WOLF-RAYET STARS IN IC 10: PROBING THE NEAREST STARBURST

PHILIP MASSEY AND SHADRIAN HOLMES

Lowell Observatory, 1400 West Mars Hill Road, Flagstaff, AZ 86001; phil.massey@lowell.edu, sholmes@astro.as.utexas.edu

Received 2002 September 25; accepted 2002 September 30; published 2002 October 11

ABSTRACT

IC 10 is the nearest starburst galaxy, as revealed both by its He surface brightness and by the large number of Wolf-Rayet (W-R) stars per unit area. The relative number of known WC- to WN-type W-R stars has been thought to be unusually high (approximately two), which is unexpected for IC 10’s metallicity. In this Letter, we report the first results of a new and deeper survey for W-R stars in IC 10. We successfully detected all of the spectroscopically known W-R stars, and based on comparisons with a neighboring control field, we estimate that the total number of W-R stars in IC 10 is about 100. We present spectroscopic confirmation of two of our W-R candidates, both of which are of WN type. Our photometric survey predicts that the actual WC/WN ratio is ~0.3. This makes the WC/WN ratio of IC 10 consistent with that expected for its metallicity but greatly increases the already unusually high number of W-R stars, resulting in a surface density that is about 20 times higher than in the LMC. If the majority of these candidates are spectroscopically confirmed, IC 10 must have an exceptional population of high-mass stars.

Subject headings: galaxies: individual (IC 10) — galaxies: starburst — galaxies: stellar content — stars: evolution — stars: Wolf-Rayet

1. INTRODUCTION

Mayall (1935) first recognized IC 10 as an extragalactic object, and Hubble (1936, p. 147) proposed that it was likely a member of the Local Group. Its location just 3° out of the Galactic plane has hampered investigations, but Hubble’s description of it as “one of the most curious objects in the sky” has proved to be prophetic. Today IC 10 is understood to be an irregular galaxy undergoing an intense burst of star formation likely triggered by infalling gas from an extended cloud that is counterrotating with respect to the galaxy proper, as discussed by Wilcots & Miller (1998), who conclude that IC 10 is a galaxy that is still forming.

The starburst nature of IC 10 was revealed primarily from the high number of Wolf-Rayet (W-R) stars found by Massey, Conti, & Armandroff (1992) and Massey & Armandroff (1995). Hodge & Lee (1990) had motivated these studies by their discovery of 144 H ii regions, the brightness of which were known to be comparable to the brightest seen in the SMC (Hunter & Gallagher 1985; Kennicutt 1988), a galaxy known to contain a substantial massive star population. Massey et al. (1992) used interference imaging to identify 22 W-R candidates, of which 15 were confirmed spectroscopically (Massey & Armandroff 1995). This number was quite unexpectedly high. IC 10 is about half the size of the SMC (van den Bergh 2000), which contains 11 W-R stars (Massey & Duffy 2001); thus, the overall surface density of W-R stars in IC 10 is at least 5 times greater than in the SMC. The galaxy-wide surface density of W-R stars in IC 10 is in fact comparable to that of the most active OB associations in M33 (Massey & Armandroff 1995). The distribution of W-R stars across IC 10 shows that this high star formation activity is not confined to a few regions (which would simply be the result of statistical fluctuations or “graininess” in the star formation rate) but rather is characteristic of the galaxy as a whole. This is the classic definition of a starburst galaxy (Hunter 1986; Searle & Sargent 1972).

However, one of the very peculiar results of these W-R studies was the abnormally large ratio of WC to WN stars given IC 10’s metallicity (log O/H + 12 = 8.25; Skillman, Kennicutt, & Hodge 1989; Garnett 1990). Figure 1 shows the relative number of WC and WN stars plotted for different galaxies of the Local Group. The interpretation of the strong trend with metallicity is straightforward: since the stellar winds of massive stars are driven by radiation pressure in highly ionized metal lines, stars of a given luminosity (and mass) will have a lower mass-loss rate in a lower metallicity system and hence will lose less mass during their lifetime. In the “Conti scenario” (Conti 1976; Maeder & Conti 1994), a massive star peels down like an onion as a result of mass loss, revealing first the equilibrium products of the CNO cycle at its surface (WN stars) and then the He-burning products (WC stars). Very massive stars will therefore evolve first to the WN stage and subsequently to the WC stage, while a less massive star might evolve only through WN. At low metallicities, the WC stars should come only from the very highest mass stars (Massey 2003).

The peculiar WC/WN ratio may be telling us something important about the star formation process in this, the nearest starburst galaxy. If the initial mass function (IMF) was top heavy (or inverted), with an overabundance of the very highest mass stars, this could explain the results. However, Hunter (2001) finds a normal IMF slope for the intermediate-mass stars in IC 10. It would be very odd for the IMF of the highest mass stars to be decoupled from that of the intermediate-mass stars. Alternatively, if the burst that produced the W-R progenitors had been extremely coeval, then an abnormal WC/WN population could certainly result (Schaerer & Vaucouleurs 1998). However, that would require a burst of duration less than 200,000 yr over a scale of a kiloparsec. Instead, a third, more prosaic possibility is that the WC/WN ratio is strongly affected by incompleteness. WN stars are much harder to detect than WC stars since their strongest emission lines are considerably weaker (see Massey & Johnson

1 Observations reported here were obtained at (1) the Multiple Mirror Telescope Observatory, a joint facility of the University of Arizona and the Smithsonian Institution, and at (2) the Kitt Peak National Observatory, a division of the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

2 Current address: Department of Astronomy, University of Texas at Austin, RLM 16.318, Austin, TX 78712-1083.
IC 10 was imaged through three interference filters with the 4 m Mayall telescope and mosaic CCD camera (8k × 8k). The data were obtained on 2001 September 19 and 20 UT. The filter system is based on that described by Armandroff & Massey (1985) and Massey & Johnson (1998), but in a large 5.75 × 5.75 inch (146 × 146 mm) format. The WC filter is centered on C II λ4650, the strongest optical line in WC stars. The WN filter is centered on He II λ4686, the strongest emission line in WN stars (although it is also present in WC stars; see Smith 1968). The continuum filter CT is centered at 4750 Å. The central wavelengths were designed for use in the fast, f/3 beam of the 4 m prime-focus camera and are roughly 50 Å in width. The exposure time was 1.5 hr in each filter, with the exposures broken into three 1800 s exposures with the telescope dithered by 150° north-south and east-west between exposures. The scale is 0.27 pixel⁻¹, and the seeing on the nine images ranged from 0.85 to 0.97, with an average of 0.92. The transparency was excellent. (For comparison, the Massey et al. 1992 survey for W-R stars in IC 10 used 1 hr exposures through each filter under 2°–2.6° seeing with drifting clouds interrupting the exposures.) Exposures of spectrophotometric standards through the CT filter were used to determine the continuum magnitudes m$_{λ4750}$ and are accurate to 0.1 mag.

The mosaic camera consists of eight separate chips, each covering 18ʹ4 (east-west) by 9ʹ2 (north-south), each large compared with the optical extent of IC 10 (with a half-light radius of 2ʹ). IC 10 had been centered on one of the chips, and it and a neighboring chip were reduced in the identical manner. The latter was intended to serve as a control. The data were processed through the IRAF mosaic pipeline with refinements from the Local Group Survey project. Instrumental magnitudes were obtained using the point-spread function fitting routine “DAOPHOT,” as implemented under IRAF. All together, 114,000 stellar images were photometered. On average, 5300 stars were measured on each frame of the control chip, and 7400 stars were measured on each frame of the galaxy chip.

Candidate W-R stars were selected by comparing the magnitude differences WC-CT and WN-CT to the uncertainty in the magnitudes based on photon statistics and read noise, after a zero-point magnitude adjustment was made based on the full ensemble of stars. Stars with magnitude differences more negative than −0.10 mag and whose significance level was greater than 3 $\sigma$ were considered valid candidates. The nine frames were treated as three independent sets, grouped by the three dithered telescope positions. Each candidate was examined on an image display by eye and checked for problems. Altogether the search revealed 238 unique candidates on the galaxy field and 135 unique candidates for the control field; many of the candidates were found multiple times. We expect that none of the “W-R candidates” in the control field are real, given their location ∼10' from IC 10. Such spurious detections are expected given the small magnitude differences that we are looking for and given the possible presence of absorption features in the CT filter with non-W-R stars. It is for this reason that we used a control field.

3. RESULTS

The search found all 24 of the spectroscopically confirmed W-R stars (Massey & Armandroff 1995; Crowther et al. 2002a), with significance levels ranging from 5.6 $\sigma$ to 83 $\sigma$. The weakest-lined star had a magnitude difference of −0.5 mag, and the strongest-lined star −2.9 mag between the W-R filter (WC or WN) and the continuum filter CT. P. Crowther (2002, private communication) kindly conveyed the specifics of which RSMV stars he had been able to confirm spectroscopically and their spectral types in advance of publication. We therefore note that

![Region around He II λ4686 shown for our two newly confirmed W-R stars. Both are of WN type. The data have been slightly smoothed. The normalized spectrum of WR 24 has been scaled by a factor of 10; zero intensity is at the bottom of the figure.](image)
our survey successfully distinguishes all of the known WC stars from the known WN stars if we adopt a dividing line of WC-WN = −0.1. Late-type WN stars will have strong N Ⅲ λ4634, 4642 lines in the WC filter, while early-type WC stars will have very broad C Ⅲ λ4650 lines spilling over into the WN filter, so stars with a small absolute magnitude difference WC-WN are hard to classify just based on our filter photometry.

The Royer, Vreux, & Manfroid (1998) W-R filter system uses five filters to help classify W-R candidates to excitation subtype (WN2, WN3, ..., WN9; WC4, WC5, ..., WC9). Thus, on the basis of their photometry alone, RSMV announced the detection of very late type WC (WC9) stars in IC 10. This result was highly surprising since WC9 stars have previously been found only in much higher metallicity environments, for reasons thought to be well understood from stellar evolution: late-type WC stars are thought to result from more enriched surface material, and the star can only peel down far enough to reveal these layers if the metallicity is high and if mass-loss rates during the O-type stages are high (Smith & Maeder 1991). Crowther et al. (2002b) has recently called that into question, suggesting instead that the late-type WC stars are the result of stronger stellar winds in the W-R phase itself, but in either event, WC9 candidates are not expected in low-metallicity environments. This too was felt to be part of the puzzle of star formation in IC 10 (RSMV). However, our survey detected none of these WC9 candidates. An attempt to perform a quantitative spectroscopic analysis of these stars by Crowther et al. (2002a) using the Gemini Observatory failed to detect any emission. We can probably conclude that these stars are not real W-R stars.

Although the detection of all the known IC 10 W-R stars and the lack of detection of the spectroscopically rejected W-R candidates give us strong confidence in our survey, there is no substitute for spectroscopic confirmation. During a period of poor seeing at the 6.5 m Multiple Mirror Telescope (2002 September 14), we took time from our main program and observed two of our new candidates using a single slit setting. We used the 800 line mm$^{-1}$ grating on the blue channel with a 2" slit to obtain 3.8 Å resolution spectra in the blue; the exposure time was 2700 s. The spectra are shown in Figure 2; both are W-R stars of WN type. The coordinates are given in Table 1, along with the equivalent width and FWHM of the He Ⅱ λ4686 line. The lines are sufficiently broad to rule out the possibility that either star is an O-type star, which might also show He Ⅱ and/or N Ⅲ emission. WR 24 is by far the brightest W-R star found in IC 10 and is likely a blend of a W-R star and another star. A blend would also explain the very weak emission (Table 1) combined with a normal line width.

In Figure 3, we show a comparison of the photometry of W-R candidates in the galaxy field with that from the control field. We expect that none of the 135 candidates in the latter are real. Given that both the galaxy field (238 candidates) and the control field covered an equal area, we calculate that IC 10 may contain ∼100 W-R stars in total. Although this number seems fantastically large, we note that 26 have now been confirmed spectroscopically: 15 by Massey & Armandroff (1995), nine by Crowther et al. (2002a), and two here.$^3$

What then can we conclude about the statistics of WC and WN stars in IC 10? First, for the spectroscopically confirmed

---

TABLE 1

| Star | $\alpha_{2000}$ | $\delta_{2000}$ | $m_{K,S}$ | Type | EW (Å) | FWHM (Å) | Comment |
|------|----------------|----------------|------------|------|--------|----------|---------|
| WR 23 | 00 20 32.79 | 59 17 16.4 | 22.3 | WN7-8 | −40 | 13 | Hydrogen, strong N Ⅲ |
| WR 24 | 00 20 27.73 | 59 17 37.2 | 18.8 | WN | −4 | 21 | |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ The numbering is a continuation of those of Massey et al. 1992 and Massey & Johnson 1998. Revised designations including the “RSMV” stars will be included once spectroscopy of the new candidates is completed.

---
W-R stars, the WC/WN ratio is now 1.2 rather than 2.0. If we simply take all of the W-R candidates in the IC 10 field and correct by the number of “WC” and “WN” detections in the control field, we would expect to find a ratio of 0.3. This ratio is only slightly higher than that of the outer region of M33, which is of similar metallicity (Fig. 4). It is true that this result is somewhat dependent on our choice of the dividing line between “WC” and “WN” in our photometry. While our choice is consistent with our knowledge of the IC 10 W-R spectral types, spectroscopy of the remaining candidates will be needed to confirm this result.

4. DISCUSSION

If our statistical correction of the number of new candidates is correct, then spectroscopy should be able to confirm an additional approximately two WC stars and ~66 WN stars in IC 10. Even so, this may not represent the complete number, given the high reddening. Thus, the mystery of the high WC/WN ratio in IC 10 may be solved.

However, spectroscopic confirmation of such large additional number of W-R stars in IC 10 would certainly make this galaxy even more unique in terms of its massive star population. Two pieces of evidence suggest that this may well be the case. First, of the spectroscopically confirmed WN stars, two are of WN7-8 type. At low metallicities, the only similar late-type WN stars are found in the 30 Dor region of the LMC, where very high mass stars abound. Studies of coeval regions containing these stars in the Milky Way suggest that they come from only the highest mass stars (Massey, DeGioia-Eastwood, & Waterhouse 2001), and we would expect the progenitors to be even more massive in a low-metallicity environment (Massey 2003). This is consistent then with IC 10 having a normal IMF but an exceptionally large population of massive stars. Second, the integrated H$\alpha$ emission suggests that IC 10 has one of the two highest rates of star formation per unit area known of a representative sample of noninteracting irregular galaxies (Hunter 1997; D. A. Hunter 2002, private communication).

The “active” area of IC 10 is approximately $8' \times 8'$ in angular extent; at a distance of 660 kpc (Sakai, Madore, & Freedman 1999), this correspond to an area of 2.2 kpc$^2$. Thus, if our estimate is correct, IC 10 could contain roughly 45 W-R stars kpc$^{-2}$. For comparison, the LMC contains $\sim 2$ W-R stars kpc$^{-2}$ (Massey & Johnson 1998). A typical Galactic OB association might contain several W-R stars and might be 100 pc in diameter, i.e., with a surface density of a couple of hundred W-R stars kpc$^{-2}$—only several times larger than what we see globally in IC 10. Thus, if confirmed, the high number of W-R stars would suggest that IC 10 has a population of massive stars similar to that of an OB association, but on a kiloparsec scale.

We are thankful to Deidre Hunter for useful discussions and to Paul Crowther for communicating the results of his spectroscopy. This work has been supported by the NSF through grant AST 009-3060.

REFERENCES

Armandroff, T. E., & Massey, P. 1985, ApJ, 291, 685

Conti, P. S. 1976, Mem. Soc. R. Sci. Liège, 9, 193

Crowther, P. A., Abbott, J. B., Drissen, L., Schild, H., Schnutz, W., Royer, P., & Smartt, S. J. 2002a, in IAU Symp. 212, A Massive Star Odyssey: From Main Sequence to Supernova, ed. K. A. van der Hucht, A. Herrero, & C. Esteban (San Francisco: ASP), in press

Crowther, P. A., Dessart, L., Hillier, D. J., Abbott, D. B., & Fullerton, A. W. 2002b, A&A, in press

Garnett, D. R. 1990, ApJ, 363, 142

Hodge, P., & Lee, M. G. 1990, PASP, 102, 26

Hubble, E. W. 1936, The Realm of the Nebulae (New Haven: Yale Univ. Press)

Hunter, D. A. 1986, Highlights Astron., 7, 539

———. 1997, PASP, 109, 937

———. 2001, ApJ, 559, 225

Hunter, D. A., & Gallagher, J. S. 1985, ApJS, 58, 533

Kennicutt, R. C., Jr. 1988, ApJ, 334, 144

Maeder, A., & Conti, P. S. 1994, ARA&A, 32, 227

Massey, P. 2003, ARA&A, in press

Massey, P., & Armandroff, T. E. 1995, AJ, 109, 2470

Massey, P., Conti, P. S., & Armandroff, T. E. 1992, AJ, 103, 1159

Massey, P., DeGioia-Eastwood, K., & Waterhouse, E. 2001, AJ, 121, 1050

Massey, P., & Duffy, A. S. 2001, ApJ, 550, 713

Mayall, N. U. 1935, PASP, 47, 317

Richer, M. G., et al. 2001, A&A, 370, 34

Royer, P., Smartt, S. J., Manfroid, J., & Vreux, J.-M. 2001, A&A, 366, L1 (RSMV)

Sakai, S., Madore, B. F., & Freedman, W. L. 1999, ApJ, 511, 671

Schaerer, D., & Vacca, W. D. 1998, ApJ, 497, 618

Searle, L., & Sargent, W. L. W. 1972, ApJ, 173, 25

Skillman, E. D., Kennicutt, R. C., Jr., & Hodge, P. W. 1989, ApJ, 347, 875

Smith, L. F. 1968, MNRAS, 138, 109

Smith, L. F., & Maeder, A. 1991, A&A, 241, 77

van den Bergh, S. 2000, The Galaxies of the Local Group (Cambridge: Cambridge Univ. Press)

Wilcots, E. M., & Miller, B. W. 1998, AJ, 116, 2363