A&A 366, L1–L4 (2001)
DOI: 10.1051/0004-6361:20000571

Astronomy & Astrophysics

Letter to the Editor

The WR content of IC10 - first detection of WC9 stars in a low metallicity environment?*

P. Royer[1,**], S. J. Smartt[2], J. Manfroid[1,***], and J.-M. Vreux[1]

[1] Institut d'Astrophysique, Université de Liège, 5 avenue de Cointe, 4000 Liège, Belgium
[2] Institute of Astronomy, University of Cambridge, Madingley Road, CB3 O4A Cambridge, UK

Received 27 November 2000 / Accepted 12 December 2000

Abstract. We present deep, narrow-band photometry of the Local Group starburst galaxy IC 10. Our dedicated photometric system provides detection of 13 new Wolf-Rayet (WR) stars and allows spectral subtypes to be assigned. Three of these new stars appear to be WC9 subtypes. If confirmed, these would be the very first WC9 stars ever detected in a low metallicity environment, hence putting strong new constraints on the formation and evolution models of massive stars. Eight of the new WR stars are of the WC subtype, which does not significantly modify the anomalously high WC/WN ratio in IC 10. However it is likely that a number of Wolf-Rayet stars of the WNE and WC spectral subtypes are still to be discovered in the heart of the galaxy.

Key words. stars: Wolf-Rayet – photometry: narrow bands – galaxies: starburst, Local Group

1. Introduction

Massive stars play a fundamental role in galaxy evolution due to their prodigious energy output into the surrounding interstellar medium. This results from their strong stellar winds, intense ionizing UV flux, and deaths in supernovae explosions. Their short lifetimes (3−10 Myrs) mean they have been important sources of chemical enrichment through wind outflows and supernovae. Conversely, the natal environment of massive stars plays an important role in their evolution. As massive stars are found in a wide variety of locations (e.g. disks of spiral galaxies, heart of nuclear starbursts in active galaxies, blue compact dwarfs, ultra-luminous infrared galaxies), it is imperative to understand the influence of the environment (particularly metallicity) on stellar evolution. Detailed observations of individual stars in nearby galaxies, covering a range of environments is a first step towards understanding their evolution and eventually understanding the unresolved populations of distant starbursts.

The WR stage represents a unique test of massive stellar evolution theories, and the relative number of WC to WN stars has been used extensively in the Local Group (Maeder & Conti 1994) to constrain the models. Due to their strong spectral characteristics, detecting, and classifying, the WR stars (using narrow-band imaging techniques) is much more reliable than photometrically classifying the un-evolved massive star population (O-type main-sequence stars), given their degeneracy in colours.

The "Conti scenario" for massive stellar evolution (Maeder & Conti 1994) suggests that the WC to WN ratio is a strong function of metallicity. This prediction is broadly consistent with the WC to WN ratios observed in most Local group environments (Massey 1999). However one clear anomaly stands out within the Local Group - the dwarf irregular galaxy IC 10.

IC 10 is located at the edge of the Local Group. Its distance and reddening have been debated in the past, with estimates of the $(B-V)$ color excess ranging from 0.75 to 2.0, and estimates of the distance modulus ranging from 22.1 to more than 27. Recent measurements indicate values around $E(B-V) \sim 1.0$ and $m-M \sim 24$ (see Borissova et al. 2000 and Massey & Armandroff 1995 for complete discussions). The oxygen abundance in H II regions has been estimated at 8.2 dex, or 0.3 $Z_\odot$ (Lequeux et al. 1979; assuming the mean of their two positions and two calibrations). IC 10 is the nearest galaxy-wide starburst and provides a unique opportunity to individually study a massive stellar population in such an environment. Massey & Armandroff (1992, hereafter MAC92) used a three-filter photometric system to perform on-line/off-line photometry on IC 10 with the aim of quantifying its WR star population. Follow-up spectroscopy allowed

Send offprint requests to: P. Royer, e-mail: proyer@ulg.ac.be
* Based on observations at the William Herschel Telescope on La Palma and at the Observatoire de Haute-Provence.
** Aspirant au Fonds National de la Recherche Scientifique (Belgium); ingénieur de recherche à l'Université de Liège.
*** Directeur de Recherche au Fonds National de la Recherche Scientifique (Belgium).

identification of 15 WR stars among their 22 photometric candidates (Massey & Armandroff 1995, hereafter MA95). Two aspects of this result were remarkable and unexpected. Firstly, with such a high number of WR stars, IC 10 has the highest relative Star Formation Rate (SFR) among the galaxies of the Local Group. Secondly, it has a very peculiar WR subtype ratio of WC/WN = 2; there is a distinct correlation between this ratio and the metallicity of the starforming environment in the Local Group (Massey 1999), and the IC 10 ratio is clearly different from that expected, if the metallicity of the galaxy is indeed 0.3 $Z_{\odot}$.

There was however a probability that MA95 results were not complete. Due to their much stronger lines, WC subtypes are much easier to detect than WN stars (Massey 1996). MAC92 had only one hour of exposure time in their WN-sensitive filter, and twice as much in their WC and continuum filters. Further their observations were not performed in optimal seeing nor transparency. Before considering the origin of IC 10's anomalous WC/WN ratio, it was necessary wise to ascertain the true completeness of the survey. This is the purpose of the present paper.

2. Observations and reductions

Observations were performed on Oct. 2–3 1999 with the 2EEV 4k × 4k mosaic camera (0.237″ pixels) at the prime focus of the 4.2 m William Herschel Telescope on La Palma. Observations were taken through 5 special narrow band filters dedicated to Wolf-Rayet detection and classification (Royer et al. 1998 - hereafter Paper I). A series of 900 s frames were obtained for each filter (see Table 1). The frames were bias corrected, flat field and then coadded. The seeing in the combined images is about 1.2″ for all filters. The photometric reduction was performed with the DAOPHOT II package (Stetson 1987) installed under ESO MIDAS. The atmospheric extinction was subtracted on the basis of the standard extinction coefficients determined for our filters during previous campaigns (the details will be discussed in a forthcoming publication). The magnitudes were adjusted to the system described in Paper I by applying zero points established in standard fields calibrated at the 1.2 m telescope of the Observatoire de Haute Provence in July 1999 and re-observed during the La Palma run. Special care was taken to correctly cross-identify the objects detected in the various filters. The intention was to avoid losing any objects, even if not detected in all filters. A total of 7462 objects were detected in at least one filter on the CCD chip where we placed IC 10. Among those, 2579 objects were detected in all filters.

Table 1. Journal of the observations. Total integrations are composed of 900 s individual frames. In Col. 3, $n+m$ means that n and m frames were obtained during the first and second night respectively

Filter	λ_c	Number of frames	Integration time (s)
$r_{\rm HeII}$	4681	$5+4$	8100
c_1	5055	$5+3$	7200
$r_{\rm CIV}$	5803	$3+4$	6300
$r_{\rm HeI}$	5871	$5+3$	7200
c_2	6047	$4+6$	9000

3. Results and discussion

The main difficulty encountered when colour selecting the WR stars (as in Paper I) is contamination by foreground cool stars. Some K and M-type stars possess a molecular absorption band in the wavelength range corresponding to our c_1 filter. Lowering their flux in that "continuum" filter, makes these stars mimic He II emission. Simulations show that, with an absorption of $A_V = 2.5$ mag (MA95), IC 10's WR stars should have $c_1 - c_2 \leq 1$ and foreground red stars should have $c_1 - c_2 \geq 1$. Hence, we rejected all stars with $c_1 - c_2 \geq 1$. If the interstellar absorption happens to be larger (Borissova et al. 2000), we might have missed some WR stars. The other colour criteria that we applied to select, classify and give binarity indication for the new WR stars are based on simulations similar to those in Paper I. The simulations were nevertheless completely recomputed in order to take IC 10's blueshift into account as well as the filter bandpass modifications introduced by the fast focal ratio of the WHT prime focus.

Twenty-one of the 22 WR star candidates in MA95 are in our field ([MAC92] 22 is outside). They were easily recovered in our colour diagrams, though 5 couldn't be detected in *all* of the filters. We confirm the WR nature of these stars, as well as their spectral classification, except for [MAC92] 5, which does not appear as a WNE but as a WCE star and is located in a small H II region. Our c_1 filter is slightly sensible to the [OIII] λ5007 nebular line because of the bandpass modification due to the converging beam at WHT prime focus. Hence, the flux continuum of the stars lying in regions emitting strong nebular lines is overestimated and their possible He II λ4686 emission appears diminished. This does not hamper the WR selection, but affects the colours of objects lying in the heart of the strongest H II regions. Nevertheless, the intensity of its C IV λ5805 emission line leaves no doubt that [MAC92] 5 is of the WC subtype.

Figure 1 shows the newly found WR stars in the l(C IV) vs. l(He II) colour diagram. The notation l(line) indicates the continuum subtracted colour index (see Paper I). All stars with He II absorption or with $l(\text{He II}) \leq 0.1$ and $l(\text{C IV}) \leq 0.1$ were excluded from the plot, as well as stars with $c_1 - c_2 \geq 1$. The WN/WC separation is also drawn. One can immediately see a number of new WR candidates in this plot, mostly of the WC subtype. The new WR candidates and their main characteristics are described in Table 2. The coordinates listed in this table were computed under IRAF on the basis of those published in MA95. The details of the detection, spectral type and binarity of MA95's WR stars will be discussed in a future publication.

Table 2. New WR candidates. The subtype classification and indications of binarity are based on synthetic colour diagrams similar to those discussed in Paper I. The "black bar" is a region in the South of the galaxy exhibiting signs of intense interstellar extinction

Star	Type	α_{2000}	β_{2000}	c_2	σ_{c_2}	Binary?	Comments
RSMV 1	WC9	0:20:21.60	59:17:14.3	22.27	0.11	n	crowded region
RSMV 2	WN7-8	0:20:28.15	59:17:14.8	21.72	0.06	n	in the "black bar"
RSMV 3	WC9	0:20:28.83	59:17:43.4	22.71	0.17	n	very next to a cluster
RSMV 4	WC	0:20:22.03	59:17.55.6	22.16	0.13	y	weak-lined or binary; crowded region
RSMV 5	WC	0:20:04:32	59:18:06.5	21.56	0.04	y	weak-lined or binary
RSMV 6	WC	0:20:03:10	59:18:27.3	22.11	0.05	y	weak-lined or binary
RSMV 7	WC9	0:20:11:30	59:18:54.4	22.44	0.07	y	crowded region
RSMV 8	WN8-9	0:20:20.64	59:18:37.7	20.25	0.03	y	in a cluster
RSMV 9	WN7	0:20:20:41	59:18:40.1	20.96	0.06	y	in the same cluster as No. 8
RSMV 10	WC	0:20:26.63	59:17:05.6	-	-	n	c_1 and c_2 lacking; in the "black bar"
RSMV 11	WC	0:20:22.82	59:17:53.9	-	-	n	c_1 and c_2 lacking
RSMV 12	WN	0:20:25.77	59:16:48.9	-	-	?	c_1, c_2 and $r_{\rm HeI}$ lacking; in the "black bar"
RSMV 13	WN	0:20:15.70	59:17:22.1	-	-	?	detected in $r_{\rm HeII}$ only

There are 13 new WR candidates. Numbers 1 through 7 easily show up in the colour diagrams. Number 8 doesn't look remarkable in Fig. 1 (it is located at $l(\text{HeII}) = 0.17$, $l(\text{CIV}) = -0.02$) but has been selected in other diagrams thanks to its HeI emission ($l(\text{HeI}) = 0.46$). Number 9 shows obvious HeII emission, but wasn't detected easily because it is a "faint" member of a cluster. The remaining four couldn't be detected in all filters, but appear as obvious candidates by visual inspection, as well as in the colour diagrams when one replaces the lacking continuum data by the corresponding limiting magnitudes.

Three of the new candidates (1, 3 and 7) exhibit a WC9 subtype behavior in our various colour diagrams. Unfortunately, the most striking of our WC9 candidates, number 3, is located on the edge of a cluster and its photometry in the continuum filters might not be excellent (crowding might also be a problem for the photometry of candidate number 4, which is faint and blended with another star). The fact that the $c_1 - c_2$ index of candidate 3 is amongst the bluest in the field (0.24) indicates that its c_1 photometry is contaminated by nebular [OIII]λ5007 emission around the nearby cluster. Removing the corresponding contaminating flux from the c_1 filter would lead to an increase of the continuum-corrected emission lines, i.e. reinforce the WR characteristics. The photometry of the two other WC9 candidates is not affected by this kind of problem. The simultaneous existence of three such candidates is an additional argument in favour of the discovery of WC9 stars in IC 10. Like most of the other candidates from number 1 to 8, the 3 WC9 candidates can not directly be distinguished as WR stars from simple visual inspection, but only come up in the colour diagrams. This is not particularly surprising since all of the most obvious candidates were pointed out by MA95.

The discovery of WC9 stars in IC 10 is rather unexpected due to its metal poor character. All WC9 stars known so far exist in high metallicity environments (inwards of the solar circle in the Milky Way). However Guseva et al. (2000) report the possible discovery of WCL subtype WR stars in Mrk 1236 and CG 798, two Wolf-Rayet galaxies with $Z \sim Z_{\odot}/8$.

Other important issues of this study are the completeness and the WC/WN ratio. The very high value (WC/WN ≥ 2) of the latter is confirmed by the present study, but the WR star census might not yet be complete. Indeed, none of MA95's very faint WR stars ($c_2 \geq 22$) stand in the heart of the galaxy, but rather in outer parts of it, i.e. in regions of lower crowding and background noise. We are thus raise the following questions: 1) could it be that most of MA95's WR stars are binaries, detected thanks to their higher combined luminosities, and 2) where are IC 10's faintest WR stars? Our colour diagrams reveal that the answer to the first question is yes: among MA95's WR stars, the weakest are the single stars and stand on the outer parts of the galaxy, while MA95's WR stars located in the heart of IC 10 appear to be binary WR stars. The colour indices indicate binarity due to the intensity of the emission lines of each star compared to the other stars of the same spectral type (see Paper I). The only exception is [MAC92] 10, which is an anomalously bright WCE star standing in the core of IC 10. This brings us to the second question: where are the faint (and the single) WR stars in the central part of IC 10? The present study uncovers a few such stars, but a number of them are undoubtedly still to be found: with a "standard" reddening law ($A_V/E(B-V) = 3.1$), IC 10 should have a combined (distance + extinction) modulus around 27 mag (Borissova et al. 2000). Hence, adopting the M_V values of van der Hucht (2000), the single WR population should be found between $V \sim 20$ and $V \sim 24$ for the WN stars, and between $V \sim 22$ and $V \sim 25$ for the WC stars. The apparent brightness of all the observed single WR stars

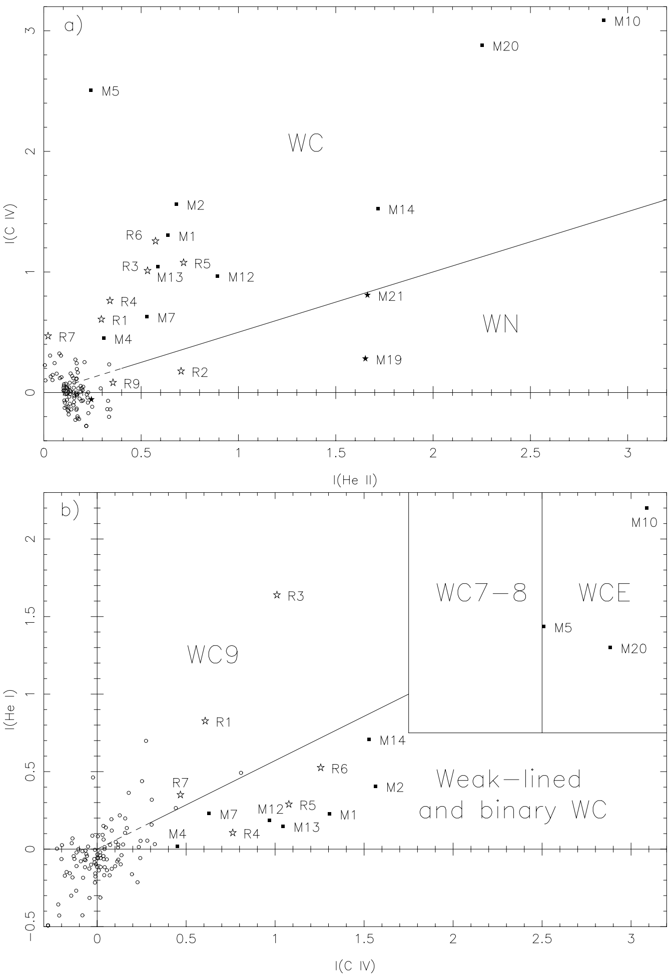

Fig. 1. a) The basic WN/WC discrimination, based on the HeII λ4686 and CIV λ5805 emission lines. Filled squares are known WC stars, filled star symbols are known WN stars. Open star symbols are the new WR candidates ("R" labels refer to RSMV, "M" labels refer to MAC92). Open circles are "normal" stars that nevertheless obey the colour criteria used in this figure (l(HeII)≥ 0.1; l(CIV)≥ 0.1; $c_1 - c_2 \leq 1$). The filled star symbol around (0.25; −0.05) is [MAC92] 17. RSMV 8 is located at (0.17; −0.02). [MAC92] 9 and [MAC92] 15 could not be measured in the continuum filters and could hence not be plotted here. **b)** The WC sub-type discrimination based on the HeI and the CIV emission lines, with symbols and colour criterions as in **a)**. The three WC9 candidates are clearly seen in the designated region, and their other colours are consistent with this classification

is consistent with these values (except for [MAC92] 10). As our limiting magnitudes stand around 22.0–22.5 (depending on the filter), we are led to the following conclusions:

– Due to their brightness, most of IC 10's WNL stars should already have been detected, unless they stand in the heart of very tight clusters or in regions with a local higher absorption;
– A number of faint WR stars (WNE and WC spectral subtypes) undoubtedly remain to be discovered. The very high WC/WN ratio may have to be revised in the future, however it is unlikely to *significantly* decrease;
– The wealth of WR stars found in IC 10 and their WC/WN distribution may be indicative of a brief, galaxy-wide, very intense burst of star formation that took place a few Myr ago. The models of instantaneous bursts of star formation indicate that some phases of their evolution lead to very high WC/WN ratios (Leitherer et al. 1999). This seems to be the only way to reconcile the metal-poor character of IC 10 and the distribution of its WR spectral subtypes.

4. Conclusion

We present a new search for WR stars in IC 10 based on a dedicated 5-filter, narrow band, photometric system. In addition to the 15 WR stars already known in this galaxy, we have detected, classified and given binarity indications for 13 new WR candidates. The enormous number of WR stars detected in IC 10 makes it by far the most active star forming galaxy in the Local Group. The WR stars detected in the present study do not significantly modify the very high WC/WN ratio previously found. Nevertheless, the WR star census in IC 10 is probably not yet complete and further slight revisions of the WC/WN count ratio are to be expected. The main surprise in this study is the fact that three of the new candidates exhibit characteristics of the WC9 subtype. This is the first detection of WC9 stars in such low-metallicity environment.

Acknowledgements. We thank the Fonds National de la Recherche Scientifique (Belgium) and the University of Liège. We acknowledge support from PPARC, from the SSTC-Belgium under contract P4/05 and by the PRODEX XMM-OM project. We thank the mechanical staff at the ING for their help in adapting our filters for WHT prime.

References

Borissova, J., Georgiev, L., Rosado, M., et al. 2000, A&A, 363, 130
Guseva, N. G., Isotov, Y. I., & Thuan, X. T. 2000, ApJ, 531, 776
Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, ApJS, 123, 3
Lequeux, J., et al. 1979, A&A, 80, 155
Maeder, A., & Conti, P. S. 1994, ARA&A, 32, 227
Massey, P., Armandroff, T. E., & Conti, P. S. 1992, AJ, 103, 1159
Massey, P., & Armandroff, T. E. 1995, AJ, 109, 2470
1996Massey, P. , in Proceedings of the 33rd Liège international astrophysical Colloquium, 1-3 July 1996, ed. J.-M. Vreux, et al., 361
Massey, P. 1999, in Proceeding of the IAU Symp. 193, ed. van der Hucht, et al., 429
Royer, P., Vreux, J.-M., & Manfroid, M. 1998, A&AS, 130, 407
Stetson, P. B. 1987, PASP, 99, 191
van der Hucht, K. A. 2000, New Ast. Rev., in press