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# WOLF-RAYET STARS IN THE GIANT H II REGION NGC 604

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## ABSTRACT

We have detected strong Wolf-Rayet emission bands in NGC 604 at all positions where the stellar continuum is strong. The W-R stars are comparable in number with the massive hot stars ionizing the H II region. The presence of about 50 W-R stars with a mean type of WN 7 is interpreted as the result of a single burst of star formation some $4\times10^6$ years ago in the core of NGC 604.

*Subject headings:* galaxies: individual — nebulae: H II regions — nebulae: individual — stars: Wolf-Rayet

## I. INTRODUCTION

The study of giant H II regions in nearby galaxies offers the unique opportunity to investigate the initial mass function of stars in regions of active star formation. In the Galaxy, giant H II regions (number of ionizing stars $\gtrsim$20) are not observed optically because of the large extinction in the galactic plane. The 30 Doradus complex in the LMC is then the most favorable case, and many stars in the central cluster around the object R136 have been studied spectroscopically. The study of the stellar populations in H II regions in other galaxies is hindered by the lack of spatial resolution ($1''=3.5$ pc at the distance of M33).

So far, only integral properties of the stellar associations ionizing these large H II regions have been studied. During the course of an investigation of emission line nebulae in nearby galaxies we have obtained spectra at various positions in NGC 604, the brightest H II region in M33. The spectra show the emission features typical of W-R stars. These data and their implications on the stellar population of the H II region are discussed.

## II. OBSERVATIONS

The observations were obtained at the European Southern Observatory (ESO), La Silla, Chile. They were originally intended to serve as comparisons for a study of H II regions in southern galaxies. M. R. observed four positions in the Nebula with the 1.5 m telescope equipped with a Boller & Chivens Cassegrain spectrograph and the ESO Image Dissector Scanner (Cullum 1979) on 1980 September 14. A dispersion of 171 Å mm$^{-1}$ was used, giving a free spectral range from 4100 to 6800 Å with a resolution of 7 Å. The entrance slit of $8''\times2''.3$ was oriented in the N-S direction. Typical integration times were 30 minutes.

The centers of the four slit positions are shown in Figure 1 (Plate 16) as small circles. Because of the poor seeing during the observations and the faintness of individual knots in NGC 604, the positional accuracy was not better than about 5″. Although positions 1 and 2 coincide within 5″, inspection of the spectra in Figure 3*a* shows that even in these close positions different stars contribute to the spectra. To search for a correlation between the newly discovered W stars and the bright knots in the nebula, the following night S. D. observed five positions with the 3.6 m telescope using similar equipment (B & C spectrograph + IDS).

The star map by Benvenuti, D'Odorico, and Dumontel (1979) served as a reference. A dispersion of 115 Å mm$^{-1}$ with a spectral range from 5400 to 7500 Å and a resolution of 5 Å was used. The $4''\times2''.2$ entrance aperture was aligned. E-W. Typical integration times of 5 minutes were used, and a positional accuracy of 2″ was achieved.

All the data were reduced using the data reduction system at ESO Garching. Flat field correction, wavelength calibration, extinction correction from a mean La Silla extinction table and flux calibration via the observed standard stars were applied to the data. Because of the large extension of the nebula, the displaced sky aperture (40″ away) was contaminated by nebular emission so that an additional exposure a few arcmin away was used for sky subtraction. This resulted in imperfect sky removal for the strongest nightsky lines but has no effect on the discussion presented. The absolute fluxes are only accurate within 30%, because the air mass was on the average 2 for the observations of NGC 604.

A complete spectrum is shown in Figure 2 in logarithmic scale to indicate the large intensity ratio between the nebular emission lines and the W-R emission bands. In Figure 3 expanded tracings of the spectral regions which contain the Wolf-Rayet bands at 4650 and 5812 Å are shown for all the observed positions. The wavelengths of the lines typical for galactic W-R stars and used in the classification scheme by Hiltner and Schild (1966) are marked along with strong nebular emission lines and the contribution from night sky. He I λ5876 is due mainly to nebular emission as can be verified by the emission line ratios published for NGC 604 (Peimbert and Spinrad 1970). The 3.6 m and 1.5 m observations are quite consistent, as can be checked by comparing 1.5(1) and 3.6(4) which coincide in position. In the latter spectrum the continuum flux is roughly 50% the value observed at 1.5(1), in agreement with the ratio of the two slit apertures, and all the features seen in the 5800 Å emission band can be traced in both spectra.

### III. PROPERTIES OF THE W-R STARS IN NGC 604

The most striking result of our observations is the discovery of the broad emission bands typical of W-R stars in most of the bright knots seen in the core of NGC 604.

In the 3.6 m spectra a correlation can be seen between the presence of the W-R emission bands and the strength of the underlying continuum. There seems to be also an inverse correlation between the strength of the continuum (or W-R band) and the strength of the nebular emission lines.

Narrow band filter photographs of NGC 604 (Rosa, Gaida, and Moellenhoff 1981) confirm these results by showing the knots at positions 3.6 (2 and 3) to be the brightest sources of [O III] λλ4959, 5007 nebular emission and practically invisible in the *V* continuum, while knots 3.6 (4 and 5) are the strongest features in the *V* photograph.

To attempt a classification of the W-R spectra, we compared them with the classification schemes of Hiltner and Schild (1966) but were unable to assign a unique spectral type to the individual spectra.

This is not surprising since we are faced with the composite spectra of a number of W-R stars in each position. As main features one can identify the N III band at λ4640, He II λ 4686, and N IV, C IV at λλ5800–5812. As noted above, He I λ 5876 is mainly of nebular origin. The nature of the identified bands suggests that W-R stars of the nitrogen sequence dominate the spectra. C IV at λλ5809–5812 is certainly present, but this does not contradict the WN classification (Smith 1973). A further, but weaker, argument for the WN classification is the fact that WN stars seem to correlate with H II regions, whereas WC stars are more often found outside emission nebulae in the field. Wray and Corso (1972) and Corso (1975) found 54 W-R stars in the entire disk of M33. Thirty seven of them have been classified into the WN and WC sequences; 19% of the WC and 63% of the WN stars are in nebulosities. The relative weakness of N V and He II lines of stellar origin suggests an average type of WN 8–WN 6.

As an independent check of this classification we can take advantage of the UV observations of NGC 604 obtained by Rosa (1980). The presence of strong P Cygni profiles in the lines of C IV 1549 Å and Si IV 1399 Å already suggested (Rosa 1980; D'Odorico, Patriarchi, and Perinotto (1980) that W-R stars may contribute to the integrated UV spectrum of NGC 604. By comparing the UV spectrum of NGC 604 with the sequence of UV spectra of W-R stars by Willis (1980), we are led to a tentative WN 7 classification, based on comparable strengths of N IV, N V, and He II lines. As noted above this classification refers only to the predominant characteristics of the spectrum.

We measured only the integral flux in the emission bands λλ4580–4730 and λλ5750–5870 as seen in our spectra.

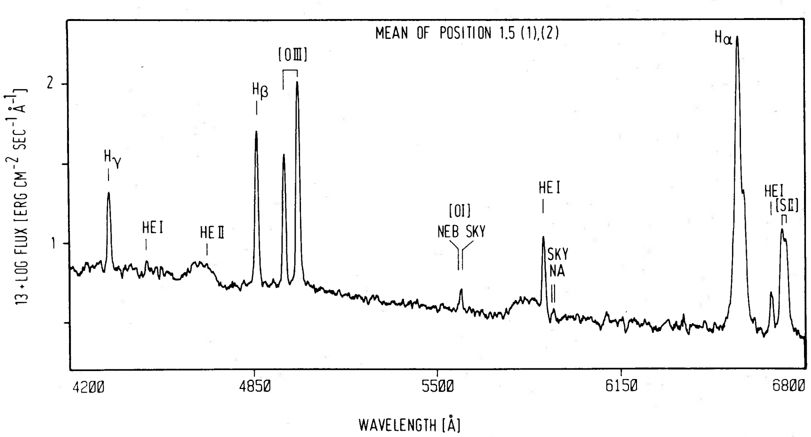


FIG. 2.—Mean of the observations of NGC 604 at positions (1) and (2) with the 1.5 m telescope. Data corrected for extinction and spectral response of the instrument.

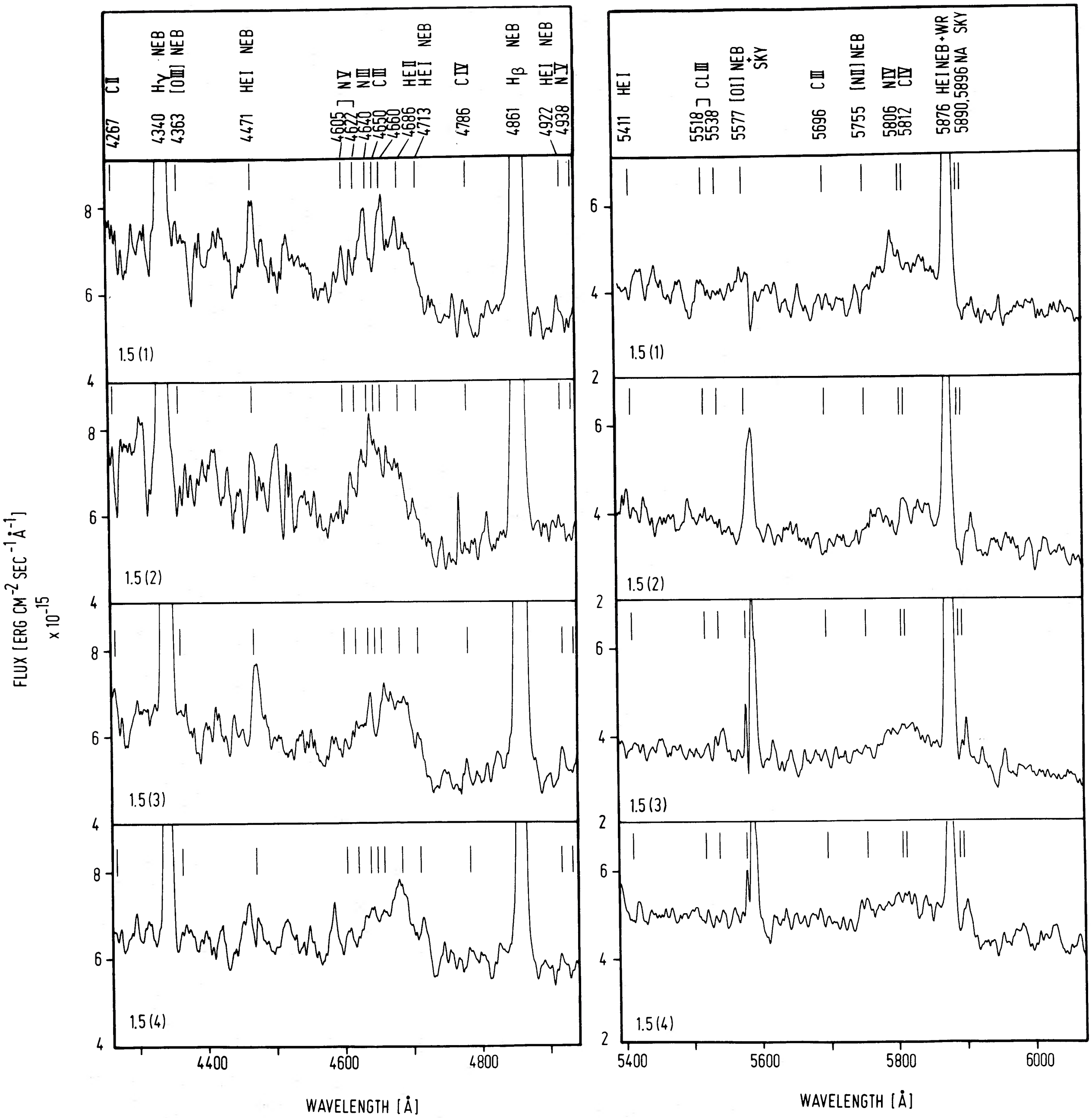


FIG. 3*a*, *b*.—Excerpts from the spectra of NGC 604 at the four positions observed with the 1.5 m telescope: The spectral intervals are centered on the 4650 and 5812 Å Wolf-Rayet bands. Wavelengths of the Wolf-Rayet lines are taken from Hiltner and Schild (1966). Sky and nebular emissions are also indicated.

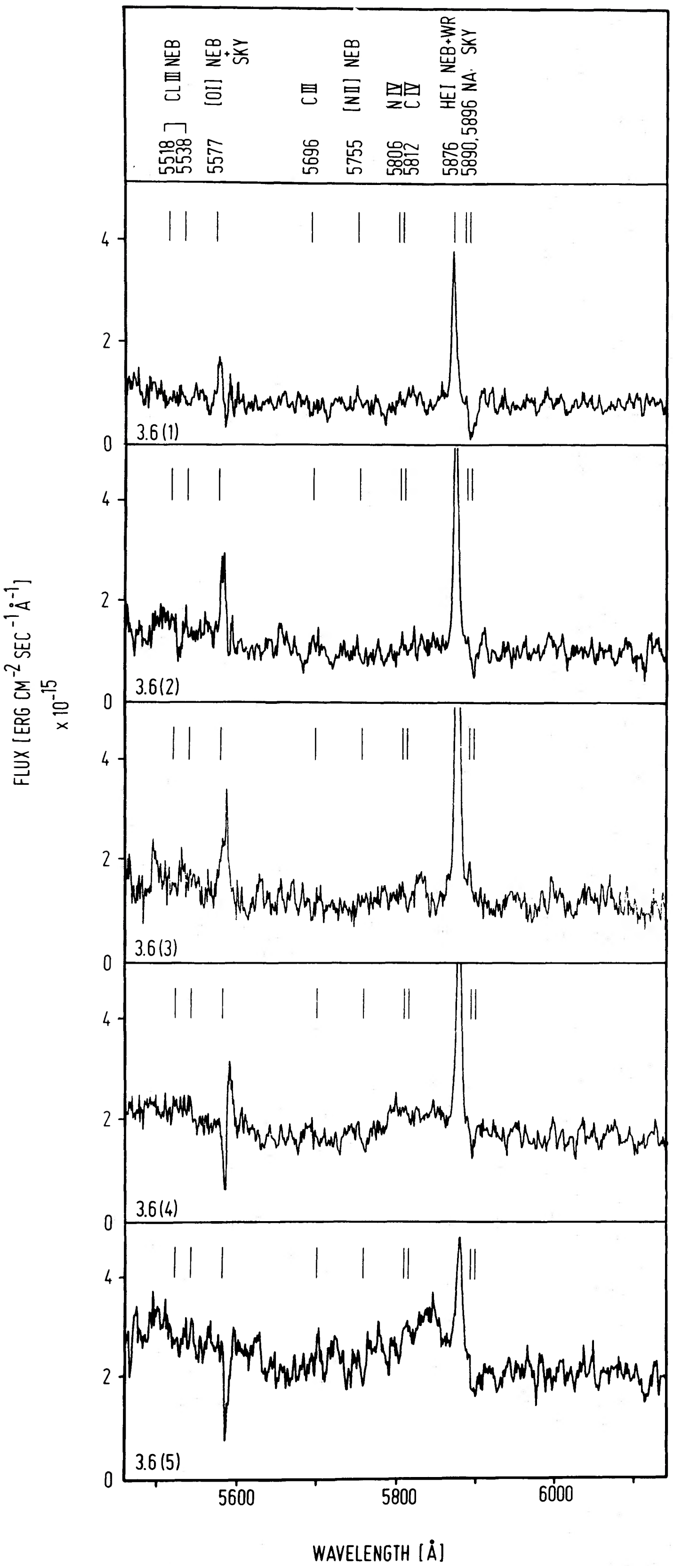


FIG. 3c.—Excerpts from the spectra of NGC 604 at the five positions observed with the 3.6 m telescope, centered on the 5812 Å Wolf-Rayet band. Line identifications as in Figs. 3a, b.

In Table 1 we list the observed equivalent widths of these bands and the monochromatic fluxes of the underlying continue for the mean of the four 1.5 m observations and position 5 of the 3.6 m spectra. As a reference we include the values for the star W-R 13 in M33 as derived from the published tracing by Boksenberg, Willis, and Searle (1977) and for the W-R star E in the list of stars in 30 Dor by Melnick (1978). The latter data have been extracted from an IDS spectrum obtained with the ESO 3.6 m telescope and kindly lent to us by Melnick. This star was chosen for its resemblance to our spectra. The values should be representative of the late WN sequence as are the additional data for the galactic WN stars taken from Smith and Kuhi (1970) and Smith (1973).

### IV. W-R AND MASSIVE STARS IN NGC 604

By comparing our spectra of NGC 604 with the data for the other W-R stars, we conclude from the equivalent widths of the Wolf-Rayet bands that about 50% of the observed continuum is due to W-R stars. Since the bulk of light in the *B* and *V* bandpasses from a Population I association is due to main sequence and supergiant O, B, and A stars and the W-R stars have comparable absolute magnitudes at these wavelengths, we estimate the ratio of W-R stars to blue stars, $N_{\text{W-R}}/N_{\text{B}}$, to be about 1.

As an additional check we compare the numbers of stars needed to ionize the H II region with the total number of W-R stars implied by our observation.

From the integral H$\beta$ flux, Benvenuti, D'Odorico, and Dumontel (1979) predicted the presence of 42 stars more massive than 40 $M_\odot$. Israel and van der Kruit (1974) required the equivalent of 33 O5 stars to account for the radio recombination continuum.

As a reference we shift the W-R star in 30 Dor in Table 1 from the LMC to the distance of M33 (56 to 720 kpc).

The absolute flux observed in the Wolf-Rayet bands then implies that about 7 W stars of similar characteristics have been observed in each position in NGC 604. Since the average continuum flux observed in the 1.5 m slit aperture represents $\sim$10–20% of the total continuum flux from the core of NGC 604 (Rosa, Gaida, and Moellenhoff 1981), and we concluded that W-R stars are present wherever a strong stellar continuum is observed, the total number of W-R stars in NGC 604 should lie between 35 and 70, in good agreement with the above estimates of the number of ionizing stars. Differential reddening might change the latter values, but it should be a minor correction since the absorption for the core of 30 Dor is of the order of $A_v = 1.2$ mag, and $A_v$ should lie between 0.5 and 1.5 mag for NGC 604 (Melnick 1979; Israel and Kennicut 1980).

In conclusion both the discussion of the equivalent widths and the comparison of the total observed flux in the Wolf-Rayet bands thus lead to a high ratio $N_{\text{W-R}}/N_{\text{B}}$.

Meader, Lequeux, and Azzopardi (1980) have recently discussed the relative numbers of W-R stars and blue and red supergiants in the Galaxy. They found the ratio $N_{\text{W-R}}/N_{\text{B}}$ to be always smaller than 0.15 in the 7–13 kpc distance interval from the galactic center, probably a reflection of the fact that the lifetime of the Wolf-Rayet phenomenon is $\sim$10% of the lifetime of a massive star and that star formation is continuous throughout the disk.

The relatively high ratio in NGC 604 can be interpreted in terms of a different evolutionary history, indicating the occurrence of a single burst of star formation.

A rough scheme based on today's models of the evolution of massive stars with mass loss (e.g., Chiosi 1981; de Loore 1980) would suggest that this burst happened some $4\times10^6$ years ago. All stars with masses between 40 and 50 $M_\odot$ and of that age, will than have reached the Wolf-Rayet phase, appearing like WN 7 or

TABLE 1

EQUIVALENT WIDTHS OF (WOLF-RAYET) BANDS AND MONOCHROMATIC FLUXES

| OBJECT | EW (Å) λλ4580–4730 | EW (Å) λλ5750–5870 | $F$ ergs cm$^{-1}$ s$^{-1}$Å$^{-1}\times10^{-15}$ $F$(4450) | $F$(5500) | NOTES[a] |
|---|---|---|---|---|---|
| NGC 604 (1.5 m obs) | 27±5 | 20±5 | 5.5±2.0 | 3.9±1.5 | 1 |
| NGC 604 (3.6 m obs) | | 36±5 | | 2.1±0.6 | 2 |
| W-R in 30 Dor | 50±10 | 36±5 | 66.1±20 | 43.0±10 | 3 |
| W-R 13 in M33 | 63 | | 0.18±0.05 | | 4 |
| HD 50896 | 44 | 28 | | | 5 |
| HD 192163 | 30.2 | 21 | | | 6 |
| HD 191765 | 22 | 32 | | | 6 |

[a]NOTES:—(1) Average of the 4 positions. (2) Position 3.6 m No. 5. (3) Star E in Melnick 1978, who classifies it as WN 6. (4) Boksenberg, Willis, and Searle 1977 classify this star as WN 5–6. (5) Smith 1973, WN 5. (6) Smith and Kuhi 1970, both classified WN 6.

WN 8 types with H-rich envelopes on top of the He burning cores.

The presence of only one supernova remnant in NGC 604 (Benvenuti, D'Odorico, and Dumontel 1979) would also imply that most massive stars have not yet become supernovae as pointed out by van den Bergh (1980, private communication). Finally, we note that the time of occurrence of the burst of star formation in NGC 604 agrees with the age ($5\times10^6$ years) derived by Humphreys and Sandage (1981) for six young associations in M33 at various distances from the center.

To summarize our results, the strong Wolf-Rayet features observed in all positions in NGC 604 where continuum was detected have been interpreted as due to predominance of WN 7–8 stars among the more massive stars in the H II region, with a present population in the range 35 to 70.

The observations also imply that the current burst of star formation is not older than $4\times10^6$ years.

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## REFERENCES

Benvenuti, P., D'Odorico, S., and Dumontel, M. 1979, *Ap. Space Sci.*, **66**, 39.
Boksenberg, A., Willis, A. J., and Searle, L. 1977, *M.N.R.A.S.*, **180**, 15P.
Chiosi, C. in *Proc. IAU Colloquium 59*, *Effects of Mass-Loss on Stellar Evolution*, Trieste 1980, in press.
Corso, G. J. 1975, *Bull. AAS*, **7**, 411.
Cullum, M. 1979, ESO Tech. Rept. 11.
de Loore, C. 1980, *Space Sci. Rev.*, **26**, 113.
D'Odorico, S., Patriarchi, P., and Perinotto, M., 1980, in *Proceedings of the ESO/ESA Workshop on Dwarf Galaxies*, ed. M. Tarenghi and K. Kjär, p. 103.
Hiltner, W. A. and Schild, R. E. 1966, *Ap. J.* **143**, 770.
Humphreys, R. M., and Sandage, A. 1980, *Ap. J. Suppl*, **44**, 319.
Israel, F. B., and Kennicut, R. C. 1980, *Ap. Letters*, **21**, 1.
Israel, F. P., and van der Kruit, P. C. 1974, *Astr. Ap.*, **32**, 363.
Maeder, A., Lequeux, J., and Azzopardi, M. 1980, *Astr. Ap.*, **90**, L17.
Melnick, J. 1978, *Astr. Ap. Suppl.*, **34**, 383.
______. 1979, *Ap. J.*, **228**, 112.
Peimbert, M., and Spinrad, H. 1970, *Ap. J.*, **159**, 809.
Rosa, M. 1980, *Astr. Ap.*, **85**, L21.
Rosa, M., Gaida, G., and Moellenhoff, C. 1981, in preparation.
Smith, L. F. 1973, in *IAU Symposium* 49, *Wolf-Rayet and High-Temperature Stars*, ed. M. K. V. Bappu and J. Sahade (Dordrecht: Reidel), p. 15.
Smith, L. F., and Kuhi, L. V. 1970, *Ap. J.*, **162**, 535.
Willis, A. J. 1980, in Proc. Second European *IUE* Conference, ESA SP-*157*.
Wray, J. D., and Corso, G. J. 1972, *Ap. J.*, **172**, 577.

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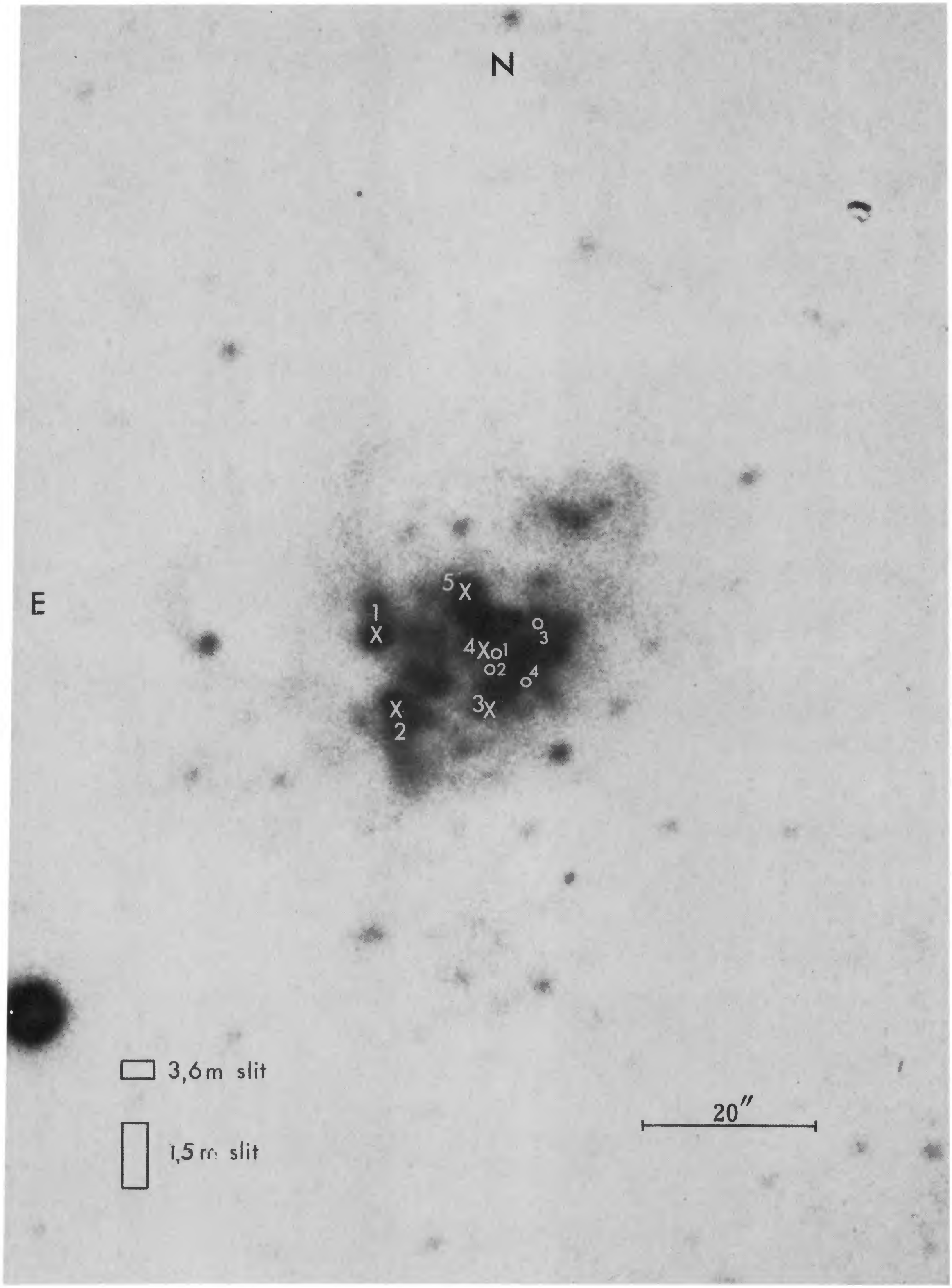


FIG. 1.—Positions of the spectrograph slit in the observations with the 1.5 m telescope (*open circles*) and with the 3.6 m telescope (*crosses*) superposed on a 103 a−O+UG2 photograph of NGC 604, taken at the f/9 Cassegrain focus of the Asiago 1.82 m telescope.

D'ODORICO AND ROSA (*see* p. 1015)