A spectroscopic survey of WNL stars in the Large Magellanic Cloud: general properties and binary status

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ABSTRACT

We report the results of an intense, spectroscopic survey of all 41 late-type, nitrogen-rich Wolf–Rayet (WR) stars in the Large Magellanic Cloud (LMC) observable with ground-based telescopes. This survey concludes the decade-long effort of the Montréal Massive Star Group to monitor every known WR star in the Magellanic Clouds except for the six crowded WNL stars in R136, which will be discussed elsewhere. The focus of our survey was to monitor the so-called WNL stars for radial velocity (RV) variability in order to identify the short- to intermediate-period (P ≲ 200 d) binaries among them. Our results are in line with results of previous studies of other WR subtypes, and show that the binary frequency among LMC WNL stars is statistically consistent with that of WNL stars in the Milky Way. We have identified four previously unknown binaries, bringing the total number of known WNL binaries in the LMC to nine. Since it is very likely that none but one of the binaries is classical, helium-burning WNL star, but rather superluminous, hence extremely massive, hydrogen-burning object, our study has dramatically increased the number of known binaries harbouring such objects, and thus paved the way to determine their masses through model-independent, Keplerian orbits. It is expected that some of the stars in our binaries will be among the most massive known. With the binary status of each WR star now known, we also studied the photometric and X-ray properties of our program stars using archival MACHO photometry as well as Chandra and ROSAT data. We find that one of our presumably single WNL stars is among the X-ray brightest WR sources known. We also identify a binary candidate from its RV variability and X-ray luminosity which harbours the most luminous WR star known in the Local Group.

Key words: binaries: general – stars: evolution – stars: Wolf–Rayet – Magellanic Clouds.

1 INTRODUCTION

The optical spectra of Wolf–Rayet (WR) stars feature broad emission lines from highly ionized elements. These emission lines arise in a fast, hot and dense stellar wind which is generally optically thick in the inner part, thereby completely veiling the hydrostatic photosphere of the WR star. Depending on the elements they show in their optical spectra, WR stars are classified into three different subtypes. If a WR star displays predominantly helium (He) and nitrogen (N), which are formed during hydrogen burning via the CNO cycle, the star is classified as WN; if the WR star displays, in addition to He, predominantly carbon (C) or oxygen (O), which are the products of 3α He burning, it is classified as WC and WO.

Due to their chemical properties, it is now generally accepted that classical WR stars are evolved objects, namely the almost bare, hydrogen-depleted, helium-burning cores of stars whose initial mass on the main sequence (MS) was, at solar metallicity, above ∼25 M⊙, i.e. that started their lives as O stars (Lamers et al. 1991; Maeder & Conti 1994). Thus, the key question of WR star
formation is how a WR star progenitor loses its outer, H-rich envelope to expose the CNO-enriched, deeper layers, and how WR star formation depends on ambient metallicity. For single stars, three scenarios have been put forward, depending on the initial mass of the star. Stars with initial masses $25 \lesssim M_\odot \lesssim 40 M_\odot$ are expected to become red supergiants (RSGs), as they experience continuous mass-loss through winds. Stars with initial masses $40 \lesssim M_\odot \lesssim 85 M_\odot$ are believed to turn into luminous blue variables (LBVs), as they experience outbursts of violent, eruptive shell ejections (Humphreys & Davidson 1979, 1994). Stars with even higher initial masses ($M_\odot \gtrsim 85 M_\odot$ at solar metallicity) are believed to reach the WN phase while they are still core-hydrogen burning, and to directly evolve into classical, He-burning WR stars (Conti 1976) without going through the LBV phase.

In close binaries, Roche lobe overflow (RLOF) is suspected to enhance WR star formation by removing the H-rich envelope of the (more evolved) primary (Kippenhahn & Weigert 1967). Paczynski (1967) was the first to note that a thus stripped He-burning core would very likely resemble a WR star. Since RSGs descend from the initially least massive O stars (see above), it follows that RLOF might thus considerably contribute to the total WR numbers, in particular in low-metallicity environments, where radiatively driven mass-loss rates are expected to be very low (see Vink, de Koter & Lamers 2000, 2001). Indeed, older, non-rotating stellar evolution models were unable to reproduce the observed WR populations at different Z without either enhancing by a factor of 2 the then-higher mass-loss rates through stellar winds or increasing the fraction of interacting binaries (Maeder & Meynet 1994). While updated models now include stellar rotation, and much better reproduce the observations without the need of increased binary interaction (Maeder & Meynet 2000), the influence of binarity on WR star formation remains unclear.

From model calculations, Vanbeveren, Van Rensbergen & De Loore (1998) found that close O + O binaries with initial periods $P \lesssim 1000$ d cannot escape RLOF if the primary star reaches the RSG stage, resulting in WR + O binaries with post-RLOF periods $\lesssim 200$ d (Wellstein & Langer 1999). Hence, in environments where RLOF is expected to become the increasingly important WR star formation channel (i.e. at lower ambient $Z$), the fraction of WR binaries with present-day periods of up to 200 d should be higher. This prediction is accessible to observational tests. For such a study, the Magellanic Clouds are the ideal laboratory: (i) the distances to both the Small Magellanic Cloud (SMC) and the Large Magellanic Cloud (LMC) are well established and $\sim$ constant for all stars (e.g. Keller & Wood 2006); (ii) reddening towards the Clouds is low and fairly constant, contrary to the Galaxy (e.g. Nikolaev et al. 2004); (iii) the WR populations in both Clouds are nearly complete (e.g. Massey & Duffy 2001, but see Massey, Olsen & Parker 2003); (iv) the WR population is large enough to allow for reasonable statistics. In total, the LMC harbours 132 WR stars (Breysacher, Azzopardi & Testor 1999, hereafter BAT99), while 12 WR stars are known in the SMC (Massey & Duffy 2001; Massey et al. 2003). To search for binaries, the total sample of 144 stars has been split into three distinct studies: Bartzakos, Moffat & Niemela (2001) reported the results on the 25 Magellanic Cloud WC/WO stars, while Foellmi, Moffat & Guerrero (2003a,b) studied the 71 then-known, early-type WNE (= WN2-WN5) stars, with the exception of the H-rich WNE stars in and around the R136 cluster in the 30 Dor region. The observations of a 72nd WNE star, which was newly discovered by Massey et al. (2003) in the SMC, were reported by Foellmi (2004).

In the present paper, we describe our intense, spectroscopic survey of the remaining 41, late-type WNL (= WN5-11) stars in the LMC. The two WN6 stars in the SMC were already studied by Foellmi et al. (2003a). Our survey includes those WN6 stars in the periphery of R136 which could be observed with ground-based telescopes without adaptive optics (AO). For the six luminous, WN5-7a stars in the very core of R136, AO-assisted, near-infrared spectroscopy using VLT/SINFONI was used; those results will be reported elsewhere (Schnurr et al., in preparation). The aim of our study is manifold. First and foremost, we will assess the binary status ($P \lesssim 200$ d) of each of our 41 program stars. This will conclude the decade-long effort of the Montréal Massive Star Group to study spectroscopically the entire WR population in the Magellanic Clouds, and pave the way to obtain a much clearer view of the role binarity plays in the evolution of massive stars at different metallicities. Secondly, binaries identified in this study can be used, in the future, to determine their respective masses by using model-independent, Keplerian orbits. Masses of WR stars are of the greatest importance in the context of the calibration of both atmospheric and evolutionary models, in particular for the most massive stars. We have ample reason to believe that at least some H-rich WN6 stars in our sample belong to the subgroup of very massive, possibly even the most massive stars known in the Local Group (Rauw et al. 1996a; Schweickhardt et al. 1999; Bonanos et al. 2004; Rauw et al. 2004). Thirdly and as a side effect, we will be able to put publicly available, archival X-ray data from Chandra and ROSAT into context with the binary status of our stars, since massive binaries with colliding stellar winds are known to be strong X-ray emitters.

The paper is organized as follows. In Section 2, we will describe the observations of our program stars. In Section 3, we will briefly describe the data reduction. In Section 4, we will describe in detail how we analysed our spectroscopic and X-ray data and the results we obtained. These results will be discussed in Section 5. Section 6 summarizes and concludes this paper.

# 2 DATA ACQUISITION

## 2.1 Spectroscopic observations

Target stars were selected from The Fourth Catalogue of Population I Wolf–Rayet Stars in the Large Magellanic Cloud (BAT99). This catalogue lists 134 WR stars of which 47 fall into the WNL (= WN6-11) class, including the two ‘slash-star’ types O3If/WN6 (supposedly H burning; Crowther & Bohannan 1997) and Ofpe/WN9 (supposedly linked to the LBV phenomenon; see Stahl et al. 1983; Stahl 1987; Crowther, Smith & Hillier 1995; Nota et al. 1996; Pasquali et al. 1997). 41 of these 47 stars (see Table 1) were observed with conventional spectrographs, and the results of those observations are reported here.

Our observations were organized in three different campaigns or ‘seasons’ between 2001 and 2003 to maximize the time coverage, and were carried out during 13 runs at six different, 2-m class, southern telescopes. The following observatories were used: Complejo Astronómico El Leoncito (CASLEO), Argentina; Mount Stromlo Observatory (MSO), Australia; Cerro Tololo Inter-American Observatory (CTIO), Chile; South African Astronomical Observatory (SAAO), South Africa; Siding Spring Observatory, Australia; Las Campanas Observatory (LCO), Chile. In total, 99 nights were
Table 1. List of our program stars as taken from the BAT99 catalogue. BAT99 numbers as well as cross-identification with the Brey, Radcliffe and/or Melnick numbers are given, together with \( v \) magnitudes and spectral types, according to BAT99. Stars without a Brey denomination are those that have been newly included into the BAT99 catalogue.

| BAT99  | Brey  | Other | \( v \) magnitude | Spectral type |
|--------|-------|-------|-------------------|---------------|
| 12     | 10a   | –     | 13.72             | O3II*/WN6-A    |
| 13     | –     | –     | 12.89             | WN10          |
| 16     | 13    | –     | 12.73             | WN8h          |
| 22     | 18    | R84   | 12.09             | WN9h          |
| 30     | 24    | –     | 13.40             | WN6h          |
| 32     | 26    | –     | 12.72             | WN6(h)        |
| 33     | –     | R99   | 11.54             | Ofpe/WN9      |
| 44     | 36    | –     | 13.47             | WN8h          |
| 45     | –     | BE294 | 12.80             | WN10h         |
| 54     | 44a   | –     | 14.32             | WN9h          |
| 55     | –     | –     | 11.99             | WN11h         |
| 58     | 47    | –     | 15.1              | WN6h          |
| 68     | 58    | –     | 14.43             | WN5-6         |
| 76     | 64    | –     | 13.46             | WN9h          |
| 77     | 65    | –     | 13.34             | WN7           |
| 79     | 57    | –     | 13.58             | WN7+OB        |
| 80     | 65c   | –     | 13.24             | O4IIf/WN6     |
| 83     | –     | R127  | 10.9             | Ofpe/WN9      |
| 89     | 71    | –     | 14.28             | WN7           |
| 91     | 73    | –     | 13.98             | WN7           |
| 92     | 72    | R130  | 11.51             | WN6+B1la      |
| 93     | 74a   | –     | 13.83             | O3IIf/WN6     |
| 95     | 80    | R135  | 13.16             | WN7h          |
| 96     | 81    | Mk53  | 13.74             | WN8(h)        |
| 97     | –     | Mk51  | 13.77             | O3IIf*/WN7-A  |
| 98     | 79    | Mk49  | 12.96             | WN6(h)        |
| 99     | 78    | Mk39  | 12.96             | O3IIf*/WN6-A  |
| 100    | 75    | R134  | 12.85             | WN6h          |
| 102    | 87    | R140a2| 12.99             | WN6+1O        |
| 103    | 87    | R140b | 13.01             | WN6           |
| 104    | 76    | Mk37Wb| 14.58             | O3IIf*/WN6-N-A|
| 105    | 77    | Mk42  | 12.80             | O3IIf*/WN6-N-A|
| 107    | 86    | R139  | 12.12             | WNL3Of        |
| 113    | –     | Mk30  | 13.57             | O3IIf*/WN6-N-A|
| 114    | –     | Mk55  | 13.59             | O3IIf*/WN6-N-A|
| 116    | 84    | Mk34  | 13.65             | WN5h          |
| 118    | 89    | –     | 11.15             | WN6h          |
| 119    | 90    | –     | 12.16             | WN6(h)        |
| 120    | 91    | –     | 12.59             | WN9h          |
| 130    | –     | –     | 12.82             | WN11h         |
| 133    | –     | –     | 12.10             | WN11h         |

\(*\)Known LBV with large photometric variations, cf. Stahl et al. (1983).

allocated, but due to bad weather conditions or technical problems, not all nights were useful. Long-slit spectrographs were used at all telescopes. The exact wavelength coverage of the spectra depended on the respective instrument used, but all sets of data included the wavelength range from 4000 to 5000 Å, thereby comprising the strategic emission lines He\(\text{II} \lambda 4686\) and N\(\text{v} \lambda 4058\) (however, see below).

To maximize the flux reaching the detector and thus achieve good signal-to-noise ratio (S/N), a slit width of 1.5 arcsec was used during the first two years, but under the very good seeing conditions on Cerro Tololo during summer, this yielded a relatively large radial velocity (RV) scatter; we will come back to this problem later in this paper. Therefore, the slit width was reduced to 1 arcsec for the last season (2003/04, only at CTIO). The obtained linear dispersion varied from \(0.65 \text{ Å pixel}^{-1}\) (SSO) to \(1.64 \text{ Å pixel}^{-1}\) (CASLEO), with the 3-pixel spectral (velocity) resolution at 4686 Å ranging from \(R \approx 2400 (~ 125 \text{ km s}^{-1})\) to \(R \approx 950 (~ 315 \text{ km s}^{-1})\). Exposure times were chosen to provide an S/N of \(~ 50–70\) per collapsed pixel in the blue continuum around 4500 Å, and were adapted to the respective telescope efficiencies and weather conditions. For our faintest stars, long exposures were broken into two or three to facilitate cosmic ray rejection.

Even under best conditions, not more than two-thirds to three-quarters of our sample (‘sequence A’) could be observed in one night. The remaining stars (‘sequence B’) were then observed the following night before sequence A was restarted again, and so forth. To further break integer-day sampling (~2-d sampling in particular), we also employed a scheme to re-observe the stars of a given sequence the following night before resuming observations of the other sequence, thereby obtaining a ~1-d sampling (i.e. observations were carried out as ABBAABAB etc.). At CTIO, where we had relatively long runs of clear contiguous nights so that we could sufficiently plan ahead, this was particularly successfully employed. Moreover, some stars were observed more frequently (i.e. once or twice every night) by default because they were of particular interest (short-period and/or supposedly very massive binaries).

At the beginning of each night, bias frames and high-S/N, internal (quartz lamp) flat-field frames were taken. For reliable RVs, a comparison-arc exposure was taken before and after each science exposure, the exception to this rule being the stars in the periphery of R136, because telescope slews were only very minor (~1 arcmin) and differential flexure of the Cassegrain spectrographs not an issue. Neither dark nor twilight flat-field frames were taken.

The observation journal is summarized in Table 2, while the instrumental properties are summarized in Table 3.

2.2 Archival X-ray data

We made use of public archives to retrieve X-ray data for our program stars. The Chandra Archive\(^{2}\) available from 2004 October and the entire ROSAT Archive\(^{3}\) have been searched for all Chandra ACIS and ROSAT PSPC and HRI observations including any of the 41 WNL stars studied in this paper. We de-archived Chandra ACIS observations for 25 WNL stars, and ROSAT PSPC and HRI observations for 13 and 3 WNL stars, respectively. A summarizing table of these observations is provided in Section 4.8 (Table 13). Further details of the selection and reduction of these observations are provided by Guerrero & Chu (2008a,b).

2.3 Archival photometry

Several microlensing surveys carry out repeated photometry towards the LMC and make their data publicly available. In order to obtain repeated photometry of our program stars, we thus browsed through the public archives of the Massive Compact Halo Object (MACHO; see Alcock et al. 1996) experiment, and the Optical Gravitational Lensing Experiment (OGLE; see Udalski et al. 2000). To
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Table 2. Journal of observations.

| Run# | Observatory | Start (UT) | End (UT) | Clear nights | Season |
|------|-------------|------------|----------|--------------|--------|
| 1    | CASLEO      | 2001 November 02 | 2001 November 09 | 6 | 1 |
| 2    | MSO         | 2001 November 09 | 2001 December 06 | 14 | 1 |
| 3    | CTIO        | 2001 December 26 | 2001 December 31 | 6 | 1 |
| 4    | CTIO        | 2002 January 23 | 2002 January 27 | 4 | 1 |
| 5    | SAAO        | 2002 November 05 | 2002 November 12 | 7 | 2 |
| 6    | CTIO        | 2002 November 19 | 2002 November 27 | 8 | 2 |
| 7    | CTIO        | 2002 December 16 | 2002 December 24 | 8 | 2 |
| 8    | MSO         | 2003 January 03 | 2003 January 18 | 10 | 2 |
| 9    | SSO         | 2003 January 27 | 2003 January 31 | 3 | 2 |
| 10   | LCO         | 2003 January 27 | 2003 February 02 | 6 | 2 |
| 11   | CTIO        | 2003 December 19 | 2003 December 29 | 10 | 3 |
| 12   | CTIO        | 2004 January 02 | 2004 January 06 | 4 | 3 |
| 13   | CTIO        | 2004 January 07 | 2004 January 09 | 2 | 3 |

Table 3. List of observatories and instruments used.

| Observatory | CASLEO | MSO | CTIO | SAAO | SSO | LCO |
|-------------|--------|-----|------|------|-----|-----|
| Telescope   | 2.15 m | 1.88 m | 1.5 m | 1.88 m | 2.3 m | 2.5 m |
| Spectrograph | REOSC | CassSpec | RCSpec | GratingSpec | DBS | WFCCD |
| Grating (lines mm$^{-1}$) | 600 | 600 | 600 | 600 | 600 | 600 |
| Dispersion (Å pix$^{-1}$) | 1.64 | 1.35 | 1.48 | 1.10 | 0.65 | 1.38 |
| $R$ @ 4686 Å (3 pixels) | 945 | 1160 | 1055 | 1420 | 2400 | 1130 |
| Spectral range (Å) | 3970–5645 | 3885–5515 | 3980–5730 | 3485–5415 | 3905–4875 | 3775–5600 |
| Comparison lamp | HeNeAr | FeAr | HeNeAr | CuAr | CuHeAr | HeH |
| Overscan | No | No | Yes | Yes | Yes | Yes |

*Blue arm only.

search the data bases, but J2000.0 coordinates as given in BAT99 were entered, and a search radius of 10 arcsec was applied in both cases. While MACHO yielded photometry of some of our targets (OGLE did not observe our program stars), the data showed too large scatter to prove useful, most likely due to the brightness of our target stars. Thus, we did not carry out any further analysis of the photometry.

3 DATA REDUCTION

Some of our observation runs, notably those at the Cerro Tololo Inter-American Observatory (CTIO), were interrupted by other, time-critical observations, and thus split into several runs. Since the spectrograph had to be set up again each time, we treated each such run individually to allow for effects of different grating positions, angles, alignments, etc. Thus, a total of 13 individual runs were processed.

Data reduction was carried out in the usual way using the NOAO-IRAF software package. Science data were corrected with average bias and flat-field frames, and object spectra were optimally extracted using APALL with the 2D trace-fit option enabled. Sky background was fitted and subtracted from the stellar spectrum for all stars with the exception of those in the periphery of R136. This cumbersome task (cf. Selman & Melnick 2005) was deemed unnecessary because despite its strength, the discrete emission spectrum of the 30 Dor nebula does not affect the strategic WNL emission line, He II λ4686. It does however affect the (intrinsic) Balmer lines of these WNL stars, which renders the determination of the hydrogen content in the star highly uncertain. This has consequences which will be examined later.

Arc frames taken before and after each science exposure were averaged and then extracted. Unfortunately, due to the lack of good comparison lines at the blue edge of our spectra, the dispersion solution is less reliable in the region bluewards of 4400 Å. This had severe consequences for the precision of the RVs measured from the N IV λ4058 emission line, which yielded very large scatter. Extracted spectra were then rebinned to uniform stepwidth, corrected for heliocentric velocities, and rectified.

The spectra were then cleaned of cosmic rays and bad pixels as far as possible; where applicable, spectra from split exposures were combined. If a cosmic ray or bad pixel fell on to a strategic emission line, great care was taken not to significantly alter the original line profile. If this was not possible, the spectrum was discarded. The final stellar spectra were then rebinned to a uniform step width of 1.65 Å pixel$^{-1}$, thereby yielding a conservative 3-pixel resolving power of $R \sim 1000$. The achieved S/N per rebinned pixel, calculated for the spectral region from 5050 to 5350 Å, is 85 on average.

4 DATA ANALYSIS AND RESULTS

4.1 Radial velocity measurements

Since in principle, we are mainly interested in changes in RVs to identify the binaries, cross-correlation, which measures shifts

4 Web interfaces for light-curve retrieval from the respective data bases are accessible at http://www.macho.mcmaster.ca/ for MACHO, and at http://bulge.princeton.edu/ogle/ for OGLE.

5 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
relative to a template, was used as our main tool, since it yielded the smallest RV scatter.

In most of our WNL stars, the spectrum is dominated by the He II λ4686 emission, which is the strongest line by a wide margin. Thus, we concentrated our RV measurements on this emission line, restricting the cross-correlation to the spectral region from 4600 to 4800 Å, which almost exclusively contains He II λ4686. To guard against an unlucky choice of template, we used an iterative approach for cross-correlation. For a first cross-correlation pass, a real, high-S/N spectrum from the data set of a given star was chosen as template. This template was cross-correlated with all other spectra. RV shifts were measured by fitting a Gaussian plus a (linear, rarely parabolic) continuum function to the cross-correlation profile. Resulting RVs were then used to shift all spectra into the template’s frame of reference. Then, an S/N-weighted average spectrum was computed using all shifted spectra, and used as a new template for a second cross-correlation pass. Again, all spectra were shifted and added, and with this ‘supertemplate’, a final cross-correlation pass was made.

The advantage of this approach is that the resulting supertemplate has a higher S/N than a single spectrum, and that (stochastic or cyclical) line-profile variations are mostly averaged out. The same is true for the potentially present spectral signature of a companion, which is maximally smeared out, because it moves in antiphase to the WNL star.6 While there were noticeable differences in RVs between the first and the second cross-correlation iterations, in most cases the third cross-correlation pass did not improve the RVs; still, it was carried out in all cases for the sake of uniformity.

Absolute (systemic) RVs were measured by fitting the He II λ4686 emission, whose peak was reasonably well reproduced by a single Gauss function (see Fig. 1). Other lines were too weak and too noisy to be used, which is particularly unfortunate for the narrow, clean and rather symmetric N ivλ4058 emission at the very blue edge of our spectra. This line also suffered from the lack of useful comparison-arc lines, which rendered impossible a reliable wavelength calibration (see Section 3), yielding an RV scatter more than twice as large as what was obtained from the He II λ4686 line.

While differences between RVs obtained from fits and from cross-correlation remained remarkably small, direct fitting yielded a slightly larger RV scatter than cross-correlation, most likely because of noise (in particular in weak-lined stars) and the line being slightly asymmetric. Potential intrinsic line-profile variability [e.g. due to wind–wind collision (WWC)] might also add to the difference. Thus, whenever it was possible, we relied on RVs obtained by cross-correlation rather than on those obtained by line fitting.

### 4.2 Standard stars and systematic shifts between observatories

Most stars show a small to very small RV scatter around or below 20 km s\(^{-1}\) (obtained by cross-correlation). However, before identifying the binary stars in our sample, another potential problem had first to be taken care of. Foellmi et al. (2003a,b) reported systematic shifts between CASLEO and SAAO. Both observatories together with others were also used for our study; therefore, we had to make sure that any RV variation is of stellar origin and not a consequence of different (and possibly variable) instrumental zero-points. In order to compute systematic shifts among the respective runs, we proceeded as follows. Of our 41 program stars, we selected those (i) which are well isolated (no composite spectrum due to crowding), (ii) for which RVs could be measured using cross-correlation, (iii) which displayed very small RV scatter and (iv) for which a preliminary period search in the period range 1 \(\leq P \leq 200\) d did not yield cyclical RV variability (the period-search method is described more comprehensively below). Stars meeting these criteria are most likely true single stars or binaries with sufficiently long periods, large eccentricities and/or low inclination angles that they can serve effectively, within our detection limits, as constant-RV standard stars. By construction, the only shifts these stars display are then solely due to systematic shifts among different observatories.

23 reference stars were thus selected (see Table 4). For each star, mean RVs were computed for each individual run. As described above, during the 2003/2004 campaign at CTIO (i.e. runs 11–13), a 1 arcsec slit width was used, hence the RV scatter is very small in these data sets, reaching a minimum during run 11 (see below). SSO

| BAT99 | \(\sigma_{\text{UV}}\) (km s\(^{-1}\)) | BAT99 | \(\sigma_{\text{UV}}\) (km s\(^{-1}\)) | BAT99 | \(\sigma_{\text{UV}}\) (km s\(^{-1}\)) |
|-------|------------------|-------|------------------|-------|------------------|
| 13    | 12.5             | 55    | 14.6             | 93    | 20.5             |
| 16    | 13.3             | 58    | 14.7             | 96    | 18.7             |
| 22    | 13.3             | 76    | 15.5             | 97    | 19.6             |
| 30    | 17.3             | 79    | 14.3             | 100   | 15.4             |
| 33    | 16.2             | 80    | 20.5             | 120   | 21.8             |
| 44    | 15.8             | 83    | 14.9             | 130   | 13.2             |
| 45    | 11.4             | 89    | 14.3             | 133   | 15.4             |
| 54    | 18.2             | 91    | 13.7             | –     | –                |

6 This is particularly the case if the WN star is the more massive component of the binary system, as is possible in luminous WNL systems. The O star then shows the larger RV amplitude; its absorption lines are hence smeared out over a larger spectral region.
were truly constant, RV measurements would be scattered around a mean velocity only due to random measurement errors. In Fig. 3, the 770 RV measurements of the 23 combined reference stars (the ‘super-reference’) are shown in histogram form. A Kolmogorov–Smirnov test yields that this distribution is normal at a 99 per cent confidence level, with $\text{RV}_j = 0 \text{ km s}^{-1} \pm 16 \text{ km s}^{-1}$, a nice a posteriori confirmation to use those 23 stars as constant stars.

We now define the RV amplitude $S$ be the span of RV such that 99.9 per cent of the measured RVs fall within this span, i.e. $S = 3\sigma_{\text{RV}}$. For constant stars, the distribution of the squared RV amplitudes $S^2$ then follows a $\chi^2$ distribution with $df$ degrees of freedom, where $df$ is the number of RV measurements per star (in our case, $df = 33$, because we have 33 data points per star on average). If a star displays a value of $S^2$ exceeding the 99.9 per cent threshold, its RV scatter is not consistent with the hypothesis that it is a constant star; hence it will be considered variable.

A $\chi^2 (x)$ function with $df = 33$ was computed. Values of the normalized $x$ for $df = 30$ and a 99.9 per cent level were taken from statistical textbooks (e.g. Kreyszig 1975) and linearly interpolated to $N$ (which is usually not tabulated); we obtained $x = 64.1$. This corresponds to the cut-off value $S^2 = 5380 \text{ km s}^{-2}$ and thus $\sigma_{\text{RV}} = 22.6 \text{ km s}^{-1}$. Stars exceeding this threshold are considered variable at a 99.9 per cent level (0.1 per cent error probability); they are listed in Table 6. The observed RV square amplitudes $S^2$ are shown in histogram form in Fig. 4, with the $\chi^2$ function overplotted after having been adjusted for the chosen bin size. As we shall see further below, most, however not all, of the stars exceeding the 99.9th percentile also display periodicities in their RV curves, and indeed are binaries.

### 4.4 Cyclical variability and period analysis

Variability, i.e. significantly large scatter, of RVs is not a sufficient criterion for cyclical variability, let alone for binarity. There are stars which are erratically variable, i.e. any measured RV scatter could be of stochastic nature. It is thus important to verify whether or not any star shows periodic RV variabilities.

#### 4.4.1 Period-search algorithms

After having corrected all data sets for systematic shifts, we reperformed a period search on the unweighted RVs of all stars in the period range from 1 to 200 d, using a code by Kaufer et al. (1996). In each step of the iteration, this code computes cleaned periodograms and window functions of unevenly distributed data points according to Deeming (1975; see also Schwarz 1978; Roberts, Leahr & Dreher 1987). Significance levels are calculated for the found periods using Lomb–Scargle statistics (Lomb 1976; Scargle 1982), i.e. by fitting sine waves to the data points and minimizing the $\chi^2$. Of those peaks that exceed the $3\sigma$ significance level, the one with the highest power is selected, and its half-width at half-maximum is adopted as 1$\sigma$ error on the period.

Our observations are fragmented into 13 runs of different duration and slightly different typical sampling frequencies between 0.5 and 2 data points per day and per star. This somewhat reduces aliasing problems, although $1 - \nu$ aliases remain well visible in most periodograms. For non-circular orbits, where significant power can be contained in the harmonics of the fundamental frequency, even more side-band peaks are generated, since the harmonics themselves suffer from aliasing. However, neither fitting higher order terms of the Fourier expansions (up to third order) nor using the analysis-of-variance (AOV) algorithm (cf. Schwarzenberg-Czerny

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**Table 5. Systematic shifts between different runs and standard deviations of RV per run, used as a posteriori error bars. See text for details.**

| Run $j$ | Observatory | RV shift $\pm \sigma_j$ | $\sigma_j$ |
|--------|-------------|-------------------------|-----------|
| 1      | CASLEO      | $-2.9 \pm 15.3$         | 15.3      |
| 2      | MSO         | $-16.1 \pm 19.0$        | 19.0      |
| 3      | CTIO        | $-3.0 \pm 20.9$         | 20.9      |
| 4      | CTIO        | $-10.7 \pm 13.3$        | 13.3      |
| 5      | SAAO        | $-8.7 \pm 17.2$         | 17.2      |
| 6      | CTIO        | 0.2 $\pm 20.7$          | 20.7      |
| 7      | CTIO        | $-1.9 \pm 17.4$         | 17.4      |
| 8      | MSO         | 3.0 $\pm 20.2$          | 20.2      |
| 9      | SSO         | $-24.9 \pm 10.4$        | 10.4      |
| 10     | LCO         | $-4.3 \pm 23.8$         | 23.8      |
| 11     | CTIO        | 0.0 $\pm 10.3$          | 10.3      |
| 12     | CTIO        | 3.6 $\pm 12.5$          | 12.5      |
| 13     | CTIO        | $-0.9 \pm 12.5$         | 12.5      |
Figure 2. Relative RVs of our program stars for the three observing seasons.
Figure 2 – continued
Figure 2 – continued

Figure 3. Histogram of RV measurements of the 23 reference stars, obtained by cross-correlation, and after correction for systematic shifts. In total, 770 data points are used. Binsize is 7 km s\(^{-1}\). The unweighted standard deviation around the mean is 16 km s\(^{-1}\).

1989) changed the results significantly. Thus, only results obtained with Lomb–Scargle statistics are quoted.

4.4.2 Stars with periodicities

Periodograms of identified cyclically variable stars are shown in Fig. 5. Almost all binary periods reported by previous studies (Moffat 1989, and references therein) were reproduced with remarkable similarity, and by combining our data with published data, we were able to further increase the accuracy of the periods (see Table 7). These revised periods were used in the further analysis. The confirmed binaries are BAT99-32, BAT99-77 and BAT99-92.

BAT99-77 is an eccentric binary system with an almost perfect 3 d period which is why it displays a forest of significant frequency peaks, harmonics and aliases. This makes it difficult to determine which period is the correct one; however, only the 3 d period yields a coherent RV curve, and a full Keplerian fit to BAT99-77’s RVs confirms the result (see Section 4.5).

In one curious case, the 2.76 d period reported for BAT99-102 (R140a2) was clearly found, however in its neighboring star, BAT99-103 (R140b). Careful inspection of our logbooks did not reveal any possible confusion at the telescope, nor is there any indication of such a mishap in Moffat et al. (1987), who first detected the binary. BAT99-102 forms a visual pair with BAT99-101 (R140a1) which even under the best seeing conditions at CTIO could not be separated. Both stars lie very close to BAT99-103, and given our relatively large slit width, some cross-contamination of emission lines is not impossible, which could lead to a detection of the same periodicity in BAT99-102, too. While we cannot propose a solution to this issue, we will from here on consider BAT99-103 as the 2.76-d binary.

Four new stars were found to display periodic RV curves: BAT99-12, BAT99-95, BAT99-99 and BAT99-113. None of these four stars was included in the study of Moffat (1989), either because it was not listed as a WR star in previous catalogue versions, or because it was too faint for Moffat’s magnitude-limited sample (V ≤ 13 mag). Note, however, that BAT99-99 is at the detection limit, as is clearly illustrated by the periodogram in which the highest peak is not very clearly pronounced; also, a full Keplerian fit did not converge (see Section 4.5), so that the 92.6 d period has to be considered very preliminary.

Table 6. Stars whose RV standard deviation σ\(_{RV}\) exceed the cut-off value of 22.6 km s\(^{-1}\) and which therefore are considered variable.

| BAT99 | σ\(_{RV}\) (km s\(^{-1}\)) | BAT99 | σ\(_{RV}\) (km s\(^{-1}\)) |
|-------|-----------------|-------|-----------------|
| 12    | 70.8            | 103   | 106.7           |
| 32    | 92.4            | 105   | 37.7            |
| 68    | 29.5            | 107   | 23.9            |
| 77    | 78.2            | 113   | 93.3            |
| 92    | 139.8           | 116   | 32.6            |
| 95    | 81.6            | 114   | 23.2            |
| 99    | 58.9            | 118   | 31.6            |
| 102   | 25.3            | 119   | 44.7            |

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the combined data sets (see above). Since we however did apply weights for the fit of the orbital solution, we did not fix the period but kept it as a free fitting parameter. In all cases, the periods found by ELEMENTS were, within the errors, identical to those obtained from our CLEAN analysis of either our or the combined data set. Fixing the value thus did not significantly change the orbital solution nor the errors. However, we again applied an iterative approach. For each data point \( j \), ELEMENTS returns the value \( \text{observed minus computed, } \langle \text{O-C} \rangle \). After the first pass of ELEMENTS, we computed the overall mean \( \langle \text{O-C} \rangle \) and the standard deviation from this mean, i.e. \( \sigma_{\text{O-C}} \). Any data point \( j \) with \( |\langle \text{O-C} \rangle| > 3 \sigma_{\text{O-C}} \) was removed from the data set, and the orbital solution was fitted again. This procedure was repeated until all data points were within \( 3 \sigma_{\text{O-C}} \) of the fitted orbital solution. Usually, this happened after the third iteration, which means that only few data points had to be discarded. Naturally, the final orbital period no longer agreed with the initial guess, because the underlying data set had been modified. Yet, deviations remained very small.

In all cases where the algorithm converged, ELEMENTS returned an elliptical orbital solution, although \( e \) was small in most cases. Therefore, we repeated the fit and forced a circular solution by imposing \( e = 0 \), with \( \phi = 0 \) defined at the time \( T_0 \) of inferior conjunction, when the WR passes in front of its companion; thus, \( T_0 \) is different from the time of periastron passage, \( T_0 \), returned from the elliptical fit. Both sets of parameters are given in Table 8.

In all cases but for BAT99-77, the overall quality of the fit, expressed by \( \sigma_{\text{O-C}} \), did not significantly deteriorate. Thus, for the rest of this study the circular solution was adopted for all stars, with the exception of BAT99-77. To illustrate the differences between the free, elliptical solution and the forced, circular one, both solutions are shown in Fig. 6. Plotted are all data points which have been retained for the fit after having applied the iterative \( \sigma \) clipping described above. For the purpose of graphical comparison only, the circular solutions shown were computed using \( E_0 = T_0 \) of the given elliptical case, so that their zero phases coincide for better clarity. Note that in the tables, the dates for \( E_0 \) and \( T_0 \) are different.

In the following, we will discuss the binary status of individual stars which display cyclical RV variability.

BAT99-12 This newly identified variable shows a clear periodicity of 3.2358 d in its RV curve obtained from the He II \( \lambda 4686 \) emission lines. Although the RV curve is somewhat noisy when the RV points are folded into the corresponding phase, the orbital fit converges. The obtained eccentricity is surprisingly large for such a short-period orbit. This might be because the He II \( \lambda 4686 \) emission is subject to severe distortions due to WWCs. Forcing a circular fit deteriorates the overall error \( \sigma_{\text{O-C}} \) only slightly, so that a circular motion with slightly changed orbital parameters was adopted for the rest of the paper. The systemic velocity \( \gamma \) obtained from the orbital fit is very large, \( \gamma = 650 \pm 8 \text{ km s}^{-1} \), and qualifies this system for a fast runaway binary (see also Massey et al. 2005). This is very remarkable given the fact that such close and massive binary systems are very ‘hard’ with respect to gravitational interactions with other cluster members. This object clearly deserves more attention; we have therefore obtained higher quality, follow-up observations which will be the subject of a future study.

BAT99-32 This star is a known binary with an orbital period of 1.9076 d, the shortest known among the WN binaries in the LMC; yet it does not display the largest RV amplitude (see BAT99-92). This might indicate that the system is seen under a low inclination angle. Within the errors, the system has a circular orbit, as might be expected for such short systems.

### 4.5 Binaries: the remaining orbital parameters

For variable stars with identified, coherent periods, we attempted to compute orbital parameters using the program ELEMENTS (cf. Marchenko, Moffat & Koenigsberger 1994). This code allows one to assign weights \( 1/\sigma_{\text{unc}}^2 \) to each data point, according to its a posteriori measurement errors determined in Section 4.2 on a per-run basis (Table 5). As input guess for the orbital period, we used the value which was obtained from the CLEAN analysis of the unweighted data points, and when available, we used the periods obtained from...
Figure 5. Window functions (WIN, upper panels) and periodograms (PER, lower panels) in the period range of 1–100 d (for BAT99-99: 20–200 d), expressed in cycles per day (c/d). BAT numbers are indicated. The frequency peak corresponding to the period quoted in this study is indicated by an arrow. Note the strong differences in y scale between the window functions and the periodograms.

BAT99-77 This star is a known binary with an almost integer-day period which makes it hard to determine. However, the orbital fit confirms our period, and yields quite a large eccentricity for such a short system. Consequently, the overall error increases significantly when a circular solution is imposed. Presently, we do not have enough data to confirm whether this is due to WWC-induced distortions of the He II λ4686 emission or whether the orbit is indeed non-circular, but for the rest of this paper, we adopt the elliptical solution.

BAT99-92 This star is a known binary. The orbital fit yields a remarkably small eccentricity, so that the circular solution is adopted. This system shows the largest RV amplitude of our program stars,
Table 7. Periods (in days) found for our program stars in this paper and previous studies. Newly identified, periodically variable stars are indicated. References are: (1) Moffat & Seggewiss (1986); (2) Moffat (1989); (3) Moffat et al. (1987; but see text for details).

| BAT99 | Previous studies | This paper | Combined data | Reference |
|-------|------------------|------------|---------------|-----------|
| 12    | n/a              | 3.2358 ± 0.0058 | n/a           | New       |
| 32    | 1.9075 ± 0.0002 | 1.9075 ± 0.0015 | 1.90756 ± 0.00012 | 1         |
| 77    | 3.0032 ± 0.0002 | 3.0034 ± 0.0042 | 3.00303 ± 0.00029 | 2         |
| 92    | 4.3092 ± 0.0040 | 4.311 ± 0.008 | 4.3125 ± 0.0006 | 2         |
| 95    | n/a              | 2.1110 ± 0.0018 | n/a           | New       |
| 99    | n/a              | 92.60 ± 0.31 | n/a           | New       |
| 103   | 2.7596 ± 0.0001 | 2.7597 ± 0.0038 | 2.75975 ± 0.00027 | 3         |
| 113   | n/a              | 4.699 ± 0.010 | n/a           | New       |

Table 8. Orbital parameters for the WR component of our binary systems. Results are given for both the free, elliptical fit and the forced, circular solution. For the latter, \( \omega \) is not defined (n/d). Depending on the eccentricity of the orbit, zero phase \( \phi_0 \) is either the time of periastron passage, \( T_p \), or the time of inferior conjunction (i.e. WR star in front), \( E_0 \).

| BAT99 | \( P \) (d) | \( e \) (km s\(^{-1}\)) | \( K \) (\(^\circ\)) | \( \omega \) (km s\(^{-1}\)) | \( \gamma \) (HJD 240,000.5) | \( \phi_0 \) (km s\(^{-1}\)) | \( \sigma_{\phi-C} \) |
|-------|-------------|-----------------|----------------|----------------|---------------------|----------------|-------------|
| 12    | 3.2358 ± 0.0058 | 0.34 ± 0.06 | 74 ± 5 | −29 ± 11 | 642 ± 13 | 52269.84 ± 0.09 | 24.8 |
| 32    | 1.90756 ± 0.00012 | 0.06 ± 0.02 | 120 ± 3 | 250 ± 22 | 288 ± 6 | 53011.57 ± 0.12 | 13.5 |
| 77    | 3.00303 ± 0.00029 | 0.32 ± 0.02 | 144 ± 4 | 7 ± 4 | 333 ± 8 | 52631.87 ± 0.04 | 10.9 |
| 92    | 4.3125 ± 0.0006 | 0.02 ± 0.02 | 204 ± 5 | 109 ± 66 | 332 ± 7 | 52998.03 ± 0.04 | 16.8 |
| 95    | 2.1110 ± 0.0018 | 0.07 ± 0.03 | 107 ± 3 | 285 ± 18 | 274 ± 9 | 52999.87 ± 0.10 | 10.6 |
| 99    | 92.60 ± 0.31 | 0 | 91 ± 19 | n/d | 337 ± 16 | 53045.90 ± 1.30 | 30.5 |
| 103   | 2.75975 ± 0.00027 | 0.23 ± 0.03 | 158 ± 4 | −41 ± 7 | 388 ± 8 | 53007.80 ± 0.05 | 19.9 |
| 113   | 4.699 ± 0.010 | 0.20 ± 0.05 | 130 ± 8 | 308 ± 16 | 390 ± 10 | 52993.07 ± 0.13 | 18.1 |

although it does not have the shortest period. This might indicate that it is seen under a large inclination angle, which renders BAT99-92 potentially interesting for a photometric campaign to obtain the inclination angle from a light curve.

BAT99-95 This is a newly discovered binary in the 30 Dor region. Despite its short orbital period, it has a remarkably small RV amplitude. A circular solution is adopted for this system.

BAT99-99 This is a newly discovered binary system located in the periphery of R136 cluster. Massey et al. (2005) has reported this star to be a binary, but not given an orbital period. From our analysis, we find a rather long period of 92.6 d, close to our detection limits (see above). Unfortunately, folding the data points into the corresponding phase yields a rather noisy RV curve. A free (elliptic) fit does not converge, so that we have forced a circular solution; however, \( \sigma_{\phi-C} \) is uncomfortably large, probably because the true orbit is elliptical indeed. We thus report a tentative set of orbital parameters for BAT99-99. Errors on individual parameters are not stated, rather we quote the \( \sigma_{\phi-C} \) of the total solution.

BAT99-103 This star is a known binary system, located in the periphery of the R136 cluster. Again, we are unable to verify whether or not the non-zero, albeit mild eccentricity is real, but the circular fit is only moderately worse. Since the RV curve is not very clean, both WWC-induced distortions and the weakness of the He\( \pi \lambda 4686 \) emission line are the most likely causes for this result.

BAT99-113 This is a newly discovered binary system in the periphery of R136. Regarding the non-zero eccentricity, the same remarks apply as for the previous system.

4.6 Systemic velocities and runaway stars

For single program star, both mean \( \overline{RV}_{sys} \) and standard deviations were computed from RVs obtained through Gauss fits to the He\( \pi \lambda 4686 \) emission line (see Section 4.1). For binary stars, the systemic velocity \( \gamma \) and its error returned from the orbital fit were used. Resulting \( \overline{RV}_{sys} \) are listed in Table 9 and shown in histogram form in Fig. 7.

Averaged over our complete sample, we find 314 ± 10 km s\(^{-1}\), somewhat more than the systemic velocity of the LMC, which is 280 ± 20 km s\(^{-1}\) (e.g. Kim et al. 1998), but consistent with the value Foellmi et al. (2003b) reported for their WNE sample stars, 324 ± 6 km s\(^{-1}\). However, we reanalysed the data of Foellmi et al. and found 345 ± 6 km s\(^{-1}\), which is then incompatible with our results for WNL stars. The origin of this systematic difference is not entirely clear, but most likely stems from the way the measurements were carried out; we used line fitting, while Foellmi et al. used bisectors.
Figure 6. Orbital solutions for the binary systems, folded into the respective phases. Shown are both the solution for the elliptical (solid) and the circular (dotted) orbit.

on selected parts of the He $\Pi$ λ4686 emission line. For consistency, we will use our values in the following discussion. In Table 10, the systemic velocities of the different subsamples are shown; all errors quoted are the error of the mean (eom = $\sigma_{RV}/\sqrt{N}$).

The measured redshift does not come unexpectedly; it is well known among observers that some emission lines of WR stars yield redshifted systemic velocities. Some authors have attributed this phenomenon to a prominent electron-scattering wing on the red
Table 9. Systemic velocities and RV scatter for our program stars.

| BAT99 | RV$_{sys}$ (km s$^{-1}$) | $\sigma_{RV}$ (km s$^{-1}$) | Binary? | Remarks |
|-------|--------------------------|-----------------------------|---------|---------|
| 12    | 650                      | 70.8                        | Yes     | Runaway |
| 13    | 277                      | 12.5                        | –       | –       |
| 16    | 330                      | 13.3                        | –       | –       |
| 22    | 255                      | 13.3                        | –       | –       |
| 30    | 345                      | 17.3                        | –       | –       |
| 32    | 288                      | 92.4                        | Yes     | –       |
| 33    | 293                      | 16.2                        | –       | –       |
| 45    | 398                      | 15.8                        | –       | –       |
| 54    | 316                      | 18.2                        | –       | –       |
| 55    | 140                      | 14.6                        | –       | Runaway?|
| 58    | 311                      | 14.7                        | –       | –       |
| 62    | 321                      | 29.5                        | –       | –       |
| 76    | 274                      | 15.5                        | –       | –       |
| 77    | 333                      | 78.2                        | Yes     | –       |
| 79    | 288                      | 14.3                        | –       | –       |
| 80    | 374                      | 20.5                        | –       | –       |
| 83    | –                        | 14.9                        | –       | –       |
| 89    | 303                      | 14.3                        | –       | –       |
| 90    | 324                      | 13.7                        | –       | –       |
| 92    | 332                      | 139.8                       | Yes     | –       |
| 93    | 373                      | 20.5                        | –       | –       |
| 95    | 274                      | 81.6                        | Yes     | –       |
| 96    | 274                      | 18.7                        | –       | –       |
| 97    | 305                      | 19.6                        | –       | –       |
| 98    | 321                      | 14.7                        | –       | –       |
| 99    | 337                      | 58.9                        | Yes     | –       |
| 100   | 307                      | 15.4                        | –       | –       |
| 102   | 317                      | 25.3                        | ?       | –       |
| 103   | 388                      | 106.7                       | Yes     | –       |
| 104   | 342                      | 18.4                        | –       | –       |
| 105   | 273                      | 37.7                        | –       | –       |
| 107   | 303                      | 23.9                        | –       | –       |
| 113   | 397                      | 93.3                        | Yes     | –       |
| 114   | 393                      | 23.2                        | –       | –       |
| 116   | 373                      | 32.6                        | –       | –       |
| 118   | 301                      | 31.6                        | –       | –       |
| 119   | 332                      | 44.7                        | Yes     | –       |
| 120   | 282                      | 21.8                        | –       | –       |
| 130   | 287                      | 13.2                        | –       | –       |
| 133   | 280                      | 15.4                        | –       | –       |

flank of the emission line (e.g. Auer & van Blerkom 1972), others to the presence of a blueshifted P Cygni absorption, diminishing the blue flank of the emission profile (e.g. Bartzakos et al. 2001). Hillier (1989), on the other hand, explains the observed redshift by radiative transfer effects in optically thick lines.7

Both Foellmi et al. (2003b, their fig. 8) and Bartzakos et al. (2001, their fig. 8) reported a negative correlation between the linewidth [full width at half-maximum (FWHM)] and the measured systemic velocities, showing that broader lines better reflected the true systemic (i.e. LMC) velocity. However, after combining the data sets for the WNL and WNE stars, we found that to the contrary, there is a positive correlation between the linewidth and the measured systemic velocities; the combined data are shown in Fig. 8. Furthermore, we have binned stars to certain FWHM ranges, and calculated the bin mean systemic velocity and its error. The results are listed in Table 11. Indeed it seems that only the most narrow-lined WNL stars (FWHM $\lesssim$ 500 km s$^{-1}$) do correctly reflect the systemic velocity of the LMC, whereas broader lined stars, i.e. those with optically thicker winds, on average yield redder systemic velocities, in line with Hillier’s (1989) explanation. Note that contrary to what Foellmi et al. (2003b) reported, the measured systemic velocities for stars with FWHMs broader than 500 km s$^{-1}$ remain essentially constant at $\sim$330 km s$^{-1}$, rather than to converge again towards the true LMC value.

Two interesting cases, BAT99-55, a constant star, and BAT99-12, a binary, are marked in Fig. 7 with their names. These stars have systemic velocities which are quite different from the systemic velocity of the LMC, 146 km s$^{-1}$ (BAT99-55) and 650 km s$^{-1}$ (BAT99-12; circular orbit assumed), respectively. Thus, these stars are excellent runaway candidates (for a definition of runaway stars, see Blaauw 1961). Moreover, Massey et al. (2005) report a systemic velocity of 430 km s$^{-1}$ for BAT99-12, obtained from absorption lines in their better resolved spectra, confirming its high systemic velocity; our much larger velocity is most likely an artefact due to the mentioned P Cygni absorption in the blue flank of the He II $\lambda$4686 emission line. The runaway nature is another property that BAT99-12 shares with its Galactic counterpart, the O4Inf star $\zeta$ Pup.

7 We are indebted to the anonymous referee for pointing this out to us.

![Figure 7. Histogram of mean systemic velocities of our program stars as measured by Gauss fits to the He II $\lambda$4686 emission line. The dashed vertical line indicates the expected systemic velocity of the LMC, 280 km s$^{-1}$.](https://academic.oup.com/mnras/article-abstract/389/2/806/973686)

![Figure 8.](https://academic.oup.com/mnras/article-abstract/389/2/806/973686)

**Table 10.** Average systemic velocities for different WN samples in the LMC, as observed in this paper (WNL, including the O3f/WN6 stars) and by Foellmi et al. (2003b; WNE). Values are in km s$^{-1}$.

| Subsample                   | RV$_{sys}$ |
|-----------------------------|------------|
| WNL, all                    | 314 ± 10   |
| WNL, no binaries, no runways| 305 ± 7    |
| WNE, all                    | 345 ± 6    |
| WNE, no binaries, no runways| 353 ± 6    |
| WN, all                     | 334 ± 5    |
| WN, no binaries, no runaways| 338 ± 5    |
| LMC                         | 280 ± 20   |

![Table 11.](https://academic.oup.com/mnras/article-abstract/389/2/806/973686)
Figure 8. Mean systemic velocities plotted against the FWHM (in velocity units) of He II λ4686 emission line for the WN stars in the LMC. Triangles denote the 41 WNL stars, lozenges denote the 61 WNE stars. Filled symbols are identified binaries. The dashed line indicates the systemic velocity of the LMC (~280 km s⁻¹). For clarity, error crosses have been omitted, but a typical error cross (±eom = ±σ/√N) is shown in the upper right-hand corner. Most stars have larger systemic velocities than the LMC, and the star-to-star scatter is significant. The two runaway candidates, BAT99-12 and BAT99-55, have been omitted for this graph so that the y axis is not unduly compressed. See text for more details.

4.7 Mean spectra and spectral types

Spectra from individual observatories were concatenated to obtain an average, high-S/N spectrum. To verify the spectral types listed in the BAT99 catalogue, the classification criteria of Smith, Shara & Moffat (1996; hereafter SSM96) were applied. In most cases, the change in spectral type was only very minor; results are listed in Table 12. The most important change is BAT99-92, which is also a confirmed binary. This star is listed as WN6 (cf. Moffat & Seggewiss 1986), but closer inspection of the spectrum reveals that BAT99-92 is hotter. However, its true spectral type is very difficult to determine because of the dominating B supergiant system. We tentatively assign a WN3:(b+(O)+)B1Ia type to this system.

We have also measured both the FWHM and the equivalent width (EW) of the He II λ4686 emission line (see Table 12), with their standard deviations of the time-series σEW as errors. Both for crowded stars, whose dilution depends on seeing or slit-positioning, and for weaker lined stars such as O3IIf/WN6 stars, σEW can be rather large. FWHMs, however, remain unaffected by dilution effects, with measurement errors of the order of 10–15 per cent in all cases. Of course, some stars might be intrinsically variable, but an in-depth study of the line-variability phenomenon and its underlying causes is a very complex task and beyond the scope of the present paper. Results of such a study are planned for a future paper.

Many of our program stars still contain residual hydrogen, and some are even expected to be still in the CHB phase. The main indicator for the presence of H in the WR spectrum is the alternating He II Pickering decrement. If not stated otherwise, nebular lines did not hamper the spectral classification. In the 30 Dor region, however, the alternating Pickering decrement of helium lines suffers considerably from nebular pollution, and the determination of the H content remains (very) uncertain; such subtypes feature a ‘-’ (or even ‘::’) to indicate this uncertainty. Note also that the un-subtracted nebular emission leads to partially filled-up absorptions. Together with our relatively low spectral resolution, which affects narrower absorption lines more than broader emission lines, some O3If/WN6 stars, whose very weak He II λ4686 emission lines (small EWs) clearly distinguishes them from genuine WN stars (Walborn 1986), display an artificially attenuated absorption-line spectrum, thus favouring a (diluted) WN- rather than an O-star classification. Indeed, Massey et al. (2004, 2005) proposed the O2IIf classification for some of the O3IIf/WN6 stars using higher resolution data and applying the criteria of Walborn et al. (2002). Nevertheless, two hot splash-stars were reclassified into WN types, BAT99-80 (now WNSa:) and BAT99-105 (now WN7), based on the relatively large EW and the presence of a He II λ5411 emission. Their spectrum resembles that of genuine, yet diluted WN stars. In turn, BAT99-68 is listed as WN5-6 in the BAT99 catalogue, although it was classified as Of by SSM96. This star is located in a cluster; hence its spectrum is severely diluted. However, because of both the weak EW and the absence of a He II λ5411 emission line, we reclassify this star as Of/WN7, the WN part of the spectral type being based on the emission-line spectrum.

Regarding the Ofpe/WN9 or ‘cool slash-stars’, we did not reclassify them, since most of them have already been reclassified into WNO-11 by Crowther & Smith (1997), and we maintain this classification. The exception is BAT99-33 (R99), which has already been reported to show a peculiar spectrum that is inconsistent with a WR classification (see Crowther & Smith 1997 for more details). We thus maintain the Ofpe/WN in Table 12, but add a ‘?’. In the case of BAT99-107, which is listed as WNL/Of, we change the spectral type to WN9h::a.

A montage of the (re)classified, mean spectra of each of our program stars are displayed in Fig. 9. Note that for stars in the 30 Dor region, nebular lines have been clipped; thus, in some spectra, the Hβ and Hγ lines are truncated.

4.8 Analysis of the X-ray data

Chandra and ROSAT archives were searched for X-ray emission from the WNL stars in the LMC. We first extracted Chandra ACIS X-ray images in the 0.3–7.0 keV energy band, and ROSAT PSPC and HRI images in the full energy range of these instruments, i.e. 0.1–2.4 keV for the PSPC and 0.1–2.0 keV for the HRI. We then compared these X-ray images with optical images extracted from

| FWHM (km s⁻¹) | 0–500 | 500–1000 | 1000–1500 | 1500–2000 | 2000+ |
|-------------|-------|----------|-----------|-----------|-------|
| N           | 10    | 16       | 16        | 40        | 17    |
| RV (km s⁻¹) | 281   | 335      | 333       | 335       | 332   |
| σ (km s⁻¹)  | 21    | 41       | 38        | 49        | 55    |
| eom (km s⁻¹)| 6.6   | 10.3     | 9.5       | 7.7       | 13.3  |
X-ray emission is detected in 15 WNL stars in the LMC, as indicated in Table 13. To confirm these detections, we defined source regions encompassing the X-ray sources at the location of the WR stars and appropriate background regions. The background-subtracted count number and count rates are also listed in Table 13. For two stars, BAT99-101/BAT99-102 and BAT99-116, the background-subtracted count number is large enough to render possible the analysis of their X-ray spectra. The spectral analysis has been performed adopting a single-temperature MEKAL optically thin plasma emission model (Kaastra & Mewe 1993; Liedahl, Osterheld & Goldstein 1995), and the photoelectric absorption model of Balucinska-Church & McCammon (1992) for the absorption along the line of sight. The chemical abundances of the X-ray-emitting gas and for the absorbing material have been set to 0.33 Z⊙. The best spectral fits indicate plasma temperatures of 0.9 ± 0.2 and 5.0 ± 1.0 keV and hydrogen column densities of (9 ± 2) × 10^{21} and (9 ± 2) × 10^{21} cm^{-2} for BAT99-101/BAT99-102 and BAT99-116, respectively. Further details of these spectral fits are provided by Guerrero & Chu (2008a,b). The X-ray luminosities in the 0.5–7.0 keV energy band of BAT99-101/BAT99-102 and BAT99-116 derived from these spectral fits are listed in Table 13. For the other 13 WNL stars detected in X-rays, their X-ray luminosities listed in Table 13 have been derived from their count rate, assuming that their X-ray emission follows a single-temperature MEKAL optically thin plasma emission model with a temperature of 1.6 keV and a hydrogen column density of 3 × 10^{21} cm^{-2} (Guerrero & Chu 2008a,b).

For the WNL stars undetected by Chandra and ROSAT observations, we have derived count rate 3σ upper limits (see Table 13) using source regions with radii matching the point spread function of each observation. These limits assume the same single-temperature MEKAL optically thin plasma emission model as above.

4.8.1 X-rays and binarity

As can be seen from Table 13, Chandra ACIS is more sensitive than ROSAT’s instruments; the latter does not yield a single detection of our program stars. We will therefore concentrate on the Chandra data for most of our discussion.

Chandra observed 25 of our 41 program stars, detecting 15 sources. WR + O binaries are expected to be bright X-ray sources because of the high-energy WWCs occurring in such systems (e.g. Prilutskii & Usov 1976). Indeed, phase-dependent profile variations of the He II 4686 emission line are readily observed in our binaries (not shown here, but see Foellmi et al. 2003b and Bartzakos et al. 2001). However, of the seven binaries observed, only five are detected, two of which, BAT99-99 and BAT99-119, are long-period binaries. Two binary systems, BAT99-95 and BAT99-113, were missed, with BAT99-95 apparently being a particularly faint X-ray source. One might suspect that short-period, close binary systems produce fewer observable X-rays, because the two winds have not yet reached their respective terminal velocities, and/or the self-absorption in the wind of generated X-ray photons might decrease the observable flux (see e.g. Owocki & Cohen 2001; Ignace & Gayley 2002). Longer period binaries, on the other hand, have larger orbital separations, so their winds are potentially faster and geometrically thinned, possibly decreasing self-absorption of the X-rays and resulting in larger observed X-ray fluxes. Along the same lines, one might also expect that binaries containing hydrogen-depleted WNb stars generate more X-rays because due to their higher mass-loss rates and faster winds, there is more wind momentum available.

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**Table 12.** Spectral types, EW and FWHM of the He II 4686 emission line of our program stars. Spectral types that have been changed by us are also given.

| BAT 99 | Spectral type | Spectral type (this paper) | EW (Å) | FWHM (Å) |
|-------|---------------|---------------------------|--------|----------|
| 12 O3If/WN6 | O3If/WN6 | −12.3 ± 1.6 | 17.9 ± 1.9 |
| 13 WN10 | WN10 | −2.7 ± 0.3 | 5.4 ± 0.7 |
| 16 WN11h | WN11h | −80.2 ± 1.3 | 12.7 ± 0.3 |
| 11 O6If | O6If | −4.6 ± 0.5 | 5.7 ± 0.7 |
| 25 WN6h | WN6h | −50.0 ± 1.5 | 13.1 ± 0.3 |
| 26 WN6h | WN6h | −74.0 ± 3.8 | 20.6 ± 2.0 |
| 33 Ofpe/WN9 | Ofpe/WN9 | −2.8 ± 0.7 | 7.6 ± 0.7 |
| 44 WN8h | WN8ha | −26.8 ± 1.0 | 9.0 ± 0.3 |
| 45 WN10h | WN10h | −7.2 ± 0.8 | 6.4 ± 0.4 |
| 54 WN9h | WN9ha | −0.5 ± 0.2 | 4.7 ± 1.5 |
| 58 WN6h | WN7h | −38.8 ± 1.3 | 12.1 ± 0.2 |
| 68 WN5-6 | Of/WN7 | −6.1 ± 1.5 | 10.0 ± 1.0 |
| 70 WN9h | WN9ha | −8.4 ± 0.6 | 6.0 ± 0.5 |
| 77 WN7 | WN7ha | −11.4 ± 3.1 | 15.0 ± 1.6 |
| 79 WN7+OB | WN7ha+OB | −26.0 ± 0.8 | 16.8 ± 0.8 |
| 80 Of/WN6 | Of/WN6 | −9.2 ± 1.5 | 24.3 ± 3.3 |
| 83 Ofpe/WN9 | Ofpe/WN9 | −65.8 ± 2.1 | 12.3 ± 0.7 |
| 89 WN7h | WN7h | −10.5 ± 3.0 | 16.1 ± 0.5 |
| 91 WN7 | WN6h:a | −13.5 ± 1.2 | 46.0 ± 3.6 |
| 93 O3If/WN6 | O3If/WN6 | −4.8 ± 0.5 | 8.6 ± 1.3 |
| 95 WN7h | WN7 | −84.6 ± 9.8 | 18.4 ± 1.1 |
| 96 WN8(h) | WN8 | −26.4 ± 6.0 | 10.8 ± 0.8 |
| 97 O3If/WN7 | O3If/WN7 | −6.2 ± 1.6 | 9.7 ± 1.1 |
| 98 WN6h | WN6 | −19.4 ± 6.2 | 19.9 ± 1.7 |
| 99 O3If/WN6 | O3If/W5ha | −4.1 ± 0.6 | 13.2 ± 1.5 |
| 100 WN6h | WN7 | −26.5 ± 3.6 | 14.4 ± 1.7 |
| 102 WN6h | WN6 | −21.5 ± 4.3 | 16.4 ± 2.0 |
| 103 WN6 | WN6 | −27.1 ± 5.7 | 24.8 ± 3.5 |
| 104 O3If/WN6 | O3If/WN6 | −4.2 ± 0.6 | 12.5 ± 1.5 |
| 105 O3If/WN6 | O3If/WN6 | −18.7 ± 5.2 | 14.9 ± 1.8 |
| 107 WNL/OI | WNL/OI | −1.7 ± 0.4 | 5.9 ± 0.7 |
| 113 O3If/WN6 | O3If/WN6 | −5.1 ± 1.6 | 15.6 ± 1.2 |
| 114 O3If/WN6 | O3If/WN6 | −3.5 ± 0.6 | 17.2 ± 1.5 |
| 118 WN5h | WN5h:a | −29.5 ± 6.5 | 26.0 ± 0.8 |
| 119 WN5h | WN5h:a | −60.0 ± 2.9 | 18.7 ± 0.9 |
| 120 WN9h | WN9h | −50.7 ± 4.1 | 17.3 ± 1.1 |
| 121 WN11h | WN11h | −5.0 ± 1.5 | 6.1 ± 0.3 |
| 122 WN9h | WN9h | −1.3 ± 0.2 | 4.9 ± 0.6 |
| 123 WN11h | WN11h | −1.1 ± 0.2 | 4.9 ± 0.6 |

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The Digitized Sky Survey (DSS). We identified each WR star in the optical images using the coordinates listed by BAT99, and then searched for X-ray emission at the location of the WR star.

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The Digitized Sky Survey is based on photographic data obtained using the UK Schmidt Telescope and the Oschin Schmidt Telescope on Palomar Mountain. The UK Schmidt was operated by the Royal Observatory of Edinburgh, with funding from the UK Science and Engineering Research Council, until 1988 June, and thereafter by the Anglo-Australian Observatory. The Palomar Observatory Sky Survey was funded by the National Geographic Society. The Oschin Schmidt Telescope is operated by the California Institute of Technology and Palomar Observatory. The plates were processed into the present compressed digital form with the permission of these institutes. The Digitized Sky Survey was produced at the Space Telescope Science Institute under US government grant NAGW-2166.
In order to test these speculations, we combined our data with those of Foellmi et al. (2003b) and plotted the observed X-ray flux versus the orbital period (Fig. 10). Non-detections of both Chandra and ROSAT are given with their upper limit, by downward-pointing arrows. As can be seen, there is no readily apparent trend in the data which could support that longer period or WNb binaries indeed do display larger X-ray fluxes than shorter period systems or such which contain WR stars with lower mass-loss rates. However, more data might help to clarify the situation.

Interestingly, BAT99-99 is X-ray brighter than BAT99-119, but this could be due in part to the large eccentricity ($e \sim 0.7$; Schnurr et al., in preparation) of BAT99-119. It is thus not unlikely that Chandra missed the moment of maximum X-ray luminosity for BAT99-119 during periastron passage. Note however that the
circular orbit which was assumed for BAT99-99 might be incorrect, and that this binary is eccentric, too. In fact, both systems merit a closer look for orbit-related X-ray variability.

4.8.2 X-rays in apparently single stars

Of the remaining 10 stars detected by Chandra, four have X-ray luminosities which are comparable to those of the confirmed binaries although they do not show RV variability: BAT99-79, BAT99-80, BAT99-93, BAT99-100. Six do display RV variability: BAT99-101/BAT99-102, BAT99-105, BAT99-107, BAT99-114, BAT99-116 and BAT99-118. Crowding might account for the recorded high X-ray fluxes, and there still is the possibility that the X-rays originate in single WR stars due to radiatively induced instabilities in their winds (Lucy & White 1980; Willis & Stevens 1996). It can however not be ruled out that these stars are long-period (\( P > 200 \) d) binaries or systems with very low inclination angles.

Two detected sources, BAT99-101/BAT99-102 and BAT99-116, are extremely luminous. BAT99-101/BAT99-102 are two visually very close stars, and thus Chandra’s aperture integrated the combined flux. BAT99-101 is a WC4 star (Bartzakos et al. 2001) and potentially a binary (Bartzakos et al. 2001), while for BAT99-102, there is some confusion. As detailed above, we find that BAT99-103 is the 2.76-d binary, not 102, as was reported by Moffat (1989). However, even if 102 is single, there might be sufficient wind momentum confined in a very small volume, and if both 101 and 102 are binaries, then there most certainly is enough WWC occurring to account for the observed X-ray flux.

BAT99-116, on the other hand, is visually isolated enough not to be subject to such ambiguities. BAT99-116 is even more X-ray luminous than the combined BAT99-101/BAT99-102 system, and comparable to the X-ray brightest WR stars known, the Galactic WN6ha stars NGC 3603-C (Moffat et al. 2002) and WR25 (Seward & Chlebowsk 1982). Both NGC 3603-C (Schnurr et al. 2008) and WR25 (Gamen et al. 2006) have been identified as binaries, and they both contain two of the most luminous WN stars known, so that there is a plausible explanation as to why these objects are so X-ray bright. However, although 116 displays significant RV variability (Section 4.3), no indication of binarity could be found. Unless the photometry published by BAT99 is wrong, 116 is not particularly optically bright, either, ~1.5 mag fainter than BAT99-119, which is a confirmed binary. Since both stars are similar enough (WN5ha for 116, and WN6ha for 119; see above) to have the around same bolometric correction (no reddening considered, but it is low and probably about similar for the two stars anyway), 116 is considerably less luminous and hence less massive than 119. Thus, if 116 is indeed single, its ratio \( L_v/L_{bol} \) is abnormally high, but if X-rays originate from WWCs in a binary, the question remains how such faint objects (the total mass has now to be split between two

![Figure 9 – continued](image-url)
stars) can provide the required wind momenta. This very intriguing system merits a closer look.

As to BAT99-118, the sheer bolometric luminosity of the object (Crowther & Dessart 1998) renders a two-star scenario more likely. BAT99-118 closely resembles 119 in terms of both spectral type and X-ray luminosity (the latter is, in fact, equal within the errors). It is thus possible that BAT99-118 will turn out to be a long-period binary as well, especially given the fact that it also shows a significantly large RV scatter.

5 DISCUSSION

5.1 Binary detectability and completeness

Before we can discuss the binary frequency among WNL stars in the LMC, we have to address the question of how many binaries we missed. To do so, let us consider some general aspects of binary detection. Most approaches dealing with how to detect a binary through RV variations are based on statistical tests which compare the observed RV scatter $\sigma_{RV}$ of a binary candidate to the (Gaussian) scatter of an observed, constant comparison star (via a $\chi^2$ test), just as we have done in Section 4.3. How large does the RV amplitude of a given binary have to be so that it can be identified as an RV-variable star? The RV amplitude $K_{RV}$ of the WR is given by

$$K_{WR} = 212.7 M_0 / (M_{WR} + M_0)^{2/3} \cdot P^{-1/3} \cdot (1 - e^2)^{-1/2} \sin i,$$

where $K_i$ is in km s$^{-1}$, all masses in $M_\odot$, and $P$ in days. For a circular orbit ($e = 0$) and continuous sampling, the RV scatter is $\sigma_{RV} = K / \sqrt{2}$, and it has to be larger than some detection threshold $\sigma_{cut}$ for the star to be considered as significantly variable. In Section 4.3, we defined the 99.9th percentile to be $\sigma_{cut} = 22.6$ km s$^{-1}$. 

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It can clearly be seen that all binaries are well above our detection threshold, and that we should in principle be able to see evolved WN stars with periods somewhat longer than 100 d. In particular, there is no reason why we should not be able to see systems with periods between 5 and 90 d, of which there is an apparent lack in our study. To miss these systems, their inclination angles would have to be extremely low. However, as Foellmi et al. (2003a) have shown, in a sample with randomly distributed inclination angles there are 6.5 times more binaries between 90° and 30° than there are between 30° and 0°; thus, it is very unlikely that there is a significant number of low-inclination systems in our sample, in particular if these harbour evolved (i.e. lower mass) WN stars, which are the primary focus of our study.

Let us further note that, while from our RV data alone, we were not able to detect the binary nature of BAT99-119, because its period of ∼160 d is too long and its orbit is too eccentric, we did detect its large RV scatter, which firmly puts it above our variability threshold. We were also able to identify BAT99-99’s period of ∼92 d and even obtain an orbital solution (albeit a preliminary one), despite the fact that this O3f/WN6 star is an unevolved object, too, and thus more massive than its companion.

Thus, we can be quite confident that systems with periods between 5 and 90 d are indeed absent in our program stars, and that we are quite complete for evolved WN binaries with periods up to 200 d. Of course, this estimate of our detection limits is very rough, because elliptical orbits and discrete sampling will modify the individual detection limit of a binary system. Since we have also searched for periodicities in our RV data, the problem of binary detection is shifted into the realm of Fourier statistics. (Note, however, that cyclical variability in the RV data is a necessary, but not a sufficient condition for binarity, because rotation or pulsation could induce a periodically variable RV pattern.) In this case, the whole situation becomes more intricate, since not only the total time-span T covered by observations compared to the systemic periods P becomes important, but also the distribution of data points in phase. Detection limits do not directly depend on the ratio of the RV amplitude K of the primary star (the signal) to the measurement error σ (the noise) in data space, but on the S/N achieved in the frequency domain.

At a given number of data points covering a certain time-span, short periods generally have a large T/P and better ‘phase-filling’, and therefore have a larger detection probability than longer periods which suffer from holes in the phase coverage and a lower S/N per frequency unit. Vice versa, the same detection probability as for longer periods can be obtained for shorter periods but lower RV amplitudes, which means that low-K (low-inclination) binaries with a given K tend to be detected more easily if they are short-period.

In the case of non-circular orbits, the eccentricity, the orientation of the orbital ellipse and the time of periastron passage seriously affect the detection probability of periods for two reasons. First, the orbital RV curve becomes distorted in a way that generates harmonics in the Fourier spectrum. Power is transferred from the fundamental to the harmonics, thereby lowering the peak of the fundamental frequency. If the orbit is highly eccentric, the fundamental peak might be pushed into the noise floor, and the period will not be detected. Secondly, the distribution of the data points over the orbital phase is even more critical, because the star spends most of the time near apastron; if the passage of periastron, where the RVs change rapidly, is missed, the RV curve will look flatter than it really is. This is a problem for any σRV-based statistics in velocity space, because it is possible that observed RVs display cyclical variability...
in the sense that a period has been found, although the observed RV scatter is not significantly large.

The standard approach to deal with this problem is a Monte Carlo simulation of a population of artificial binaries by randomly drawing orbital parameters following a pre-determined distribution function, and applying the desired test statistics in RV and/or frequency space, or by actually full Keplerian fitting; for reasons of convenience and computational expense, usually only the former is done. From the detected fraction of artificial binaries, one can reconstruct the true binary frequency among the artificial sample by statistical means. [For an excellent description of this approach and all related problems, see Kouwenhoven (2006).]

The main problem, however, is to determine reasonable distribution functions for the respective orbital parameters, because the results of the simulation will obviously depend strongly on what initial assumptions were made for the underlying, true binary population. For their WNE stars in the LMC, Foellmi et al. (2003b) used distribution functions for Galactic O stars (based on statistics published by Mason et al. 1998; also see references therein); they found that 35 per cent of the binaries in their sample were missed. For our study, the most relevant assumption Foellmi et al. used was that the orbital periods $P$ are distributed flat in log $P$, i.e. there are as many binaries between 1 and 10 d as there are between 10 and 100 d, etc. In our WNL sample, we have found eight binaries with periods shorter than 100 d. Of these eight binaries, only one, BAT99-99, has a period between 10 and 100 d; the remaining seven binaries have periods ranging between 1 and 10 d. Thus, without any sophisticated Monte Carlo simulation, we can immediately determine that we would have missed six binaries in the period range from 10 to 100 d, but of course only if we believed that we are complete in the period range from 1 to 10 d and that our chosen period distribution is correct.

But how sound is this assumption? Indeed, the distribution function for pre(RLOF), O + O binary periods is not suited for statistics of post-RLOF populations, when one of the model predictions is that orbital periods change due to binary interaction. Clearly, however, any other choice of distribution function would produce a different result. Moreover, our analysis above indicates that it is unlikely that we missed binaries between 5 and 90 d, and of course one must not forget that we operate with small numbers. Thus, even if we had a way to obtain the true number of expected binaries from the number of observed binaries, we would have to show first that the observed number is statistically not consistent with the expected value; otherwise, any correction would not be justified. Because of those severe imponderabilities, we cannot carry out any statistical correction, but consider the number of binaries that we have found as a lower limit only. We will also consider that, whatever the detection bias is, Baratzakos et al. (2001), Foellmi et al. (2003b) and this paper suffer from it in roughly the same way, given that we have carried out more or less the same kind of observations. In regard to the achieved RV precision, one can argue that the somewhat better precision obtained in this study is compensated by the fact that classical WNL stars are expected to be, on average, more massive than WNE and WC/WO stars, because they had less time to shed mass by stellar winds; thus, RV amplitudes of WNL binaries will, on average, be somewhat smaller than those of WNE and WC/WO binaries. Since neither of the three studies used a more sophisticated detection threshold than the RV scatter of (presumably) constant, reference stars, we feel that all three studies have around the same detection probability for periods up to $\sim$200 d. Thus, we consider the three studies to be directly comparable.

5.2 The binary frequency among the WNL stars in the LMC

The present survey encompassed all 41 WNL stars listed in the BAT99 catalogue outside R136. The remaining six WNL stars in the core of R136 required higher spatial resolution, e.g. AO-assisted spectroscopy with VLT/SINFONI; the work is in progress and results will be published elsewhere (Schnurr et al., in preparation), but preliminary results indicate that there is no short-period ($P \lesssim 20$ d) binary among those stars. Foellmi et al. (2003b) reclassified one of their program stars, BAT99-78, to WN6 (i.e. to WNL); in turn, one of our stars, BAT99-92, was recognized to be an early-type WN3b star (cf. Section 4.7). Thus, the respective numbers of WNE and WNL stars which have been studied remain unchanged. There are 47 WNL stars in the LMC.

In this study, we are only interested in binaries with periods up to $\sim$200 d. A binary counts as detected only if an orbital solution could be established. Using this criterion, eight stars have been recognized as binaries (cf. Table 14): BAT99-12, BAT99-32, BAT99-77, BAT99-92, BAT99-95, BAT99-99, BAT99-103, BAT99-113. By combining our RV data with those of Moffat (1989) and with unpublished polarimetry, a ninth binary, BAT99-119, was identified (Schnurr et al., in preparation). Moffat (1989) reported six binaries among the 14 WNL stars he had studied. Our study has added four previously unknown WNL binary systems to that list, and confirmed four known binaries and their orbital periods. One of Moffat’s (1989) binaries, BAT99-107, was however found to be a single star. From significantly large RV scatter, visual brightness or high X-ray luminosity, two additional stars, BAT99-116 and BAT99-118, qualify as binary candidates in the period range of interest (i.e. up to 200 d), while more stars might be binaries with (considerably) longer periods than that. With BAT99-32 being a WNE binary, the confirmed WNL binary frequency is $8/41 = 20$ per cent.

Interestingly, no binaries or RV variables can be found among the WN8,9 stars in our sample as a matter of fact, they yield the smallest RV scatter of our sample stars – whereas WN6,7 stars do show binaries among them. This seems to confirm the findings of Moffat (1989), who suspected that this dichotomy reflected deeper differences between WN6,7 and WN8,9 stars. He argued that Galactic WN8,9 stars tended to be single runaways (an observation that we cannot confirm from the systemic velocities measured for our WN8,9 stars in our sample), and that in the LMC, WN8,9 stars tend to avoid clusters, very much unlike WN6,7 star. While since Moffat’s conclusion still holds.

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**Table 14.** Known binaries among the WNL population of the LMC, where the O3f/WN6A stars have been counted. The improved period for BAT99-119 was taken from Schnurr et al. (in preparation).

| BAT99 | Period (d) | Spectral type | Comments |
|-------|------------|---------------|----------|
| 12    | 3.24       | O3f/WN6A      | New      |
| 32    | 1.91       | WN6(h)        |          |
| 77    | 3.00       | WN7(h)        |          |
| 95    | 2.11       | WN7           | New      |
| 99    | 92.60      | O3f/WN6-A     | New      |
| 103   | 2.76       | WN6           |          |
| 113   | 4.70       | O3f/WN6-A     | New      |
| 119   | 158.80     | WN6(h)        |          |
5.3 Comparison with WNE and WC/WO stars

Among the 61 WNE stars in the LMC, Foellmi et al. (2003b) reported only five certain binaries, two systems with unreliable orbital solutions (which we count as identified), and two potential binaries; we have added to this BAT99-92, so that the confirmed binary frequency among the WNE stars in the LMC is now 8/61 = 13 per cent. If one combines the results for WNE and WNL stars, one obtains 102 WN stars studied among which 8 = 16 are confirmed binaries; thus, the confirmed binary frequency is 16/102 = 15 per cent. Among the 24 WC/WO stars, Bartzakos et al. (2001) studied 23 and reported three confirmed binaries. The 24th star is very faint and thus likely single. While they also reported five potential binaries, even the one with the largest RV scatter, MG6, failed to be significantly (99 per cent confidence level) variable; therefore, we consider their remaining binary candidates to be constant as well. This brings the binary frequency among all WC/WO stars in the LMC to 3; thus, the binary frequency is 3/24 = 13 per cent. Values are quoted in Table 15. Note that the binary frequencies among the different subgroups (WNL, WNE and WC/WO) are statistically fully consistent with each other.

6 SUMMARY AND CONCLUSION

We have carried out spectroscopic monitoring of all 41 WNL stars in the LMC that could be observed by conventional, ground-based observations. Measured RV curves were used to identify binaries with orbital periods from 1 to ~200 d, because these systems were expected to be post-RLOF candidates (cf. Vanbeveren et al. 1998). Additionally, publicly available archive data from X-ray satellite missions were searched for our program stars to obtain X-ray luminosities. The results of our study can be summarized as follows (see also Table 14).

(i) We have identified four previously unknown binary systems: BAT99-12, BAT99-95, BAT99-99 and BAT99-113.

(ii) We confirmed the previously known binaries BAT99-32, BAT99-77, BAT99-92. However, while we could reproduce the 2.76 d period that Moffat (1989) had reported for star BAT99-102, we did so for star BAT99-103. It presently remains unknown whether Moffat (1989) or we wrongly identified the binary.

(iii) We also confirmed that BAT99-119 is a binary; however, we had to combine our RV data with those of Moffat (1989) to do so, and it required further combination with previously unpublished polarimetry to identify the 159 d period of the system. For reasons of completeness, we list the results here, but the complete study will be published elsewhere (Schurr et al., in preparation).

(iv) One star, BAT99-107, had been suspected binary by Moffat (1989), but we were unable to reproduce that results. Therefore, we consider 107 to be single (i.e. not a binary with an orbital period in the quoted range).

(v) Two binary candidates were identified from their RV variability and their X-ray luminosities, BAT99-116 and BAT99-118. Both systems merit a closer look, because 116 is one of the brightest X-ray sources among all WR stars, while 118 is the most luminous WR star and thus, the most luminous unevolved star known in the Local Group (cf. Crowther & Dessart 1998).

(vi) One of our program stars, BAT99-92, a binary, was recognized to be a WNE and not a WNL star.

(vii) Thus, our study brings the total number of known WN binaries to 8, and the binary frequency among WNL stars in the LMC to 20 per cent, which is fully consistent with the results for WC/WO stars (Bartzakos et al. 2001) and WNE stars (Foellmi et al. 2003b); thus, there is no statistically significant differences between different WR populations in the LMC. However, the overall binary frequency is only half of what was predicted from model results by Maeder & Meynet (1994). The implications of this low binary frequency for massive star evolution will be discussed in a forthcoming paper.

Remarkably, none of the WNL binaries contains a classical, hydrogen-deficient, helium-burning WR star; instead, the WN components are young, unevolved, objects (hot O3If/WN6 stars or more extreme WN5-7ha stars), which most likely are very luminous and hence very massive Of stars, and possibly even the most massive stars known. These binaries offer the tremendous opportunity to directly weigh these extreme stars using model-independent, Keplerian orbits. Follow-up observations have partly been obtained and are currently reduced, or are under way. The results of these observations will be published elsewhere.

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Table 15. Spectroscopic binary frequencies for three different subgroups in the LMC.

| Subgroup       | Frequency | References          |
|----------------|-----------|---------------------|
| WNL            | 8/41 = 0.20 | This paper          |
| WNE            | 8/61 = 0.13 | Foellmi et al. (2003b) |
| WNL + WNE      | 16/102 = 0.15 |                  |
| WC + WO        | 3/24 = 0.13 | Bartzakos et al. (2001) |
| WR all         | 19/126 = 0.15 |                  |

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