in NGC 595, and that it was ejected from it during the first stages of the cluster formation by interaction with other massive stars (see Gies and Bolton 1986), the average speed necessary to reach its present location (supposing an average 4×10^6 yr for an O star lifetime) is 25–50 km s^{-1}, which is not exceedingly high. Its uncertain membership in NGC 595 is indicated by parentheses in Table 5.

Star 1, which was previously identified with the bright star HS 170 (see CM) and hence classified as superluminous, is now seen to be the northern extension of the elongated knot containing at least two stars. This is also the case of star 2, which is clearly resolved from another bright star $\sim 2''$ to the SE (HS171). Even in the net emission-line images, star 2 is elongated and could be composed of two W-R stars. The new estimated magnitudes of stars 1 and 2, not allowing for possible multiplicity, are still quite high, but no more than some WNL stars, e.g., as seen in 30 Dor (see Moffat 1989).

One spectroscopically confirmed Of/WN star (CM4, MC30, here candidate 10) is only marginally brighter than the background in the net images. Its spectrum (Fig. 2*b* in MC) shows very weak emission lines, and it may be just at the limit of detection with our technique. Star 11 (HS 164; not shown in Fig. 4) is very weak in the net 4686 image but shows up well in the net 4650 image. We tentatively classify it as Of/WNL, but confirming spectroscopy is required. As for MC33, we do not include it formally in NGC 595 because of its relatively large separation from the core of the nebula.

Finally, stars 7 and 9 emerge in the net emission images (star

TABLE 5

WOLF-RAYET STARS IN NGC 595

Star	m_{4780}	$M_{4780}(A_B)$	Continuum − 4686	W_{4686}	Continuum − 4650	$W_{4640/50}$	Spectral Class	Remarks[a]
1	18.6	−6.9 (1.2)	0.7	32	0.6	21	WN	CM6, MC32, AM6, N of HS 170
2	17.7	−7.9 (1.3)	0.3	11	0.3	9	WNL	CM5, MC31, NW of HS 171
3	20.3	−5.0 (1.0)	0.9	45	1.5	86	WC	MC29, AM5
4	18.5	−6.6 (0.8)	0.9	45	0.6	21	WN?	LMA79, AM4
5	18.6	−6.5 (0.8)	0.9	45	0.6	21	WN?	HS165, LMA78, AM3
6	19.5	−5.6 (0.8)	1.0	53	0.5	17	WN	HS167, MC28, AM2
7	20.2	−5.4 (1.3)	0.5	20	0.2	6	WN?	AM7
8	20.5	−4.8 (1.0)	0.8	38	0.3	9	WN	MCA4
9	19.6	−6.1 (1.4)	0.5	20	0.1	3	WN?	New candidate
10	17.6	−7.9 (1.2)	...	...	...	...	Of/WN	CM4, MC30, *v.* weak
MC 33[b]	20.8	−4.0 (0.5)	1.4	92	2.2	190	WC	AM8, runaway?
11[b]	18.4	−6.4 (0.5)	0.1	3	0.3	9	Of/WNL?	HS164, runaway?

[a] CM = Conti and Massey 1981; MC = Massey and Conti 1983; AM = Armandroff and Massey 1985; HS = Humphreys and Sandage 1980; LMA = Lequeux, Meysonnier, and Azzopardi 1987; MCA = Massey, Conti, and Armandroff 1987.

[b] Outside the main core.

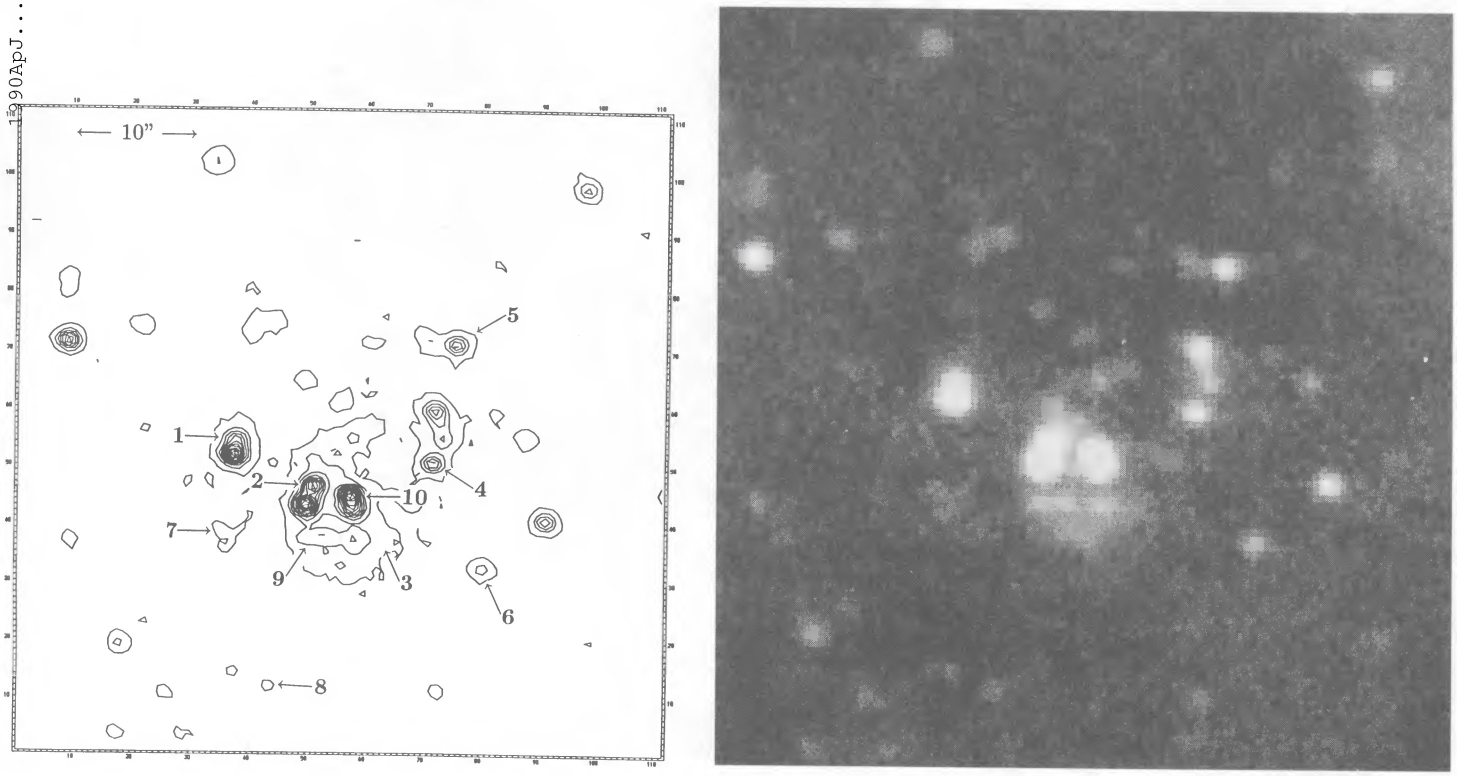


FIG. 4*a*

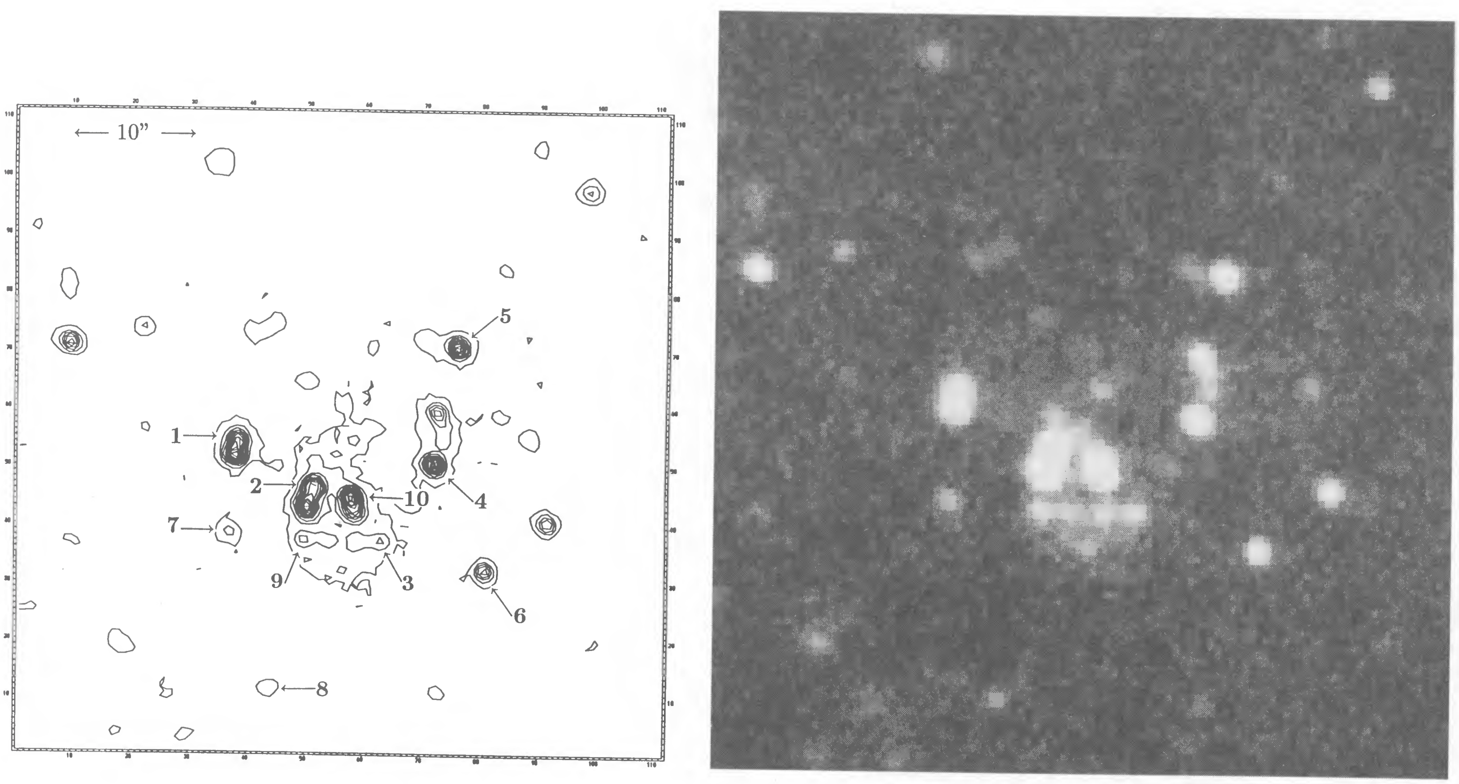


FIG. 4*b*

FIG. 4.—Same as Fig. 1, for NGC 595

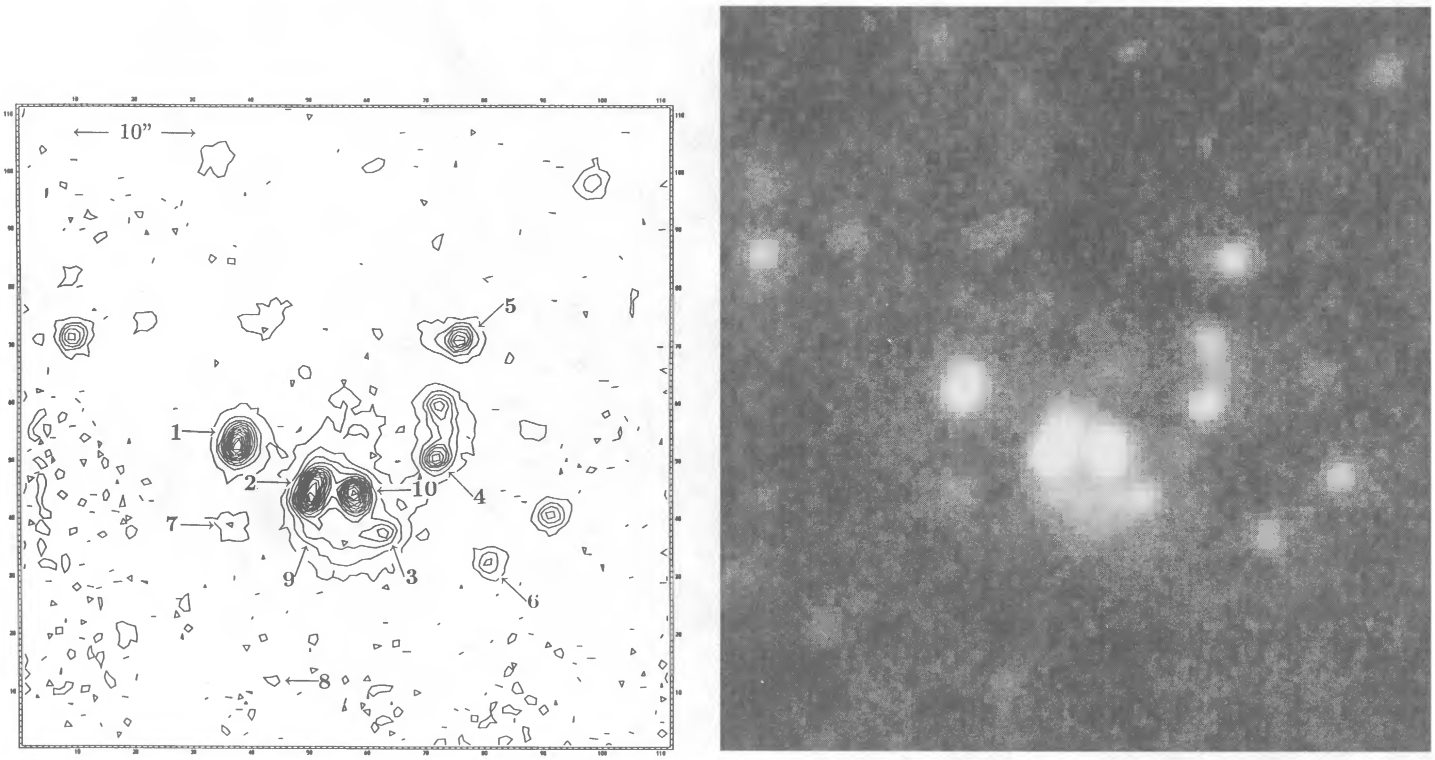


FIG. 4*c*

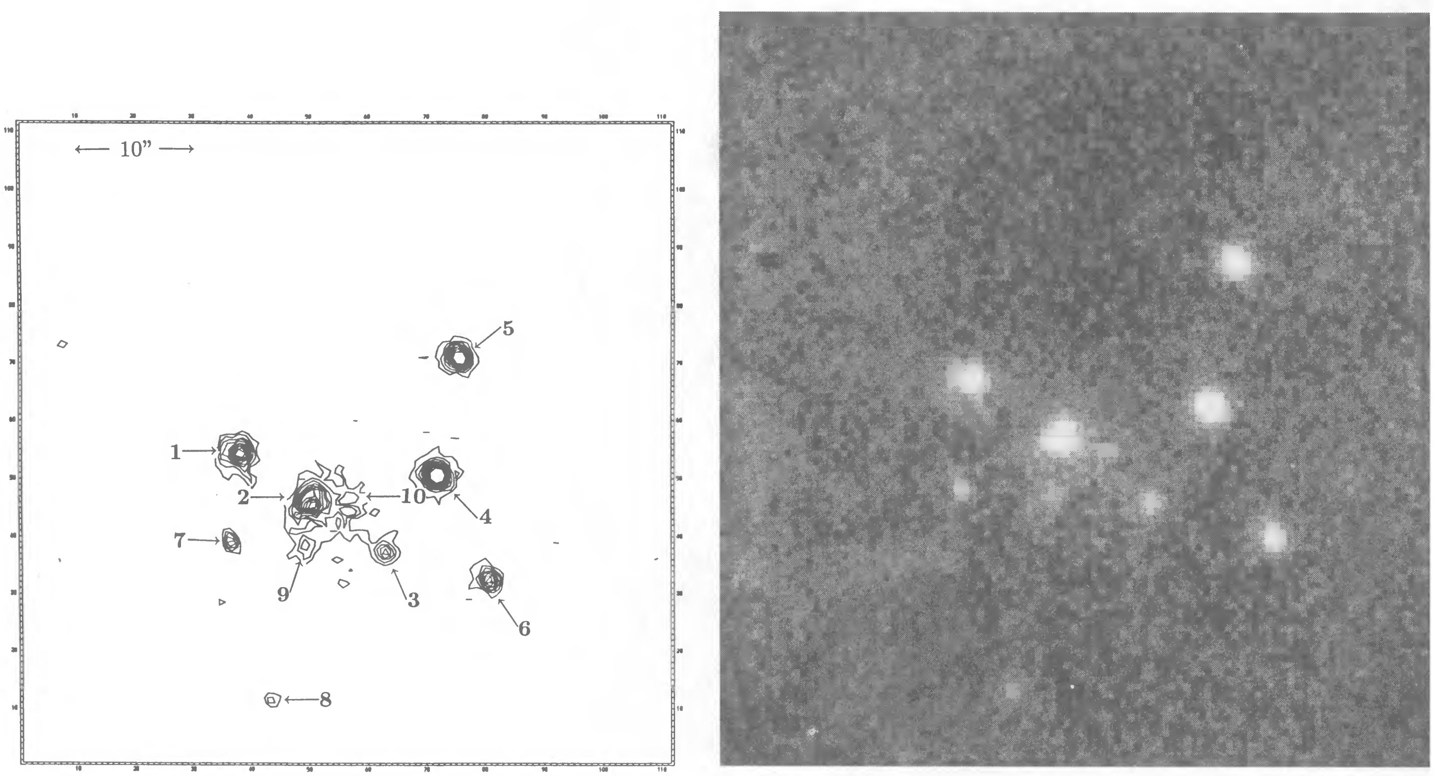


FIG. 4*d*

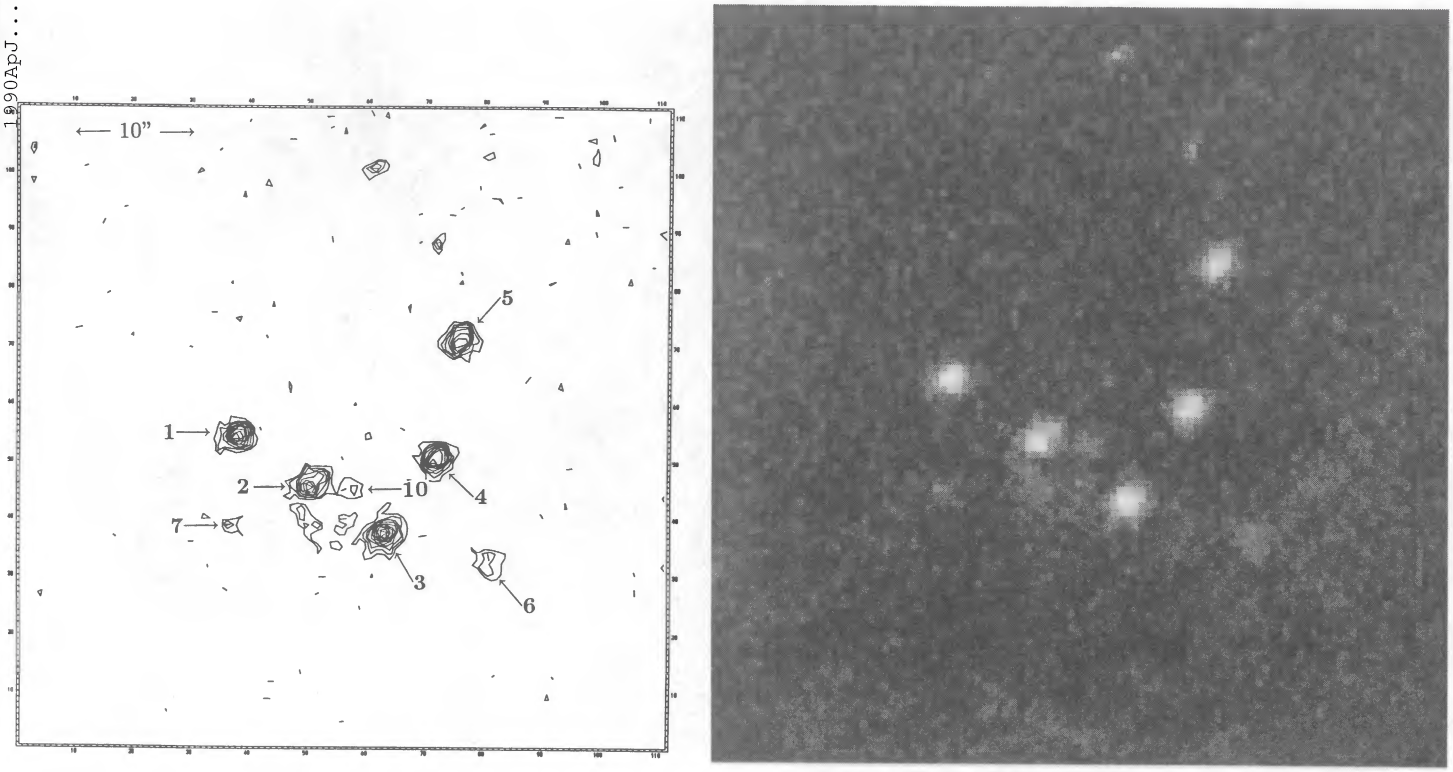


FIG. 4e

7 was also detected by Armandroff and Massey 1985), but spectroscopy is needed to confirm their W-R status.

c) NGC 592

The images of NGC 592 are shown in Figure 5, and details concerning the W-R candidates are presented in Table 6. Unfortunately, only one pair of images was useful for our purpose. Thin clouds were present during the exposure, preventing us from going deeper than $B \sim 20.5$. Two W-R candidates show up: star 1 is another example of a putative "superluminous" W-R star: it has been spectroscopically confirmed as a genuine W-R star but was erroneously identified with the bright star HS67 (CM3). Both stars are clearly resolved in our images. Star 2 is probably a WN star, but spectroscopy is required to confirm it. The W-R star MCA2 (Massey, Conti, and Armandroff 1987) which lies $\sim 20''$ to the W of HS67 has escaped detection here because of its faintness. As no net 4650 image has been obtained, we cannot locate the candidates in Figure 3. However, their net 4686 flux is comparable to that of other WN stars in the other two regions (log $F_{4686} = -13.65$ for star 1 and -14.00 for star 2).

The variable source M33 X-3 (Trinchieri, Fabbiano, and Peres 1988; Peres *et al.* 1989), which may be an X-ray binary system (Markert and Rallis 1983) is located $\sim 7''$ away from the W-R star 1 and $12''$ from the W-R candidate 2. Since the uncertainty on the position of M33 X-3 is only $2\overset{''}{.}7$, it is probably not associated with any of the two W-R stars. A few other blue stars are located closer to the X-ray source.

IV. GENERAL DISCUSSION

Figure 3 shows that the fluxes in the emission lines of all W-R candidates (with the possible exception of N604-1) lie within the boundaries defined by single, Galactic W-R stars. This fact supports the hypothesis that the so-called superluminous W-R objects, which have still not been resolved, are indeed tight clusters containing one (or perhaps two in some cases) normal W-R star. In GHRs at the distance of M33, one should not expect to resolve all the brightest stars individually from the ground (for comparison purposes, the Pleiades open cluster has a diameter of ~ 4 pc, which corresponds to $1\overset{''}{.}2$ at the distance of M33). Of course, the actual number of W-R stars in each knot cannot be determined precisely with these

TABLE 6

WOLF-RAYET STARS IN NGC 592

Star	m_{4780}	$M_{4780}(A_B)$	Continuum − 4686	W_{4686}	Spectral Class	Remarks
1	18.5	−7.0 (1.2)	0.8	38	WN	CM3(MC17), SW of HS67
2	19.1	−6.4 (1.2)	0.7	32	WN?	New candidate
MCA2[b]	20.5?	−5.0 (1.2)?	...	...	WN	Not detected as W-R here

[a] CM = Conti and Massey 1981; HS = Humphreys and Sandage 1980; MCA = Massey, Conti, and Armandroff 1987.
[b] Outside the main core.

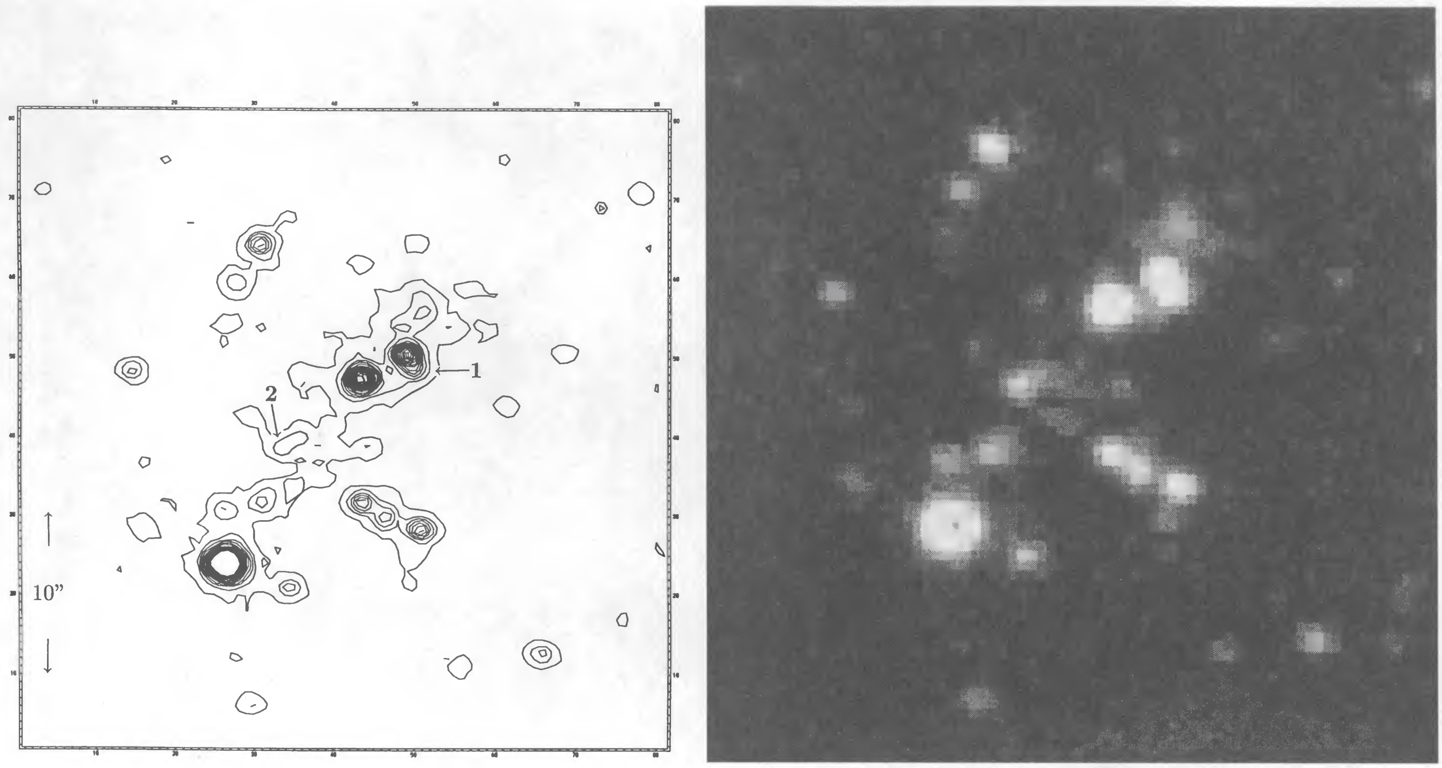


FIG. 5*a*

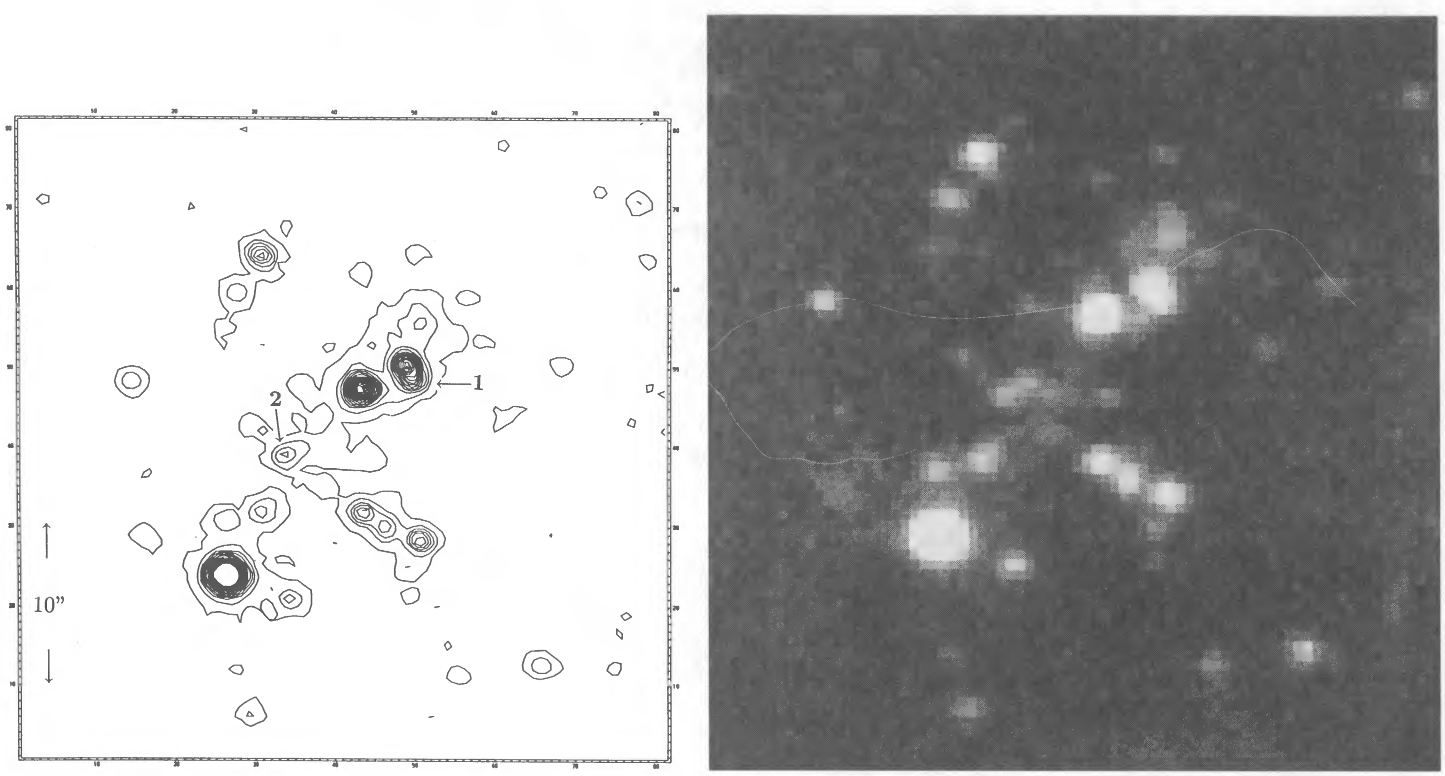


FIG. 5*b*

FIG. 5.—Same as Fig. 1, for NGC 592: (*a*) continuum (4780 Å); (*b*) on-line 4686 Å; (*c*) net 4686 Å. The "holes" appear at the position of bright red stars due to the effective wavelength difference between the continuum and emission-line filters (see § II).

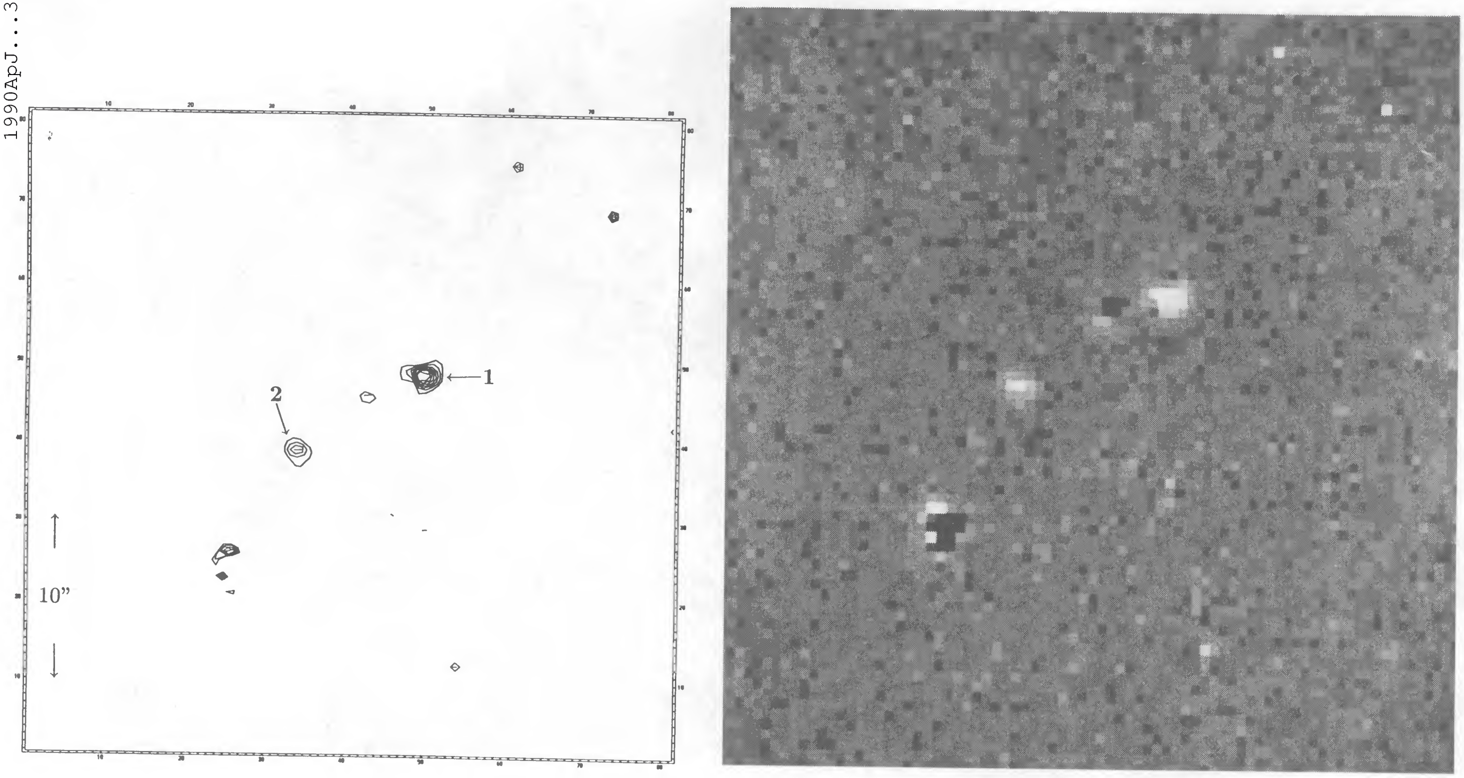


FIG. 5c

data alone, because a large number of abnormally weak emission-line Of/W-R stars could mimic the appearance of a single, "normal" W-R star (at least in the brightest knots, where the co-added continuum light of these stars would produce the high observed luminosity). However, there is no *a priori* need to postulate such an anomaly.

In NGC 604, seven objects are either spectroscopically confirmed W-R stars or very good candidates (objects 1, 2, 3, 4, 5, 6, and 9). Three candidates (objects 7, 8, and 10) still require spectroscopic confirmation. Assuming that only one W-R star is present in each emission-line object (which is, as mentioned before on the basis of emission-line flux, a reasonable hypothesis), NGC 604 contains between seven and 10 W-R stars. This is roughly one-half the number of W-R stars found in the core of 30 Dor or ~ one-third of the total number of W-R stars estimated to lie in the 30 Dor nebula (Moffat *et al.* 1987).

Surprisingly, NGC 595 contains roughly the same number of W-R stars as NGC 604, despite its smaller stellar mass (by about a factor of 3). The total W-R line flux is also very similar in the two regions, although the Hβ luminosity is ~4 times smaller in NGC 595 (Terlevich and Melnick 1981). We will return to this point later.

Comparing the number of W-R stars with the number of O stars is a very delicate operation in crowded and distant regions such as NGC 604 and NGC 595 because, as one cannot count the numerous O stars individually, one is forced to derive the number of O stars from integrated properties by assuming an initial mass function (IMF), the uncertainty of which can itself affect the W-R/O ratio. Let us assume, as a working hypothesis, that the IMF is universal. Viallefond, Goss, and Allen (1982) have derived the total mass of young stars in a dozen GHRs from their excitation parameter U and supposing a constant IMF slope ($dN \propto M^{-\alpha}dM$) with $\alpha = 3$. From the Hα flux and assuming a Salpeter IMF ($\alpha = 2.35$), Kennicutt (1984) has also derived the total stellar mass of OB stars in a sample of nearby GHRs. The relative mass of the different overlapping GHRs is similar in both studies. In Table 7, we compare the number of W-R stars with the total stellar mass in the four largest GHRs in the Local Group. The stellar mass has been normalized to that of 30 Dor. Although the 30 Dor nebula is very extended (with filaments extending out to 600 pc from the center), most of the stars, gas and dust are concentrated in the inner 150 pc. Viallefond, Goss, and Allen (1982) use a radius of 70 pc to evaluate the stellar mass in 30 Dor, while Kennicutt prefers 185 pc. As a compromise, we include in Table 7 all W-R stars found within 130 ± 50 pc from R136 (Moffat *et al.* 1987). Within the errors, the ratio $N_{\text{W-R}}/M_*$ is comparable in all GHRs except NGC 595, which seems quite rich in W-R stars. This fact was already evident from Figure 4, where there is a sufficiently large number of W-R stars that one

TABLE 7

MOST MASSIVE LOCAL GROUP GIANT H II REGIONS

Region	M_*	$N_{\text{W-R}}$	$N_{\text{W-R}}/M_*$	[O/H]
30 Dor (core)	1	24 ± 5	24 ± 5	8.37[a]
NGC 604	0.35	7 ± 2.5	20 ± 7	8.51[b]
NGC 595	0.15	8 ± 3	55 ± 20	8.44[b]
NGC 3603	0.1	2 ± 1.5	20 ± 15	8.39[c]

NOTES.—M_* has been normalized to unity for the 30 Dor core with radius 130 pc. The uncertainty in the number of W-R stars is assumed to be Poissonian. The error in M_* is assumed to be negligible compared to that of $N_{\text{W-R}}$.

[a] Rosa and Mathis 1987.

[b] Vilchez *et al.* 1988.

[c] Melnick, Tapia, and Terlevich 1989.

can easily recognize the stellar pattern of the region from the W-R stars alone.

Three main parameters can in principle affect the W-R/O ratio: metallicity, the slope of the IMF, and the age of the burst. Smith (1988) argues that metallicity is the major controlling factor in a W-R population. She shows that the number ratio of WC and WNE stars (which are less sensitive to incompleteness) to OB stars, as well as the WC/WNE number ratio, are well correlated with metallicity in the Local Group galaxies. Such correlations are expected if the evolution of O to W-R stars is accelerated by high metallicity in the atmospheres of the progenitor O stars. Table 7 shows that the value $[O/H] \equiv 12 + \log(O/H)$ is quite similar in all GHRs, and therefore metallicity alone is unlikely to explain the differences.

Changes in the IMF slope have been invoked to explain differences in W-R/O ratios between galaxies and with galactocentric distances in our Galaxy and M33 (MC; Conti *et al.* 1983). However, Blaha and Humphreys (1989) show that, within the uncertainties, the IMF for massive stars in the field is the same in the Galaxy and the Magellanic Clouds. In GHRs, the IMF is very poorly known; even relatively close objects such as NGC 3603 and 30 Dor suffer from incompleteness, due to crowding. Although the W-R/O number ratio in these two regions seems compatible with the ratio in the field (MSS), an improvement in the OB stellar counts in the GHR directly is necessary to confirm it (Lapierre, Moffat, and Shara 1990). We should note that NGC 595 is closer (deprojected galactocentric distance $R = 1.57$ kpc) to the center of M33 than is NGC 604 ($R = 3.06$ kpc), and that the relatively high W-R number in the former GHR could reflect the fact that proportionately more massive stars are born close to the center of M33 (flatter IMF) if the Massey and Conti (1983) interpretation is correct. However, Freedman (1985) showed that there is no evidence for a change in the slope of the luminosity function as a function of radius, nor for statistically significant variations from one association to another in M33. Moreover, detailed photometry and spectroscopy of individual stars in the brightest GHR in the SMC, NGC 346 (Massey, Parker, and Garmany 1989), have shown that despite the low metal abundance in the SMC, the slope of the upper end of the IMF in that region is similar to that found for massive stars near the Sun and the SMC. In any case, for M33's GHRs, only high resolution imaging from space will enable us to derive a viable IMF.

Arnault, Kunth, and Schild (1989) have computed synthetic W-R/O ratios as a function of time, metallicity and IMF for cases of instantaneous burst (IB) and continuous star formation (CSF). They show that, for an IB at solar metallicity, the W-R/O ratio increases rapidly between ~ 3 and 4 Myr after the burst (time necessary for the most massive O stars to leave the main sequence, expel their hydrogen layers, and reach the W-R phase), stays constant until ~ 6 Myr after the burst, and decreases rapidly afterwards as the post main sequence becomes dominated by stars below the W-R producing limit (initial mass ~ 30–$40\ M_{\odot}$). Thus, two very young regions of slightly different ages can have very different W-R/O ratios, all other parameters being the same. Also, differences in the duration of the burst, even as small as 1 Myr, could produce differences in W-R/O ratios (the longer the burst, the lower the maximum W-R/O ratio). In this context, NGC 595 would be the most evolved GHR (age ~ 4–6 Myr), having reached its maximum W-R/O ratio, while the others would be slightly younger.

It is also interesting to note that, as for 30 Dor, the W-R population of the three largest GHRs in M33 is dominated by WN stars. The WC/WN number ratio is 0.25–0.4 in NGC 604, in rough agreement with the general ratio for M33 field stars (0.3) at the same galactocentric distance (MC). In NGC 595, this ratio is ~ 0.15, i.e., similar to 30 Dor, but much lower than the ratio for field stars at the same galactocentric distance (1.2) in M33 (CM). In NGC 592, no WC star is present. In fact, with the exception of one star in IC 131 (Vilchez *et al.* 1989), all other W-R stars detected in M33's giant H II regions are of WN subtype (MC). Moreover, very few WNE stars are found in GHRs: 30 Dor contains only 3 WNE stars (and 17 or more WNL stars), whereas WNE stars dominate in the rest of the LMC. This is also the case in NGC 3603 (which contains two to three WNL stars) and in the Carina nebula (three WN7, one WC). Evolutionary models by Langer (1987) and Maeder (1990) show that the length of the WNL phase is relatively short for the less massive W-R stars, whereas the most massive stars spend a large fraction of their post–main-sequence life as WNL stars. In this context, the predominance of WNL stars in GHRs may be explained if either the average mass of W-R progenitors in GHRs is higher than in the field or if the observed GHRs are so young that only the most massive stars have left the main sequence. A detailed photometric and spectroscopic study of a large number of GHRs with high spatial resolution might be able to answer this question.

V. CONCLUSIONS

We have shown that narrow-band CCD imagery under good seeing conditions is a very powerful tool to detect W-R stars in very crowded associations such as giant H II regions. With this technique, we have been able to clear up some of the previous confusion from aperture spectroscopy; in particular, many of the previously claimed "superluminous (WNS) W-R stars" are shown to be close multiple system, probably consisting of normal stars. A few WNS stars in GHRs remain to be carefully observed in M33, namely MC3 (in NGC 588), MC8 and MC9 (in MA1) and MC23 (in IC 132). Of course, spectroscopy is still an absolute requirement to confirm the W-R status of the candidates and to classify them appropriately. However, good observing conditions are necessary and a narrow ($\lesssim 1''$) slit should be used.

Although the number of O stars is difficult to obtain with any accuracy from ground-based observations, this work does indicate that the W-R/O number ratio in M33's GHRs based on W-R counting and global light for O stars is significantly smaller than unity, contrary to previous estimates (D'Odorico and Rosa 1981*a*). Although (*a*) recent studies tend to demonstrate that the IMF slope for massive stars is constant in the field for nearby galaxies (Freedman 1985; Blaha and Humphreys 1989; Pierre and Azzopardi 1988) and (*b*) our observations show that there is no need to postulate an abnormal IMF in M33's GHR, a more definitive discussion about the IMF in extragalactic giant H II regions will have to await *Hubble Space Telescope's* (*HST*)—or equivalent—high-resolution imagery.

As the age of the GHR may have a considerable effect on its W-R/O ratio, it would be very worthwhile obtaining reliable estimates of the ages of the regions studied here. For this, it will be necessary to obtain spectral types of the brightest individual O stars.

It is also important to increase the statistics by increasing the number of objects studied. For example, in NGC 300, an Sd galaxy member of the Sculptor Group, two GHRs are comparable in size and Hα flux to NGC 595: regions 53 and 137 (from the catalog of Deharveng *et al.* 1988), in which strong W-R features have been spectroscopically detected. To get the same physical resolution as we have obtained in this work requires ~0".5 seeing, which is sometimes available from the ground. M101 contains a few "hypergiant" H II regions up to 5 times more massive than 30 Dor. Among them, NGC 5461 appears to contain a large number of W-R stars (D'Odorico, Rosa, and Wampler 1983) and is therefore an excellent potential target for HST imagery.

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