A MODERN SEARCH FOR WOLF–RAYET STARS IN THE MAGELLANIC CLOUDS. II. A SECOND YEAR OF DISCOVERIES*

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Received 2015 May 3; accepted 2015 May 21; published 2015 July 2

The numbers and types of evolved massive stars found in nearby galaxies provide an exacting test of stellar evolution models. Because of their proximity and rich massive star populations, the Magellanic Clouds have long served as the linchpins for such studies. Yet the continued accidental discoveries of Wolf–Rayet (WR) stars in these systems demonstrate that our knowledge is not as complete as usually assumed. Therefore, we undertook a multi-year survey for WRs in the Magellanic Clouds. Our results from our first year (reported previously) confirmed nine new LMC WRs. Of these, six were of a type never before recognized, with WN3-type emission combined with O3-type absorption features. Yet these stars are 2–3 mag too faint to be WN3+O3 V binaries. Here we report on the second year of our survey, including the discovery of four more WRs, two of which are also WN3/O3s, plus two “slash” WRs. This brings the total of known LMC WRs to 152, 13 (8.2%) of which were found by our survey, which is now ~60% complete. We find that the spatial distribution of the WN3/O3s is similar to that of other WRs in the LMC, suggesting that they are descended from the same progenitors. We call attention to the fact that 5 of the 12 known SMC WRs may in fact be similar WN3/O3s rather than the binaries they have often assumed to be. We also discuss our other discoveries: a newly discovered Onfp-type star, and a peculiar emission-line object. Finally, we consider the completeness limits of our survey.

Key words: galaxies: individual (LMC, SMC) – galaxies: stellar content – Local Group – stars: evolution – stars: Wolf–Rayet

1. INTRODUCTION

For many years our knowledge of the Wolf–Rayet (WR) population of the Magellanic Clouds was considered “essentially” complete (see, e.g., Massey & Johnson 1998). The accidental discovery of several weak-lined WN-type WRs over the years, and our own discovery of a strong-line WO star (Neugent et al. 2012a), made us realize that if we wanted an accurate value for the relative numbers of WC-, WO-, and WN-type WRs for comparing with evolutionary models, we needed to conduct a modern survey for WRs using the same techniques we had successfully applied to M33 (Neugent & Massey 2011) and M31 (Neugent et al. 2012b). We therefore began a multi-year observational program using the Las Campanas Swope 1 m telescope to image fields in the LMC and SMC through a set of interference filters centered on C II λ4650, He II λ4686, and neighboring continuum. Candidates are identified by eye after the frames are reduced and run through image subtraction software. Follow-up spectroscopic observations of the WR candidates are then carried out with the Magellan 6.5 m Clay telescope.

The results from the first year of this project were reported by Massey et al. (2014, hereafter Paper I), which further describes the motivation and our observing strategy. When we began our survey, we realized it was possible that we would find nothing very interesting. Instead, with the survey only 15% complete, we had already confirmed nine newly found WRs in the LMC, a 6% increase in the total number of LMC WRs known. Of these, one was another very rare WO-type WR, only the third found in that galaxy. All of the WRs discovered since the Breysacher et al. (1999) catalog (BAT99), including those from our survey, were of WN type (with the exception of the two WOs), confirming our suspicions that previous surveys had been biased toward WCs, as these stars have much stronger lines and thus are easier to find (Massey & Johnson 1998).

Most interesting, however, was that six of these newly found WN stars were unlike any other WRs previously recognized, showing a WN3-type emission spectrum combined with an O3-type absorption spectrum. We realized that these were unlikely to be true WN3+O3 V pairs. For one thing, O3 V stars are extremely rare: only a few dozen are known in all of the LMC, and the idea that six would be paired with newly found WN3s was simply not credible. It would also be impossible to understand in terms of (single-star) evolution: a very massive star will be in the O3 V stage only for the first million years or so of its life, but it takes 3–4 Myr to produce a WR star. Finally, and most definitively, these newly found WRs were quite faint, with V ~ 16. They had absolute visual magnitudes M_V ~ −3, about 2.5 mag fainter than the M_V of O3 V stars. In other words, these stars were impossibly faint to be WN3+O3 V binaries. We succeeded in modeling the optical spectrum of one of these stars using CMFGEN (Hillier & Miller 1998), finding that we could reproduce the absorption and emission-line spectra with a single set of physical parameters, using an effective temperature of 100,000 K, a He/H number ratio of 1.0, a nitrogen mass-fraction of 0.011 (corresponding to 10× solar using the Anders & Grevesse 1989 values), reduced carbon and oxygen abundances (0.05× solar), and a mass-loss rate of 1.2 × 10^{-6} M_{\odot} yr^{-1}, with a clumping volume filling factor of 0.1. Compared to a recent modeling study of other LMC WNs by Hainich et al. (2014), the 100,000 K effective temperature was at the high end of what...
was normally found but not anomalous, the bolometric luminosity \( \log L/L_\odot \sim 5.6 \) was at the low end, but also not anomalous, but the mass-loss rate was quite atypical, down a factor of \( 3-5 \times \) from what we would expect (Massey et al. 2015). We are currently in the process of refining this model based upon recently acquired Hubble Space Telescope (HST) UV and Magellan NIR data, as well as extending our study to other WN3/O3s.

We have now completed the second year of our survey, including spectroscopic follow-up of our candidates, and report here the discovery of two additional WN3/O3 stars, two newly found WR “slash stars,” plus a rare Onfp-type star and a peculiar emission-line star.

2. OBSERVATIONS AND REDUCTIONS

As stated above, our interference-filter imaging was conducted using the 1 m Swope telescope. The SITe#3 CCD camera that we used in the first year of our survey had been replaced with a new system containing a 4110 × 4096 e2v device with 15 μm pixels. This provides a 29′9/ (EW) × 29′7/ (NS) field of view, or 0.25 deg\(^2\), a 2.6× improvement over the old system. The chip is read out using four amplifiers, and so the read-time dropped from 127 s with the SITe#3 camera to 37 s with the new camera, another substantial improvement.

The e2v camera is a bit more sensitive as well, although we kept to the same exposure times: 300 s through each of our three interference filters. Further details are given in Paper I.

For calibration, we obtained ten bias frames each day, although there was very little (≤1 ADU) bias structure with the new camera. With the large field of view, dome flats contained a 10% gradient, and we relied upon twilight flats for flat-fielding. We obtained 5 or more twilight sky flats through each filter during the clear nights, dithering the telescope between each exposure. If there was cirrus, we used flats from a clear night.

There is a significant shutter pattern present from the iris shutter in short exposures (1% peak to valley in a 5 s exposure); in order to take advantage of rapidly fading twilight, we measured the shutter pattern using dome flats during one afternoon, and then used this pattern to correct the short twilight exposures appropriately.\(^4\) Modest corrections for nonlinearity were applied to the data from each quadrant using the correction coefficients kindly provided by Carlos Contreras based on measurements made on 2014 August 24; the corrections amount to a maximum of 2.8%, 1.1%, 0.8%, and 1.4% for the four quadrants over the full data range.

We were assigned 10 nights for our second year of imaging, (UT) 2014 September 6–10, and 2014 November 5–9. We were also able to obtain some observations during four additional nights during engineering tests of the new camera, on 2014 August 12–13 and 2014 August 14–16. The seeing was unusually poor for Las Campanas during several of our nights, with the result that we repeated many fields, insisting that the seeing be adequate for the crowding in a particular field, generally <4.5 pixels FWHM, corresponding to <2″, but some fields required significantly better seeing. We also found that the image subtraction technique was badly compromised if the seeing varied by more than about 10% on the three images, and so we repeated exposures if we were not achieving this much consistency. Since some data were also taken through light cirrus, we also checked the photometric zero-points on each frame using the AAVSO Photometric All-sky Survey B-band magnitudes listed in the UCAC4 catalog (Zacharias et al. 2013), and repeated any fields that were suspect. In the end, we observed 137 new fields, 63 in the SMC and 74 in the LMC, covering approximately 14.5 deg\(^2\) and 17.0 deg\(^2\), respectively. The outlines of these fields are shown in Figures 1 and 2 in red. We also show the outlines (in green) of the regions observed in 2013 with the SITe#3 camera. There is considerable overlap: in some cases we wanted to double-check that we were doing as well as we did last year, and in other cases we wanted to re-observe a field that had been taken under poorer conditions. We calculate that the total area we have so far surveyed is 17.3 deg\(^2\) in the SMC and 24.8 deg\(^2\) in the LMC, approximately 60% and and 57% of our intended survey areas in the two galaxies. We are scheduled for another 10 nights in 2015 November; if conditions are similar, we should readily be able to complete our survey.

Analysis of the frames followed the same method we used in Paper I, where we employed the image subtraction code High Order Transform of Point-spread function ANd Template Subtraction (HOTPANTS) described by Becker et al. (2004). The larger field of view of the camera led to some poor results in the corners, but we have enough overlap on adjacent fields that we feel this is not a practical issue. Along with the image subtraction, aperture photometry was run on the frames and photometrically significant candidates were identified. The combination of the two techniques proved very valuable in identifying potential WR stars. Accurate (0″5) coordinates were obtained by running the data through the “astrometry.net” software (Lang et al. 2010) locally installed on our machines.

Prior to attempting spectroscopic confirmation, candidates were examined through VizieR to make sure they were not already known emission-line sources; this eliminated a number of objects, mostly planetary nebulae. (We were already suspicious of these as they had no counterparts on the continuum frames.) In addition, inspection of the candidates’ 2MASS colors allowed us to eliminate red stars, which show up as candidates as there is a strong absorption band in the continuum filter (see Paper I as well as Neugent & Massey 2011). In the end, we had 4 new candidates in the SMC, 10 new candidates in the LMC, along with 3 additional candidates from the first year which we had not managed to observe (all in the LMC). One additional LMC candidate is awaiting imaging in excellent seeing as it is rather crowded.

Spectroscopic followup was carried out on the 6.5 m Magellan Clay telescope using the Magellan Echellette (MagE) spectrograph (Marshall et al. 2008) during a single night of observing, (UT) 2015 January 9. MagE provides full spectral coverage in the optical from 3100 Å to 1 μm at a resolving power \( R \) of 4100 using a 1″ slit. The sky was clear, and the seeing (as reported on the guide camera) was 0″7–1″0.
Exposure times were typically 600–1200 s, with a few longer and a few shorter. Bias frames and various flat-field exposures (Xe-flash and dome flats) were taken, but as described in Paper I and Massey et al. (2013), we found that we actually did better in terms of the signal-to-noise ratio (S/N) by not flat fielding our data, as the MagE chip is quite uniform and obtaining high signal-to-noise flats over such a large wavelength regime presents quite a challenge. The individual orders were combined after flux calibration using observations of spectrophotometric standards. The data were extracted using Jack Baldwin’s “mtools” IRAF routines, and wavelength calibrated and fluxed with the usual IRAF echelle reduction tasks.

3. NEW DISCOVERIES

Six of our candidates proved to be “winners,” with strong He II λ4686 emission. Of these, four are newly found WR stars, two of which belong to the newly recognized WN3/O3 type (Paper I), and two of which are “slash” WRs (one “hot” and one “cool”). Of the other two stars with He II emission, one is a rare Onfp supergiant, and the other is an emission-line star with very peculiar line profiles. Among the “losers” (stars without He II λ4686 emission), four are late-type stars which we failed to eliminate before observing, and which will not be discussed further here. Six are previously unknown B-type stars. These stars lacked emission at He II λ4686, and were detected at

Figure 1. Survey coverage of the SMC. The green outlines denote the fields we observed in 2013 (Paper I), while the red denotes the fields covered in 2014 (this paper). The large circle shows the regions of our intended survey and has a diameter of 6° and is centered on α2000 = 1°08′00″, δ2000 = −73°10′00″. The image come from the R-band “parking lot” camera image of Bothun & Thompson (1988).
marginal levels; we included these in our spectroscopy followup in order to make sure we were not missing any weak-lined WRs. One other candidate had been identified as a RR Lyr variable that was detected at a high significance level. Although variability could produce a false WR candidate (if the star was fainter in the continuum exposure (CT)), we observed this to be sure it had been correctly identified as an RR Lyr star. The spectrum was that of an A-type star, as would be expected for an RR Lyr.

3.1. New WR Stars

Four of our LMC candidates proved to be WR stars. We list their identifications and properties in Table 1. Two of these stars are additional examples of the WN3/O3 class that we introduced in Paper I, bringing the total of this type to eight. The other two are “slash” stars (see, e.g., Bohannan & Walborn 1989; Crowther & Smith 1997, and Crowther & Walborn 2011). In general, we rely upon the expanded classification system of Smith (1968) as summarized in Table 2.
of van der Hucht (2001), as this provides consistency not only with the Milky Way WRs (van der Hucht 2001), but also with most previous classifications of LMC and SMC WRs (BAT99 and Massey et al. 2003), as well as recent studies of the M33 and M31 WR populations (Neugent & Massey 2011 and Neugent et al. 2012b, respectively). The total number of WRs known in the LMC is now 152, of which 13 (8.6%) were found as a result of our survey.\(^5\) We discuss the four newly found WRs here.

\(\text{LMCe}159\text{-}1\) and \(\text{LMCe}169\text{-}1\), two \text{WN3/O3} stars. Two of our newly found WR stars are of the type we have begun calling \text{WN3/O3}, as described in Paper I. We show their spectra in Figure 3, and their identification and properties in Table 1. Like the six \text{WN3/O3} stars we discovered in Paper I, \text{LMCe}159\text{-}1 and \text{LMCe}169\text{-}1 show H and He II absorption but no He I. N\text{v} is strongly in emission (Figures 3(a) and (b)). Note that the emission is stronger and the absorption a bit weaker in \text{LMCe}169\text{-}1. In Figure 3(c) we compare the spectra of our two new discoveries to the spectrum of LMC170\text{-}2, one of the prototypes of the \text{WN3/O3} class that we discuss in Paper I and Massey et al. (2015). The presence of hydrogen in the absorption spectrum is apparent by comparing the strengths of the odd-n Pickering He II lines (He II \(\lambda\lambda 4026, 4200, 4542\)) with the even-n lines, which are coincident with the Balmer hydrogen lines. (Our modeling of LMC170\text{-}2 suggests a He/H number ratio of \(\approx 1.0\).)

One of the chief arguments against the \text{WN3/O3} stars in Paper I being \text{WN3+O3} V binaries was that these stars were about as faint as we would expect for an early-type WN star (such as a WN3), but that they were much too faint to also include an O3 V star. As we show in Table 1, the same is true here. These new additions are even fainter than the stars in Paper I, with absolute visual magnitudes \(M_V\) corresponding to \(-2.6\) and \(-1.8\). These can be compared to the average absolute magnitudes of early-type LMC WNs given by Hainich et al. (2014): \(-3.8\) for \text{WN3s} and \(-2.7\) for \text{WN2s}. In fact, \text{LMCe}169\text{-}1 may be the faintest WR star known in the LMC (or anywhere); the only other contenders are BAT99\text{-}23, a \text{WN3} star described as having hydrogen in its spectrum, and BAT99\text{-}69, a WC star in a crowded region whose identification may be confused; we are indebted to Brian Skiff for his notes on the latter. In calculating the \(M_V\) values we have assumed typical reddening for LMC OB stars (see Massey et al. 1995), i.e., \(A_V = 0.4\) based upon an average \(E(B-V)\) of 0.13. This is quite consistent with the observed \(B-V\) colors of these stars based upon the photometric survey of Zaritsky et al. (2004). These stars are about 3 mag too faint to include an O3 V component, which typically has \(M_V \approx -5.4\) (Conti et al. 1988). We comment further on this in Section 4.

\(\text{LMCe}132\text{-}1\), an \text{O3.5} If*/WN7 star. The blue classification region of the spectrum is shown in Figure 4(a). The hybrid O3.5 If*/WN6 was introduced by Walborn (1982) to describe the spectrum of Sk\text{-}67\text{°}22, which became the prototype for the “hot” slash stars that show spectral characteristics intermediate between O3 If and WN6 stars. Crowther & Walborn (2011) subsequently refined this, using the presence of a P Cygni profile in the H\beta line to require this intermediate classification, just as we find here. Using their criteria, we classify this star as O3.5 If*/WN7. True to the classification criteria given in their Table 2, there is even extremely weak N\text{v} \(\lambda 4603, 19\) emission present (Figure 4(b)). H\alpha is strongly in emission, as shown in Figure 4(c). The photometry is consistent with normal reddening.

Such hot “slash stars” are likely hydrogen-burning objects. Should they even be counted as WRs? We note that the BAT99 contains nine examples of such objects, including Sk\text{-}67\text{°}22 (BAT99\text{-}12), the prototype of this class. None of these have been “demoted” to Of-type status, although a fresh look at these stars in the light of the Crowther & Walborn (2011) study is probably warranted. If these nine stars count as WRs, so should \text{LMCe}132\text{-}1.

\(\text{LMCe}063\text{-}1 = \text{Sk}-69\text{°}240\), a \text{WN11} star. This star was recognized as an emission-lined object by Henize (1956), who cataloged it as LHA 120-S131. It was classified as a Be star as part of the objective prism survey of Sanduleak (1970), where it is listed as Sk\text{-}69\text{°}240, but it subsequently became clear that whatever the star is, it is not a Be star. Shore & Sanduleak (1984) obtained a better optical spectrum, as well as an ultraviolet spectrum with \text{IUE}. They describe the optical spectrum as a pure emission-line spectrum (without P Cygni profiles), with the Balmer lines in emission to \(n = 10\), He I

\begin{table}[h]
\centering
\begin{tabular}{lcccccccc}
\hline
ID\textsuperscript{a} & \(\alpha_{2000}\) & \(\delta_{2000}\) & \(V\textsuperscript{b}\) & \(B-V\textsuperscript{b}\) & CT & WN-CT & He II \(\lambda4686\) & \(M_V\) & Sp. Type & Comment \\
& & & & & & mag & \(\log(-\text{EW})\) & & & \\
\hline
LMCe063\text{-}1 & 05 38 24.30 & \(-69 29 13.5\) & 13.04\textsuperscript{d} & +0.28\textsuperscript{d} & 13.2 & -0.08 & 4.1 & 0.4 & 8 & \(-5.9\) & WN11 & Sk\text{-}69\text{°}240 \\
LMCe132\text{-}1 & 05 14 17.55 & \(-67 20 35.7\) & 14.34 & -0.13 & 14.4 & -0.08 & 4.0 & 0.7 & 8 & \(-5.9\) & O3.5 If*/WN5 & \ldots \\
LMCe159\text{-}1 & 05 24 56.89 & \(-66 26 44.5\) & 16.34 & -0.23 & 16.4 & -0.22 & 10.2 & 1.3 & 20 & -2.6 & WN3/O3 & \ldots \\
LMCe169\text{-}1 & 05 21 22.84 & \(-65 52 49.0\) & 17.12 & -0.19 & 16.9 & -0.34 & 15.5 & 1.4 & 27 & -1.8 & WN3/O3 & \ldots \\
\hline
\end{tabular}
\caption{Newly Found WRs}
\end{table}

\textsuperscript{a} This number includes the 134 WRs cataloged by BAT99, minus the two demotions and seven additions discussed by Neugent et al. (2012a); Hainich et al. (2014) argues that two of these additions are uncertain, namely Sk\text{-}69\text{°}194 (B0 Ia+WN, according to Massey et al. 2000), and LH90\text{-}36 (B1 + WN, also according to Massey et al. 2000). We plan to resolve this controversy in the near future. The number also includes the nine newly found WRs in Paper I and the four discussed here, but does not include HD 38489, which we speculate in Paper I could be a B[e] + WN binary.

\textsuperscript{b} Photometry from Zaritsky et al. (2004).

\textsuperscript{c} We assume an apparent distance modulus of 18.9 for the LMC, corresponding to a distance of 50 kpc (van den Bergh 2000) and an average extinction of \(A_V = 0.4\) (Massey et al. 1995, 2007).

\textsuperscript{d} Based upon our spectrophotometry, the “emission free” values would be \(V \approx 13.11\) and \(B-V \approx +0.23\), derived from the continuum fluxes at 4400 and 5500 Å.
emission, and He II λ4686 and N III λ4634, 42 in emission. The IUE spectrum showed the usual stellar wind lines (Si IV λ1400, C IV λ1550, N V λ1245, and He II λ1640). A high dispersion (R ~ 7000) photographic optical spectrum is shown in Figure 28 of Stahl et al. (1985), who describe the line profiles as “unique,” with the H and He i emission split by a sharp central absorption.

Our own spectrum of this interesting object is shown in Figure 5. Strong He i and hydrogen lines dominate the spectrum (Figure 5(a)). He II λ4686 emission is indeed weakly present, but we were suspicious of the identification of the neighboring feature as N III λ4634, 42, given the very choppy appearance (Figure 5(b)). Instead, we realized this emission is dominated by N II, as witness the strong N II λ3995 line we find in the blue (Figure 5(c)).

Comparing this star to others in the literature, we were struck by the similarity to He3-519 (Walborn & Fitzpatrick 2000) and HDE 269582 (Bohannan & Walborn 1989). Both of these are examples of “cool” slash stars, what were originally called Ofpe/WN9 stars, but are generally classified as WN9-11 today (see, e.g., Crowther & Smith 1997). Following this, we would classify the star as WN11. We note that the WN11 stars have a strong linkage to luminous blue variables (LBVs) (Crowther 1997); indeed, Walborn et al. (2012) reported that HDE 269582 is currently undergoing a major LBV outburst. The one way our spectrum differs significantly from “normal” WN11s is the presence of the peculiar absorption lines splitting the hydrogen and strong He i emission lines, perhaps indicating the presence of a disk. (There are some similarities to the Oe stars

Figure 3. Normalized spectra of two newly found WN3/O3 WRs. The blue portions of our spectra are shown in the top two figures for (a) LMCE159-1 and (b) LMCE169-1. Note that the absorption is weaker, and the emission stronger, in LMCE169-1. In (c) we compare the spectra of these two newly found WN3/O3s with each other and with the WN3/O3 star LMC170-2 discussed in Paper I and Massey et al. (2015).
discussed by Sota et al. 2014; we are grateful to Nolan Walborn for pointing this out.

Our wavelength coverage extends further into the blue and at higher signal-to-noise than is usually the case for such stars, and we call attention to the fact that there are some pure absorption lines in the spectrum, as shown in Figure 5(d). We see here a sequence of He I lines, mostly triplets from the 1$\text{s}2p^3P^o$–1$\text{s}4d^3D$, with $n \geq 8$ ($n = 8$ corresponding to He I $\lambda 3634$ line). It is interesting that these high-order lines are in absorption, while lower members occurring at wavelengths above the Balmer jump are not (e.g., He I $\lambda 4471$, which is the 1$\text{s}2p^3P^o$–1$\text{s}4d^3D$ transition). We also find in this figure a sea of P Cygni profiles to the upper Balmer lines; we can count upper Balmer lines to H28.

Figure 4. Normalized spectrum of LMCe132-1, a newly found O3.5 If*/WN7 “slash” WR. In (a) we show the region from 3850 to 5000 Å with the principal lines indicated. Note in particular the P Cyg profile in H$\beta$ which results in this star being called a hot “slash” WR. The broad absorption feature just to the red of the H$\beta$ emission is the diffuse interstellar band at 4881 Å. In (b) we expand the region around N $\text{iii}$ $\lambda$4634, 42 and He $\text{ii}$ $\lambda$4686. In (c) we show the region around H$\alpha$.

3.2. Other Emission-line Stars

Besides the four WRs discussed above, our spectroscopy has identified two additional emission-line stars in the LMC. We list the properties of these stars in Table 2. In each case, a simple classification eludes us. We discuss each of these stars below.

LMC156-2, an O$nfp$ star. The spectrum of this star is shown in Figure 6. At first blush, the star seems to be an O6.5 If, with He I $\lambda$4471 a bit weaker than He II $\lambda$4542, and the supergiant “If” luminosity classification due to strong N $\text{iii}$ $\lambda$$\lambda$4634, 42 and He II $\lambda$4686 emission. However, a closer examination reveals multiple strange things: as shown in Figure 6(b), N $\text{iii}$ $\lambda$$\lambda$4634, 42 is anomalously broad, and the
He II λ4686 emission shows a strong absorption component on the bluewards side, a classic P Cygni profile. The He II λ4686 line is formed in the stellar winds in O-type supergiants, and is a good mass-loss indicator, as is Hα, and we see in Figure 6(c) that the Hα profile is similarly afflicted. Such stars were first classified as “Onfp” by Walborn (1973) and Magellanic Cloud members of this class have been discussed more recently by Walborn et al. (2010). The exact nature of these stars is not well understood. Walborn et al. (2010) find that most members of this group are binaries. Measurements of the radial velocities would tend to support this in the case of LMC156-2 as well: the He II λ4200, 4542 lines have a radial velocity approximately 70 km s⁻¹ more negative than that of He I λ4471, with Balmer lines of intermediate velocity.

LMCe034-1 (unknown type emission-line star). The most interesting find besides our new WRs has been that of this very peculiar emission-line star. We give an overview of its spectral features in Figure 7(a). The spectrum is dominated by hydrogen and He II emission lines; indeed, the strongest line is that of He II λ4686. Figure 7(b) shows that the profiles consist of a skinnier component on top of a very broad component. The base of the He II λ4686 line extends from 4660 to 4716 Å, or ±1800 km s⁻¹! The narrower component is only skinnier by comparison, extending ±550 km s⁻¹. Note the
Table 2
Other Emission-line Stars

| ID          | α2000  | δ2000  | V     | B − V | He II λ4686 | Mv | Sp. Type | Comment                  |
|-------------|--------|--------|-------|-------|-------------|----|----------|--------------------------|
| LMC156-2    | 04 51 10.59 | −69 33 21.1 | 13.65 | −0.13 | ...         | ...| −5.3     | Onfp                     |
| LMCe034-1   | 05 31 42.05 | −70 37 54.0 | 18.02d | −0.09d | 1.8         | ...| −2.2     | NE member of 251 pair.   |

Notes.

a Designation from the current survey. We have denoted the c2v fields with a small “e” to distinguish them from our numbering system from Paper I, i.e., LMCe159 is distinct from LMC159. We plan to impose less idiosyncratic designations once our survey is complete.
b Photometry from Zaritsky et al. (2004) unless otherwise noted.
c We assume an apparent distance modulus of 18.9 for the LMC, corresponding to a distance of 50 kpc (van den Bergh 2000) and an average extinction of A_{V} = 0.40 (Massey et al. 1995, 2007).
d “Emission free” photometry derived from the continuum fluxes at 4400 and 5500 Å.

Figure 6. Normalized spectrum of LMC156-2, an Onfp star. In (a) we show the region from 3850 to 5000 Å with the principal lines identified. In (b) we expand the region around NIII λ4634, 42 and He II λ4686. In (c) we show the region around Hα.
sharp absorption features on the Balmer lines, getting progressively stronger toward higher lines. These occur on the blue edge of the narrower emission, and are somewhat reminiscent of the "unique" profiles we discussed in regards to LMCe063-1. We do not see any evidence of Nv λ4603, 19, Nv λ4058, Nm λ4634, 42, or the Nm complex 4600–4650 Å, despite the good signal-to-noise (50 per spectral resolution element) in these regions.

LMCe034-1 is a member of a 2″1 pair, and because of this, photometry in the literature is a little ambiguous. In Table 2 we have used the "continuum" magnitude that we measure from our spectrophotometry, converted to the Vega (standard UBVRI) system. We do find that this star varies in light. We took two exposures of this field, once on (UT) 2014 September 10 under poor conditions, and once on (UT) 2014 November 11. We measured LMCe034-1 as 0.90 ± 0.03 mag fainter on the continuum image in the first exposure as in the second. It is also possible that the He II λ4686 emission was weaker based on the WN image, but that is harder to judge, given the poorer quality of the data.

What do we make of this peculiar object? We can rule out it being an AM Her cataclysmic variable based on its radial velocity and apparent brightness. John Hillier, Howard Bond, and Nolan Walborn were all kind enough to comment on the spectrum. Although broad components like this are often attributed to Thompson scattering, in this case the profiles look too boxy for that explanation. Instead, Hillier has offered the useful conjecture that we may be looking at a two-component wind. After all, the skinner component is none too skinny. A useful conjecture that we may be looking at a two-component explanation can not be ruled out, and we will continue to monitor this star for radial velocity variations. (We saw none in two spectra separated by 5.5 hr.) Nevertheless, the fact that both the broad and narrow components show up in most of the lines suggests that this is an unlikely explanation for the peculiar spectrum, regardless of whether the star is a binary (with an unseen companion) or not. Walborn has instead noted the similarity to NGC 16 24-2 (Wade et al. 2012), and has suggested that the strange profiles are due to a combination of photospheric and magnetospheric components.

3.3. Non-emission Line Stars

As mentioned above, six of our candidates turned out to be normal B-type stars. These candidates were marginal, having magnitude differences between the WN and CT filters of ~0.1 mag or less. Given the number of stars involved, our methodology is bound to produce a few false positives. We give the identifications of these B stars in Table 3 for completeness, but do not discuss these in detail. We were guided by the Walborn & Fitzpatrick (1990) atlas in the classification.

LMCe019-1 was identified as an RR Lyr variable by the Optical Gravitational Lensing Experiment (OGLE; LMC-RRLYR-06881) with a maximum magnitude of I = 15.72, an amplitude of 0.8 mag, and a period of 0.5 days (Soszyński et al. 2009). Our spectrum shows this to be of A-type, consistent with it being an RR Lyr star. Given its magnitude it really must be a star in our own halo. It was detected at a very significant level (14σ) but the spectrum clearly showed no emission. The magnitude difference between the WN and CT filters was 0.3 mag. Our imaging must have caught this star as it was changing brightness most rapidly.

4. SUMMARY, DISCUSSION, AND FUTURE WORK

We describe here the results of our second year of surveying the Magellanic Clouds for WR stars. We have covered 57%–60% of our intended survey area, finding (in total) 13 new WRs in the LMC, bringing the total number of WRs known in the LMC to 152%, 8.6% of which have been found as part of our survey. What does this imply for the overall numbers?

In the first year, our survey of the LMC concentrated on the regions where WRs were already known, both as a test of whether or not we would readily detect the known ones (we did, other than in the most crowded regions near R136 in

Figure 7. Fluxed spectrum of LMCe034-1, a peculiar emission-line star. In (a) we show an overview of the spectrum from 3850 to 6700 Å, with the principal lines identified. In (b) we expand a region to show the peculiar line profiles.
Table 3
Non Emission-line Stars

| ID      | $\alpha_{2000}$ | $\delta_{2000}$ | $V^b$ | $B - V^b$ | $M_V^c$ | Type     |
|---------|-----------------|-----------------|-------|-----------|---------|----------|
| SMCe107-1 | 01 05 55.19    | −71 15 48.2    | 15.45 | −0.23     | −3.7    | B1−B1.5 III |
| SMCe107-2 | 01 06 13.72    | −71 11 22.3    | 15.06 | −0.12     | −4.0    | B2 I     |
| LMC197-1  | 05 23 41.11    | −69 04 45.4    | 16.54 | −0.12     | −2.4    | B3 III   |
| LMC222-3  | 05 12 54.99    | −68 41 12.0    | 15.82 | +0.08     | −3.1    | B1 V     |
| LMCe019-1 | 05 11 17.41    | −71 02 44.2    | 16.21 | ...       | ...     | RR Lyr (A-type) |
| LMCe050-1 | 05 43 58.62    | −70 14 21.6    | 13.93 | −0.21     | −5.0    | B2.5 I   |
| LMCe116-1 | 05 00 12.31    | −67 45 17.5    | 14.89 | −0.02     | −4.0    | B2 III   |

Notes.

a Designation from the current survey. We have denoted the e2v fields with a small “e” to distinguish them from our numbering system from Paper I, i.e., LMCe159 is distinct from LMC159. We plan to impose less idiosyncratic designations once our survey is complete.

b Photometry from Zaritsky et al. (2002) for the SMC stars, and Zaritsky et al. (2004) for the LMC stars, unless otherwise noted.

c We assume apparent distance moduli of 19.1 and 18.9 for the SMC and LMC respectively, corresponding to distances of 59 and 50 kpc (van den Bergh 2000), respectively, and average extinctions of $A_V = 0.28$ and $A_V = 0.40$ (Massey et al. 1995, 2007).

d From Zacharias et al. (2013).

e From Soszyński et al. (2009).

30 Dor), but also based on the principle that that is where most of the massive stars would be found. As our result, in our first year of the survey we found nine new WRs in the LMC despite surveying only 15%. Thus we were not completely surprised that although we more than doubled the survey area we detected only four new WRs this year. We are encouraged by the fact that we are detecting many Of-type stars with weaker He II and cool WRs would be only 1 star, and thus our not finding any new SMC WRs in the SMC, but we can argue that since there are regions we had previously surveyed. We have as yet found no new WRs in the SMC, but we can argue that since there are only 12 known WRs in the SMC, a similar 8.6% increase would be only 1 star, and thus our not finding any new SMC WRs (yet) may well be due to small number statistics.

Of the 13 LMC WRs we have so far found as part of our survey, 12 of these are WNs. Although this confirms our suspicion that previous studies have selectively missed WNs because they are weaker lined, it has changed the WC+WO to WC evolutionary models computed with $z = 0.006$ and an initial rotation of 40% of the breakup speed (C. Georgy 2012, private communication, and used by Neugent et al. 2012b). What we can say is that this number is less suspect than in the past. We note that the discrepancy with the models is probably slightly larger than this, as we have included in our counts both the hot and cool “slash” stars; the evolutionary models can recognize surface abundances, but not the small changes in wind density that would drive Hβ from pure absorption into P Cygni.

Doubtless the most interesting thing revealed by our survey has been the eight faint WN3 stars which show O3-type absorption spectra, what we are referring to as the WN3/O3s. These stars are faint visually, with $M_V \sim −3.6$ to $−4.6$, and also show absorption spectra typical of very early O stars (see Table 1 of Massey et al. 2003). Perhaps these are similar to the WN3/O3 stars we have discovered in the LMC. We are currently investigating this possibility. Although the SMC WRs are often considered to be binaries, we will note that Conti et al. (1989) argued that instead they may simply have weaker stellar winds, allowing the presence of photospheric absorption lines. This is consistent with the results of our modeling for the LMC WN3/O3s.

We are now at a point in our survey where we feel we should address our completeness. As discussed in Paper I, surveys such as ours are not simply fluxed-limited: an Of-type star, for instance, will be bright but with a relatively small (<10 Å) equivalent width of He II λ4686. Thus, although there is plenty of flux in the line, the star is hard to detect either photometrically or by image subtraction because the magnitude difference is small. It is really the contrast between the brightness in the on-line exposure (through either the WN or WC filter) and that in the CT that determines the detectability. The “flux-limit” argument comes into play in that as we go fainter the photometric errors increase, and thus a given
magnitude difference becomes less significance relative to the photometric error. Note that difference in magnitude between the on-line and off-line filter (Δm) is mainly just another way of characterizing the equivalent width.

Given that we really did not know how deep we needed to go before we discovered the WN3/O3s, it is a legitimate question of are we going deep enough? We can answer this by examining the magnitude difference Δm against the continuum magnitude CT in Figure 9. Since our survey detected most of the known WRs in our fields (see Paper I) we have constructed this diagram for all of the WRs we found as part of our program (both previously known and newly discovered). We have also constructed the 3σ and 5σ error limits in our photometry (WN-CT or WC-CT, whichever was stronger). There are several noteworthy aspects of this figure. First, we confirm that the Of-type stars are among the hardest to detect. We also find that the latest type WNs (WN10-11, previously known as the “slash” WRs) are also very difficult to detect, due to their very weak He II λ4686 lines. However, at the same Δm that characterizes the WN3/O3s, our 5σ detection limit is at least a magnitude fainter than where we are finding these stars. This strongly suggests that we are not missing a fainter population of WN3/O3s.

Figure 8. Location of WRs in the LMC. “Normal” WRs are shown with red x’s, while the WN3/O3s are shown as circles (green if from Paper I and cyan from the present paper).
Figure 9. Detection limits for our survey. We plot the magnitude difference \(\Delta m\) between the emission-line filter and continuum (whichever was stronger) against the continuum magnitude CT for both the previously known and newly found WRs in the LMC and SMC. The WOs are included with the WCs for simplicity. We have ignored stars in BAT99 with uncertain or ambiguous content in these galaxies. The WNs are indicated, where we have adopted a conservative 0.02 mag lower limit to the photometric error at the bright end.

We have also used this opportunity to examine our deep WR surveys of M33 (Neugent & Massey 2011) and M31 (Neugent et al. 2012b). Our conclusions are that while we detected the vast majority of WRs (if they are similar to those in the LMC), we certainly would have missed the WN3/O3s in these galaxies: the combination of faintness with weak lines would have placed them below our detection limits in those galaxies. Thus, we plan a deeper survey of these galaxies in the near future.

As mentioned in Section 1, we expect to finish our survey during the next Magellanic Cloud season, weather permitting. When we are done, we will have a thorough census of the WR content in these nearby, relatively metal-poor galaxies. While we expected to emerge with a solid knowledge of the numbers and types of WRs in these galaxies, the real value has been in what we did not expect to find, such as the WN3/O3 and various peculiar emission-line stars described here and in Paper I. We look forward to the new discoveries that await us next year.

We are grateful for the excellent support we always receive at Las Campanas Observatory, as well as the generosity of the Carnegie Observatories and Steward Observatory Arizona Time Allocation Committees. We are also indebted to the anonymous referee for useful suggestions, which have improved the paper. We thank Carlos Contreras for his helpful advice on the e2v camera, and Nolan Walborn, John Hillier, and Howard Bond for useful comments. Support for this project was provided by the National Science Foundation through AST-1008020, and through Lowell Observatory. This research has made use of the VizieR catalog access tool, CDS, Strasbourg, France. The original description of the VizieR service was published in (Ochsenbein et al. 2000). We note in particular the usefulness of the Catalog of Stellar Spectral Classification prepared by our colleague at Lowell Observatory, Brian Skiff. We also made use of data products from the 2MASS, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the NSF.

Facilities: Magellan:Clay (MagE spectrograph), Swope (e2v imaging CCD).

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