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Wolf-Rayet stars detected in five associations of NGC 300*

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Abstract. A search for WR stars in five associations of the Sc galaxy NGC 300 has permitted to better locate, in crowded regions, some of the already known objects and to discover six new WR stars. The on-line/off-line imaging technique was applied using the SUperb Seeing Imager (SUSI) of the ESO New Technology Telescope (NTT) installed at La Silla, Chile. Of the twelve WR stars identified up to now in these associations, three remain to be definitely confirmed by slit spectroscopy, however they have detection significances $\geq 8\sigma$ and can therefore be considered bona fide WR stars. It is argued that after the present survey most, possibly all, of the WR stars contained in the associations studied have been discovered. The average "O/WR" ratio of 2.6 ± 0.8 obtained from the comparison of the numbers of WR and zero-age-main-sequence O5 stars is well in the range of the values found for other galaxies, in particular M 33 generally considered as a twin of NGC 300.

Key words: galaxies: NGC 300; M 33; star clusters; stellar content stars: evolution – stars: Wolf-Rayet.

1. Introduction

There is nowadays overwhelming evidence that Wolf-Rayet (WR) stars represent a late phase in the evolution of massive stars. The differences observed in the WR/O and WC/WN star ratios for the solar vicinity and the Magellanic Clouds, where the WR star census is believed to be fairly complete, are currently interpreted in terms of a metallicity effect. These ratios are indeed extremely sensitive to mass loss, itself very sensitive to the local metallicity Z (Azzopardi et al. 1988; Arnault et al. 1989; Maeder 1991). However, other factors may also play a role (Massey 1985). The data on the WR content of Local Group galaxies other than the Magellanic Clouds are still very incomplete and conclusions based on the available information are certainly affected by small number statistics. Therefore it is worthwhile to continue and complete surveys of WR stars in nearby galaxies.

The Sc galaxy NGC 300, one of the major members of the Sculptor Group, appears as a suitable candidate for a systematic search for WR stars, due to its moderate distance modulus $(\text{m-M})_0 = 25.93$ mag (Deharveng et al. 1988) and to its favorable, almost face-on, orientation. In addition, NGC 300 shows a marked abundance gradient, the metallicity in the nucleus being roughly solar (Deharveng et al. 1988; Vila-Costas and Edmunds 1992). Previous investigations already revealed WR spectral features in four bright HII regions of NGC 300 (D'Odorico et al. 1983; Deharveng et al. 1988) and 13 individual WR stars were subsequently identified in the central part of the galaxy (Schild and Testor 1992; Testor and Schild 1993). More recently, Azzopardi et al. (1995) confirmed the WR nature of another 9 objects, increasing to 22 the total number of WR stars known in NGC 300. Here we present identifications for further WR stars in five associations of NGC 300.

2. Observations

2.1. Monochromatic imaging

During the period 14-18 October, 1995, we (JB, MA) conducted at La Silla an observing run with the New Technology Telescope (NTT) in order to complete our WR star survey in NGC 300 (Testor et al. 1996). A slitless spectroscopy detection technique combining a grism and an interference filter (λ_o = 4700 Å, $\Delta\lambda \approx 150$ Å) was applied using the ESO Multi-Mode Instrument (EMMI). On one night, very good seeing conditions (0.52 to 0.80 arcsec FWHM) prompted us to observe crowded stellar regions with SUSI, the SUperb Seeing Imager. The on-line/off-line imaging technique with interference filters centered on the strong WR emission lines around 4680 Å and on the adjacent continuum was then used. WR stars show up strongly in this spectral region due to the emission mainly from λ = 4686 HeII (WN type) and λ = 4650 CIII, CIV (WC type). The emission filter had a central wavelength of 4681 Å and a band-width of 60 Å; the continuum filter was centered at 4746 Å and had a band-width of 48 Å. The SUSI camera provided a field of view

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* Based on observations collected at the European Southern Observatory, La Silla, Chile (observing proposal ESO No. 56.D-0361)

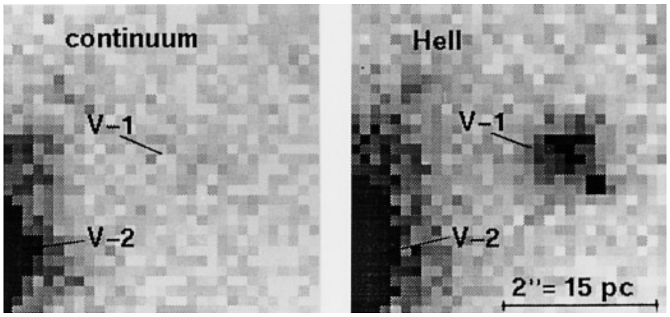

Fig. 1. Illustration of the on-line/off-line detection technique. For the selected star (V-1) the "WR excess" resulting from the difference between the emission line and continuum intensities corresponds to an 8σ detection. The group of four bright pixels near star V-1 (bottom right) in the HeII frame corresponds to a spurious image.

of 2.2×2.2 arcmin and was equipped with a TEK 1024^2 CCD having a pixel size of 24 μm corresponding to 0.13 arcsec on the sky. Integration times were carefully adjusted to take into account the differences in transmission of the two filters: 15 min in the emission-line filter and 16 min in the continuum filter. The on-line/off-line detection technique is illustrated in Fig. 1. For the selected star, one of our faintest WR candidates, the "WR excess" resulting from the difference between the emission line and continuum intensities is well visible, it corresponds to an 8σ detection.

2.2. Slit spectroscopy

During the same observing run, multiple object spectroscopy of WR candidates (some of them detected by means of slitless spectroscopy at an earlier phase of the survey) was carried out using the MOS mode of EMMI. Fixed slit widths of 1.2 arcsec were punched in the mask. The dispersion used was 248 Å/mm (5.9 Å/pix). A spectroscopic observation consisted of three 40 min MOS exposures allowing to obtain, using a standard routine, an image free from any spurious features. One spectrum (star No. V-3) was obtained during a previous run, in October 1991, by one of us (GT) at the 3.6m telescope with the ESO Faint Object Spectrograph Camera (EFOSC) at a dispersion of 120 Å/mm (3.2 Å/pix). The detectors associated with EMMI and EFOSC were respectively a TEK 2048^2 CCD and a TEK 512^2 CCD.

2.3. Photometry

During the observing run, Johnson UBV frames could not be secured thus preventing a subsequent accurate photometric calibration of the fields observed. Magnitudes of the WR stars were therefore estimated in the following way. Instrumental m_{4746} photometric magnitudes were determined with the DAOPHOT package (Stetson 1987) based on a PSF determination especially well adapted to crowded fields as implemented in the MIDAS system. For all the stars, in each field, relative magnitudes were obtained with a standard deviation error going from 0.02 to 0.3 mag in the range of magnitudes from 17.2 to 21.8. The m_B magnitudes of the WR stars were then derived using two "standards" located in our field I, namely the star R 22 (cf. Humphreys and Graham 1986) and the variable star No. 18 (cf. Graham 1984) for which the mean value of m_B = 21.1 was adopted with an estimated error of $\sim$ 0.4. The overall accuracy of the m_B magnitudes thus obtained is certainly not better than $\pm$ 0.5 mag.

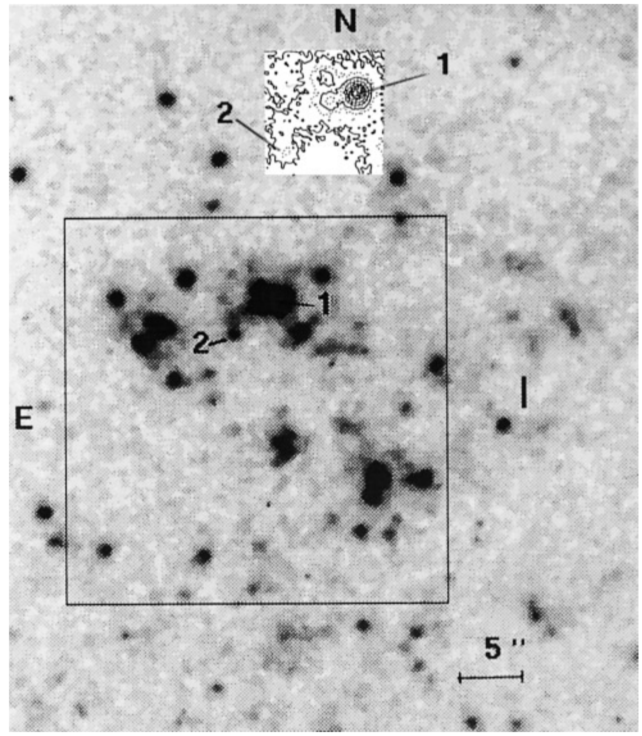

Fig. 2. Narrow HeII λ4681 image of the NGC 300-I association surveyed for WR stars. The box refers to the adopted boundaries; the inset corresponds to a factor 1.7 enlargement.

3. Results

3.1. The NGC 300 associations surveyed

The stellar complexes referred to in the present study have a typical angular size of 30 arcsec. Adopting a distance of 1.53 Mpc for NGC 300 (cf. Deharveng et al. 1988) this corresponds to a dimension of about 220 pc. Such a value is well in the range of the diameters of associations in other galaxies (cf. Hodge 1985 and references therein) and compares particularly well with the mean size of 203 pc derived for the associations of M 33, the galaxy considered as the counterpart of NGC 300 in the northern hemisphere. As the NGC 300 associations have not yet been catalogued in a systematic way, we simply use Roman numerals to designate the five ones surveyed for WR stars. The coordinates and size of each association as well as the number of stars detected with DAOPHOT are provided in Table 1; the adopted boundaries[1] are shown in Figs. 2 and 3. The numbers of

[1] For fixing the boundaries of the associations, boxes were preferred to circles because they allowed an easier counting of the "member"

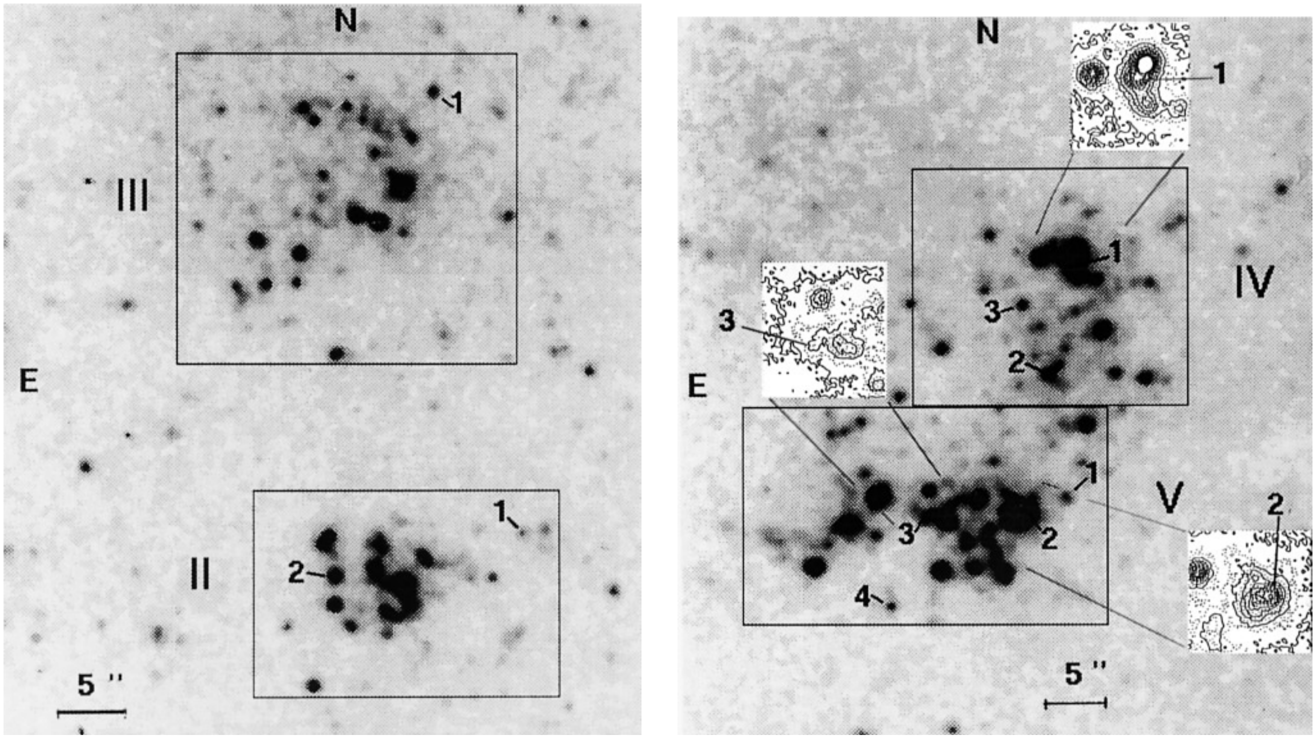

Fig. 3. Narrow HeII λ4681 images of the NGC 300-II, III, IV, and V associations surveyed for WR stars. The boxes refer to the adopted boundaries; the insets correspond to a factor 1.7 enlargement.

Table 1. Associations of NGC 300 surveyed for WR stars.

Association	α (2000)	δ (2000)	Dimension (arcsec)	Number of stars	m$_B$ range	HII region
I	0 54 50.1	-37 38 30	30 x 30	49	19.4-23.3	77, 79
II	0 55 03.3	-37 43 17	24 x 16	32	18.6-22.1	119a
III	0 55 03.7	-37 42 48	26 x 24	46	19.2-22.5	118a
IV	0 55 12.1	-37 41 20	21 x 18	44	18.4-22.7	137b,d
V	0 55 12.8	-37 41 37	28 x 17	47	18.3-22.5	137a,c

Note to Table 1: *Column 7:* The identification numbers of the HII regions are from Deharveng et al. (1988).

the associated HII regions (cf. Deharveng et al. 1988) are also indicated.

Six WR stars were previously identified in these associations by Testor and Schild (1993). Thanks to the excellent SUSI images, in very crowded regions we have been able to better locate some of the already known objects and to detect six new WR stars. Table 2 lists the coordinates, spectral types and magnitudes of all the WR stars known in the five associations studied. Finding charts are provided in Figs. 2 and 3 which reproduce the images obtained with the HeII emission filter. The coordinates were determined using as reference objects the WR stars previously detected in the fields by Schild and Testor (1992). They should be accurate to within 2 arcsec. The last column refers to the m$_B$ magnitudes derived from the continuum measurements at λ = 4746 Å (see Sect. 2.3).

3.2. The WR subtypes

The WR spectral subtypes given in Table 2 were determined using the observational material described in Sect. 2.2. The classification was derived by visual inspection of the spectra using the "standard" criteria (cf. Smith 1968, van der Hucht et al. 1981, Breysacher 1981), taking into account for the WO/WC type stars the FWHM of the CIII λ4650 and CIV λ5811 emission features. According to Smith et al. (1990), the widths of these strong lines are indeed useful guides to determine the subclass when the other classification criteria, based on weaker line intensity ratios, cannot be employed. For the faint stars, the obtained MOS spectra did not allow an unambiguous classification; three of the stars discovered by Schild and Testor (1992) have been assigned a revised spectral type. The three stars for which we have no slit spectra are tentatively classified WN or WC on the basis of their luminosity in the continuum filter. The WN-type stars tend indeed to appear systematically brighter in this filter than the WC-type stars.

stars with DAOPHOT, also avoiding the intersection of very close associations like Nos. IV and V.

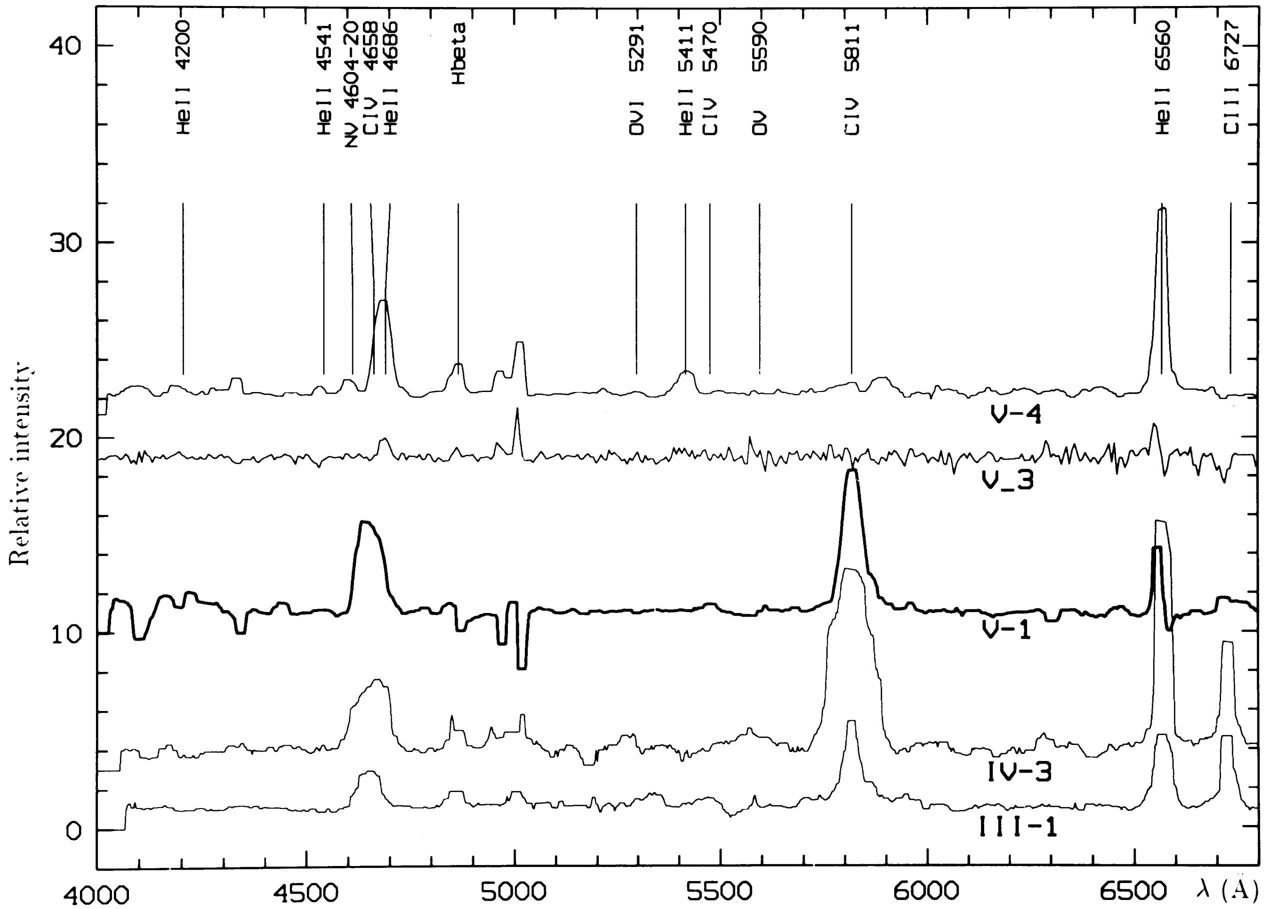

Fig. 4. MOS spectrograms of the WR stars III-1, IV-3, V-1, V-3 and V-4, with identification of the dominant emission features.

The spectra of stars I-1, II-2, IV-2 and V-2 have already been published (cf. Schild and Testor 1992; Testor and Schild 1993: their stars WR9, WR7, WR5 and WR4 respectively). In Fig. 4 are displayed the spectra corresponding to stars III-1 (WR12), IV-3 (WR13), V-1, V-3 and V-4. Thus, of the twelve WR stars detected in the five NGC 300 associations investigated, only three remain to be definitely confirmed and classified by means of slit spectroscopy. Two of them (I-2, II-1) correspond to an 8σ detection, the third one (IV-1) to a 13σ detection. We can therefore consider that they are bona fide WR stars.

3.3. The "O/WR" ratio

Although the Hα luminosity cannot always be considered as a totally reliable indicator of the stellar population in sites of massive star formation (Conti 1996, Testor and Niemela 1996) it remains, beyond the Local Group, the best tracer of the luminosity generated by stars. With reference to the paper by Devereux and Scowen (1994), the Lyman continuum photon rate in photons per second, N_{Lyc}, produced by stars surrounded by an HII region can be derived from the flux of Hα photons, $F(H\alpha)$, yielded by the ionization process in the nebula using the following equation:

$$N_{Lyc} = 0.83 \times 10^{62} \times 10^{E_{B-V}} F(H\alpha) D^2$$

which also takes into account the extinction. D is the distance in Mpc. The N_{Lyc} value thus obtained can then be expressed in terms of an equivalent number of ionizing stars of a given spectral type.

To estimate the "number of O stars" in each of the NGC 300 associations/HII regions (roughly the same areas are studied), the respective WR star contributions to the Lyman continuum fluxes derived from the integrated Hα fluxes had to be determined first. Instead of using the mean value of 3.5×10^{49} photons s^{-1} adopted by Garmany et al. (1994), we have derived the number of Lyman continuum photons per second produced by the WR stars from a set of values calculated for us by W. Schmutz (1996, personal communication) which takes into account the various WR spectral types represented in the associations and the absolute magnitudes of the stars (adopted absorption-free distance modulus: 25.9 mag). Considering the uncertainties in both our spectral classification and magnitude determination, the following mean values, resulting from the calculations by Schmutz (1996), were finally adopted for the WR contributions:

– WC+WN: 3.0×10^{49} photons s^{-1}
– WO4/WC: 0.8×10^{49} photons s^{-1}
– WN ($M_v > -6.5$): 1.4×10^{49} photons s^{-1}
– WN ($M_v < -6.5$): 4.3×10^{49} photons s^{-1}

Table 2. WR stars in the NGC 300 associations.

Association	Star No.	Other identification	α (2000)	δ (2000)	Spectral type	Magnitude (m_B)
I	1	WR 9	0 54 49.9	-37 38 21	WC+WN	19.4
	2		0 54 50.2	-37 38 23	WC*	21.4
II	1		0 55 02.6	-37 43 13	WC*	22.0
	2	WR 7	0 55 03.8	-37 43 17	WN9-10	20.2
III	1	WR 12	0 55 03.2	-37 42 39	WC5-6	22.3
IV	1		0 55 12.0	-37 41 17	WN*	19.2
	2	WR 5	0 55 12.1	-37 41 26	WC5-6	20.6
	3	WR 13	0 55 12.3	-37 41 20	WO4	>22.7
V	1		0 55 12.0	-37 41 35	WC4-5	>22.5
	2	WR 4	0 55 12.3	-37 41 37	WN7	19.0
	3		0 55 12.9	-37 41 37	WN4-6	21.5
	4		0 55 13.1	-37 41 43	WN4-5	22.2

Notes to Table 2: *Column 1:* Association number
Column 3: The star numbers are from Testor and Schild (1993)
Column 6: The presence of an asterisk (*) indicates that the spectral type is inferred from the brightness of the star in the continuum filter.

Table 3. Stellar content of the NGC 300 associations.

Association	HII region	F(Hα) ($10^{-16} ergs^{-1} cm^{-2}$)	E_{B-V}	$N_{(WR+O)Lyc}$ ($10^{49} s^{-1}$)	N (WR)	$N_{(WR)Lyc}$ ($10^{49} s^{-1}$)	N_{Lyc} ($10^{49} s^{-1}$)	N (O5V)
I	77,79	7666	0.31	30.4	2	3.8	26.6	6
II	119a	6015	0.30	23.3	2	2.2	21.1	5
III	118a	4978	0.29	18.9	1	0.8	18.1	4
IV	137b,137d	5393,2904	0.21,0.32	28.8	3	5.9	22.9	5
V	137a,137c	8214,2987	0.25,0.22	38.0	4	7.9	30.1	7

Notes to Table 3: *Column 1:* Association number
Column 2: HII region numbers from Deharveng et al. (1988)
Column 3: Integrated Hα flux determined by Deharveng et al. (1988)
Column 4: Color excess
Column 5: Total number of Lyman continuum photons per second
Column 6: Number of WR stars in the association
Column 7: Number of Lyman continuum photons per second produced by the WR stars
Column 8: Corrected Lyman continuum flux: $N_{Lyc} = N_{(WR+O)Lyc} - N_{(WR)Lyc}$
Column 9: Equivalent number of ionizing zero-age-main-sequence O5 stars.

The colour excess $E_{B-V} = C(H\beta)/1.46$ (cf. Pottasch 1984) of the HII region(s) surrounding each stellar group was determined using the C(Hβ) values given by Deharveng et al. (1988). The O stellar content of the various NGC 300 associations (Table 3) was computed assuming that, once the WR stars have been excluded, the Hα luminosity of the associated HII regions is exclusively powered by zero-age-main-sequence O5 stars for which the individual Lyman continuum flux is 4.2×10^{49} photons s^{-1} (Panagia 1973).

The average "O/WR" ratio of 2.6 ± 0.8, which results from the comparison of the numbers of WR and O5 stars in the five NGC 300 associations studied in the present paper, is well in the range of the values (2.3 - 3.7) given by Massey (1996) for the ratio of the number of massive ($> 40 M_{\odot}$) OB stars to the number of WR stars, in a sample of galaxies. The agreement with the "$OB_{(>40 M_{\odot})}$ / WR" ratio of 2.9 derived from seven fields in M 33 (Massey 1996) is quite remarkable, M 33 being indeed generally considered as a twin of NGC 300. However, it has to be kept in mind that one is dealing here with small number statistics.

4. Conclusions

The WR star survey that we have carried out in NGC 300 has an estimated detection threshold of $m_B \approx 22.5$ (Testor et al. 1996). Taking into account the relative inaccuracy of our magnitudes (cf. Sect. 2.3), with the adopted distance modulus of 25.9 for NGC 300, this corresponds to a limiting absolute magnitude of - 3.4 $\pm$ 0.5. In the LMC, where the WR star census is believed to be fairly complete, the visual absolute magnitudes of the faintest WN and WC type stars found in associations are - 4.0 and - 4.2 respectively (Breysacher 1986, 1988). If we assume that the situation is similar in NGC 300 i.e., WR stars fainter than - 4.0 are essentially encountered in the field, then the present survey has presumably led to the identification of most (possibly all) of the WR stars contained in the five associations investigated. As a result, the above derived "O/WR" ratio cannot be strongly biased by an incompleteness in the WR star detection and must therefore be regarded as having some significance. On the contrary, the uncertainties in the spectral classification of some of the WR stars, as well as the small number of this type of stars in the NGC 300 associations, prevent us at the moment from drawing conclusions based on the WR subtypes, regarding evolutionary status and correlation with metallicity.

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