Two new Wolf-Rayet stars in the LMC

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ABSTRACT
We report the discovery of two previously unknown WN3 stars in the Large Magellanic Cloud. Both are bright (15th magnitude), isolated, and located in regions covered in earlier surveys, although both are relatively weak-lined. We suggest that there may be O(10) remaining undiscovered WNE stars in the LMC.

1 INTRODUCTION
Population I Wolf-Rayet stars are spectroscopically conspicuous tracers of the upper end of the initial mass function, with progenitor masses believed to be in excess of ∼25M⊙ (Crowther 2007). In the extragalactic context, Wolf-Rayet (WR) populations are particularly sensitive to metallicity, such that both the number of WRs per unit mass (or, equivalently, the WR:O-star ratio), and the ratio of nitrogen- to carbon-sequence (WN:WC) stars vary considerably between the Galaxy, Large Magellanic Cloud (LMC), and Small Magellanic Cloud (SMC).

Because of their strong emission-line spectra, Wolf-Rayets are relatively easy to identify from very-low-dispersion spectroscopy. The first systematic search for LMC WRs using objective-prism spectroscopy yielded 50 objects (Westerlund & Rodgers 1959), although many of these had previously been recorded in the Henry Draper catalogue and its Extension (e.g., Morel 1988). Subsequent objective-prism searches by Fehrenbach et al. (1976), Azzopardi & Breysacher (1979, 1980), and Morgan & Good (1985, 1990) roughly doubled the sample size, with a handful of other observations, including studies in crowded fields, leading to the total of 134 entries in the current, ‘BAT99’, catalogue (Breysacher et al. 1999).

With this tally, the LMC WR population is generally considered to be known to a substantial degree of completeness. Any remaining objects are likely to lie in very crowded regions (although there has been much progress in this direction in the Hubble Space Telescope era; e.g., Walborn et al. 1999), to be heavily reddened (although LMC reddening is generally small, and intrinsically reddened WC-late stars are believed to be rare in the LMC), to lie in unexamined outskirts of the LMC, or to be weak lined. Here we report the serendipitous discovery of two bright, isolated WNE stars. Both are within the area searched by Azzopardi & Breysacher (1980), but are moderately weak-lined.

2 OBSERVATIONS
We have conducted several programmes of spectroscopic observations of the bright-star content of the LMC (B ∼ 15.5) using the 2dF and AAOmega instruments on the 3.9-m Anglo-Australian Telescope. The original 2dF system was a dual-spectrograph, multi-fibre instrument which allowed up to 400 intermediate-dispersion spectra to be obtained simultaneously across a 2°-diameter field of view (Lewis et al. 2002); we used it with 1200B gratings, giving R ∼ 2000 over the wavelength range ∼3800–4900Å. AAOmega utilises the same fibre-positioner system, but introduces new spectrographs with many innovations, including dichroic beam-splitting which allows blue and red spectra to be recorded simultaneously (Sharp et al. 2006). We used 1700B (R ∼ 3500, ∼4100–4750Å) and 1000R (R ∼ 3400, ∼5650–6800Å) gratings.

Although poor weather impacted severely on individual programmes, the powerful multiplexing capability of these instruments has none the less resulted in the accumulation of spectra of tolerable to good quality for more than ∼3000 early-type stars. An initial examination of this dataset has revealed two new WR stars.

Neither object has any designation from previous surveys listed in the CDS Simbad database so we adopt a nomenclature based on extending the Breysacher et al. (1999) catalogue. Basic stellar parameters are reported in Table 1 and the spectra are shown in Fig. 1. BAT99-5a is ∼5′ from LH 5 and its associated H II regions LHA 120-N83 and N90 (Lucke & Hodge 1970, Henize 1956), and is ∼2.4′ from the cluster NGC 1756, but there is no obvious physical connection with any of these objects. BAT99-15a has no nearby LH associations or LHA H II regions.

1 WR status has been disputed for BAT99-4 (Moffat 1991), BAT99-6 (Niemela et al. 2001), and BAT99-107 (Taylor et al. 2011). Massey et al. (2000) identify Sk −69°194 as a WN3 star with extremely weak λ4686 emission (Wλ ∼ −2Å), presumably attributable to dilution by the companion, although Foeckl et al. (2003) were unable to confirm the discovery; and Evans et al. (2011) report VFTS 682 as a new, heavily reddened WN5h star in 30 Dor.

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2.1 Classification

Both stars have similar, early WN types; although our wavelength coverage doesn’t include the full suite of classification criteria, the lack of detectable N iv λ4057 coupled with moderately strong N v λλ4604, 4620 indicates WN3, confirmed by weak C iv λλ5801, 5812 in the case of BAT99-15a. The λλ4340, 4860 emissions in BAT99-15a appear to be stronger than λ4541, suggesting hydrogen Balmer emission in addition to He ii Pickering emission (Smith et al. 1996; these lines are too weak in BAT99-5a to draw conclusions); it also shows weak absorption at Hγ–He and possibly at He ii λ4541), leading to a WN3h+abs classification.

[The only plausible alternative classifications are as transition Of/WN stars (cf. Crowther & Walborn 2011). Although Fig 1 doesn’t allow us to rule out weak P-Cygni absorption at Hβ in BAT99-5a to draw conclusions]; it also shows weak absorption at Hγ–He (and possibly at He ii λ4541), leading to a WN3h+abs classification.

[There are 12 stars in the BAT99 catalogue that have single-star WN3 classifications according to Poellmi et al. (2003); these have V magnitudes in the range 14.67–16.98 and (B–V) colours −0.28:+0.31 according to the compilation by Bonanos et al. (2009). Assuming (B–V)0 = −0.30, RV = 3.1 then leads to a range in V0 of 14.4–15.7 for this sample (mean 15.1 ± 0.4 s.d.). With the same assumptions we find V0 = 14.7, 14.9 for BAT99-5a, 15a, respectively, from the data in Table 1.]

2.2 Intrinsic line strength

The leptokurtic (‘triangular’) shape of the He ii λ4686 emission in both stars suggests that their spectra are weak-lined intrinsically (rather than reflecting substantially diluted stronger emission; e.g., Marchenko et al. 2004).

Table 1. Basic observational properties; co-ordinates are from the UCAC-2 catalogue on the ICRS system (Zacharias et al. 2004), and photometry is from Massey et al. (2002). N v equivalent widths are summed for λλ4604, 4620.

|星号 | α,δ (J2000) | B, (B−V), (V−R) | Wλ (N v, λ4686) |
|---|---|---|---|
| BAT99-5a; WN3 | 4h 55m 7.60s | 15.11 | −6.4Å |
| BAT99-15a; WN3h+abs | 5h 2m 59.24s | 15.19 | −4.0Å |

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Footnote 3: Photometry from Zaritsky et al. (2004) gives V0 = 13.9, 14.6,
consistent with the known LMC WN3 single-star population, and with the view that the weak line strengths largely arise intrinsically, rather than through dilution.

If we nevertheless suppose that the differences in equivalent widths between 5a and 15a are due solely to modest dilution by an early-type companion in the latter case, then such a companion would have to contribute $\sim 25\%$ of the continuum flux; that is, it would have $B \sim 16.8$, corresponding to an early-B main-sequence star (with $V_0 \sim 15.2$ for an isolated WR primary). A mix of the spectra of BAT99-5a and HD 144470 (B1 V) in a continuum ratio of 3:1 does produce a reasonable match to the observed blue-region spectrum of BAT99-15a, although the presence of absorption lines by itself does not necessarily imply an OB binary companion for BAT99-15a.

[We observed this target at two epochs, two years apart, and the data show no evidence for variability or for radial-velocity shifts, whether in absolute terms ($\Delta V = +3 \pm 17 \text{ km s}^{-1}$) or differentially between emission and absorption lines ($\Delta(\Delta V) = +1 \pm 42 \text{ km s}^{-1}$).]

3 DISCUSSION

Morgan & Good (1990) asserted that “there are probably no undetected WR stars in the LMC in the $m_V$ range 17–19 except perhaps in obscured or crowded regions”, and there has been little to challenge that view in the intervening time. However, subsequent serendipitous discoveries (Massey et al. 2000; Evans et al. 2011; this paper) hint at the possibility of significant numbers of brighter undiscovered objects, particularly among relatively weak-lined WNE stars. (WC stars, with their typically stronger emission lines, are less likely to have been overlooked.)

Our reasonably well-defined but essentially random sample allows us to examine this issue. By merging results from photometric surveys by Zaritsky et al. (2000), Udalski et al. (2000), and Massey et al. (2002), we estimate that there are $\sim 50,000$ stars in the LMC brighter than $B = 15.5$. We have obtained spectra of sufficient quality to identify WR-type spectra for $\sim 3500$ targets, finding two new WNE stars; together, these numbers suggest that there may be as many as $\sim 25$ similar objects yet to be discovered. Alternatively, we have ‘rediscovered’ 25 known WRs in our wider dataset, or $\sim 20\%$ of the known population; if we have discovered a similar proportion of an unknown population, this instead indicates perhaps $\sim 9$ WNEs as yet undiscovered. Of course, these estimates are little more than informed guesses given the small-number statistics, but none the less suggest that perhaps a dozen or so weak-lined WNE stars, or $\sim 20\%$ of the WNE population, may remain to be discovered in the LMC. If this conjecture proves correct, the dominance of WNE over WNL stars (and of WN over WC types) in this metal-poor galaxy is only strengthened.

but the result for BAT99-5A is compromised by a rather large formal error on the $B$-band measurement.

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REFERENCES

Azzopardi M., Breyssacher J., 1979, A&A, 75, 243
Azzopardi M., Breyssacher J., 1980, A&AS, 39, 19
Bonanos A. Z., Massa D. L., Sewilo M., Lennon D. J., Panagia N., Smith L. J., Meixner M., Babler B. L., Bracker S., Meade M. R., Gordon K. D., Hora J. L., Indebetouw R., Whitney B. A., 2009, AJ, 138, 1003
Breyssacher J., Azzopardi M., Testor G., 1999, A&AS, 137, 117
Crowther P. A., 2007, ARA&A, 45, 177
Crowther P. A., Walborn N. R., 2011, MNRAS, 416, 1311
Evans C. J., Taylor W. D., Hénault-Brunet V., Sana H., de Koter A., Simón-Díaz S., Carraro G., Bagnoli T., Bastian N., Bestenlehner J. M., Bonanos A. Z., Bressert E., Brott I., Campbell M. A., Cantiello M., et al., 2011, A&A, 530, A108
Fahrenholtz C., Dufflot M., Acker A., 1976, A&AS, 24, 379
Foellmi C., Moffat A. F. J., Guerrero M. A., 2003, MNRAS, 338, 1025
Foellmi C., Moffat A. F. J., Marchenko S. V., 2006, A&A, 447, 667
Henize K. G., 1956, ApJS, 2, 315
Lewis I. J., Cannon R. D., Taylor K., Glazebrook K., Bailey J. A., Baldry I. K., Barton J. R., Bridges T. J., Dalton G. B., Farrell T. J., Gray P. M., Lankshear A., McCowage C., Parry I. R., Sharples R. M., Shortridge K., 2002, MNRAS, 333, 279
Lucke P. B., Hodge P. W., 1970, AJ, 75, 171
Marchenko S. V., Moffat A. F. J., Crowther P. A., Chené A.-N., De Serres M., Eenens P. R. J., Hill G. M., Moran J., Morel T., 2004, MNRAS, 353, 153
Massey P., Penny L. R., Vukovich J., 2002, ApJ, 565, 982
Massey P., Waterhouse E., DeGioia-Eastwood K., 2000, AJ, 119, 2214
Moffat A. F. J., 1991, A&A, 244, L9
Moffat A. F. J., 1988, Bulletin d’Information du Centre de Donnees Stellaires, 35, 31
Morgan D. H., Good A. R., 1985, MNRAS, 216, 459
Morgan D. H., Good A. R., 1990, MNRAS, 243, 459
Niemela V. S., Seggewiss W., Moffat A. F. J., 2001, A&A, 369, 544
Sharp R., Saunders W., Smith G., Churiol V., Correll D., Dawson J., Farrel T., Frost G., Haynes R., Heald R., Lankshear A., Mayfield D., Waller L., Whittard D., 2006, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series Vol. 6269 of Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series. Performance of AAOmega: the AAT multi-purpose fiber-fed spectrograph
Smith L. F., Shara M. M., Moffat A. F. J., 1996, MNRAS, 281, 163
Taylor W. D., Evans C. J., Sana H., Walborn N. R., de Mink S. E., Stroud V. E., Alvarez-Candel A., Barbá R. H., Bestenlehner J. M., Bonanos A. Z., Brott I., Crowther P. A., de Koter A., Friedrich K., Gräfener G., et al., 2011, A&A, 530, L10
Udalski A., Szymanski M., Kubiak M., Pietrzyński G., Soszyński I., Wozniak P., Zebrun K., 2000, Acta Astronomica, 50, 307
Walborn N. R., Drissen L., Parker J. W., Saha A., MacKenty J. W., White R. L., 1999, AJ, 118, 1684
Westerlund B. E., Rodgers A. W., 1959, The Observatory, 79, 132
Zacharias N., Urban S. E., Zacharias M. I., Wycoff G. L., Hall D. M., Monet D. G., Rafferty T. J., 2004, AJ, 127, 3043
Zaritsky D., Harris J., Thompson I. B., Grebel E. K., 2004, AJ, 128, 1606