Wolf–Rayet binaries in the Magellanic Clouds and implications for massive-star evolution – I. Small Magellanic Cloud

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ABSTRACT
We have carried out an intensive spectroscopic campaign to search for binaries via periodic radial velocity (RV) variations among all the nitrogen-rich WN Wolf–Rayet (WR) stars in the Small Magellanic Cloud (SMC), and all WNE stars in the Large Magellanic Cloud (LMC). We present in this first paper the results for the SMC. Along with the results of Bartzakos et al. on the only carbon/oxygen-rich WR star (AB8, WO4+O4), the whole WR population of the SMC (11 stars) has now been investigated intensively for periodic RV variability. We have also retrieved time-dependent photometric data in the public domain from the OGLE and MACHO projects, and X-ray data from the ROSAT and Chandra archives, to provide additional constraints on the binary character. Contrary to theoretical expectations that predict a virtually 100 per cent binary frequency in the SMC, we find a normal (∼40 per cent) WR binary frequency in this galaxy. We also find the clear presence of hydrogen in the winds of the single WR stars in the SMC, even for the stars with an early spectral subtype. We discuss the possible reasons and implications of this for stellar evolution of massive stars in such a low-metallicity environment, e.g. the influence of rotation versus the necessity of a very high initial mass of the progenitors for single stars, and the possible past occurrence of Roche lobe overflow for binaries.

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

1 INTRODUCTION

Metallicity is a key parameter that influences the evolution of massive stars (Maeder 1991). Number ratios of different stellar populations are often used to test the influence of the initial ambient metallicity on the internal evolution of stars. One of the best examples is the number ratio of blue supergiants (BSG) to red supergiants (RSG), which is predicted to increase strongly as Z increases (see, e.g., the review of Langer & Maeder 1995). Models without rotation predicted no RSG in the Small Magellanic Cloud (SMC), although the observed RSG/BSG ratio in this galaxy is 10 times larger than that in our galaxy. Models with rotation, which tends to be enhanced at low Z (Maeder & Meynet 2001), seem to provide a good solution of this long-standing problem.

Wolf–Rayet (WR) stars also provide a very good test of the influence of metallicity on stellar evolution, since, as noted by Langer & Maeder (1995), their evolution mainly depends on the effects of mass loss, erasing most of the uncertain hydrodynamical processes involved in RSG and BSG evolution.

Most WR stars show little or no evidence of hydrogen in their spectra, and typically exhibit broad emission lines mainly of helium and nitrogen or carbon/oxygen. Therefore, these stars are thought to be the final stage in the evolution of massive stars (the well-known ‘Conti scenario’; Conti 1976; Maeder & Conti 1994), revealing the burning products of previous evolutionary stages, before they explode as supernovae. The broad, strong emission lines are the consequence of a strong and expanding hot wind, which can reach terminal speeds ranging from 1000 to 3000 km s−1 and mass-loss rates up to ∼10−4 M⊙yr−1.

Two sequences of single WR stars are defined based on the detection of broad emission lines of nitrogen or carbon and oxygen in their spectra. In the WN sequence, we distinguish between late-type (WNL = WN6–11) and early-type (WNE = WN2–5) stars. The former often show hydrogen in their spectra, in contrast to the latter, which are normally mostly depleted in hydrogen. WNE stars are usually hotter and less luminous than WNL stars. The second sequence, the WC/WO stars, shows enhanced abundances of carbon and oxygen, the burning products of helium. Since WC/WO stars are also less luminous and often even hotter than WNE stars, they are thought to be the last evolutionary stage of WR evolution.
These two sequences are also applied to binary stars with a WR component, although a possible interaction of the two stars in close binaries is expected to strongly modify this picture; one purpose of this work is to examine this question.

A very global evolutionary scheme can be drawn from an observational point of view. After a main-sequence stage (mainly as an O-type star), the star experiences a short, unstable intermediate stage (presumably as an active RSG and/or a luminous blue variable – LBV) of very uncertain duration and mass-loss rate, to finally evolve to the WR stage, principally characterized by strong helium and nitrogen emission lines. In this stage, heavier fusion products appear at the surface, as a consequence of the strong stellar wind. The star goes from WNL to WNE, to finally reach in most cases a WC stage before exploding as a supernova of type Ib or Ic (see, e.g., Langer & El Eid 1986).

From a theoretical point of view, after the core hydrogen-burning stage (identified as the main-sequence phase), the star evolves through a shell hydrogen-burning stage. For moderately massive stars, this leads to a large increase of the radius of the star, and therefore is identified as the RSG phase. For even more massive stars, the Eddington limit is expected to be surpassed, and the star experiences an LBV phase, preventing it from reaching the low surface temperatures of a true RSG. From both points of view (i.e. observation and theory), this stage (RSG or LBV) is crucial in short-period binary evolution. Either as an RSG or LBV, the star is expected to lose a large (but still poorly known) fraction of its H-rich envelope. Finally, the star enters a core helium-burning phase as a Wolf–Rayet star.

Mass loss is a consequence of momentum transferred from photons to ions at the stellar surface, so mass loss should be heavily dependent on the opacity of the surface ions and consequently on the initial and subsequent metal content of the star. Therefore, we can expect that in the Magellanic Clouds, and particularly in the Small Magellanic Cloud (SMC; \(Z = 0.002\)), the mass loss by stellar wind in single stars will be significantly reduced compared with that of a Galactic star \((Z \approx 0.02)\), in the solar neighbourhood, for the same initial mass. Radiatively driven wind theory predicts \(M \propto Z^{1/2}\) (Kudritzki et al. 1989). A higher metallicity implies stronger opacity, and therefore a stronger mass loss via stellar wind, revealing fusion products at the surface of the star sooner on an evolutionary time-scale. The star becomes rapidly less massive, favouring the WC/WO phase (Meynet et al. 1994). Lower metallicity on the other hand, leads to fewer WC/WO stars, as is clearly seen in both Magellanic Clouds, with a stronger effect in the SMC: with 11 WR stars in this very low-metallicity galaxy, 10 of subtype WN (see below) and only one is of subtype WC/WO.

Consequently, with significantly smaller metallicity than the solar neighbourhood, the MCs are the best targets to study these questions of how ambient metallicity and binarity affect the evolution of massive stars. Moreover, they provide a unique environment, with almost no gradient of \(Z\) throughout the galaxy, a unique distance and very low visual extinction.

An additional consequence of the opacity-driven mass loss is the dependence on \(Z\) of the minimum mass required to form a WR star from a single progenitor: 25 \(M_\odot\) for the Galaxy, 35 \(M_\odot\) for the LMC and 45 \(M_\odot\) for the SMC (Maeder 1998). Therefore, the number ratio of WR to O stars is also expected to depend on the initial metal content. Maeder & Meynet (1994) have shown that single-star evolution models cannot reproduce the various WR/O, WN/WC and WNL/WNE number ratios observed in the galaxies of the Local Group. They argued that an ad hoc mass-loss rate that is twice the ‘standard’ value is better suited to accounting for these ratios, although they stressed at that time that no clues were present to explain such a high mass-loss rate. Along with this enhanced mass-loss rate, they stressed that the binary channel is also needed to correctly account for the different number ratios. In this binary channel, the binary interaction (namely the Roche-love overflow – RLOF) allows the formation of a WR star from a progenitor with initial mass below the minimum mass required to form a WR star from a single progenitor. In situations of low metallicity, a large fraction of WR stars is therefore expected to be formed via RLOF, thus dramatically modifying the output WR population. Maeder & Meynet (1994) used an initial binary frequency of 8 per cent among O stars to reproduce adequately the number ratios discussed for different metallicities, although no limiting orbital periods or simulations of such interactions in close binary stars are presented.

Using the results for all galaxies in the Local Group studied by Maeder & Meynet (1994), Bartzakos et al. (2001) computed the binary frequency of WR stars for each MC. More precisely, one defines \(\phi = \frac{WR_{RLOF}}{O}\) as the number ratio of WR stars formed owing to RLOF to the total of O stars. As seen in fig. 11 of Maeder & Meynet (1994), a frequency \(\phi = 0\) underestimates the number ratio WR/O (\(= \frac{WR_{single}}{O} + \frac{WR_{RLOF}}{O}\)) for most of the galaxies in the Local Group. Assuming a linear interpolation between \(\phi = 0\) and 0.05 and taking a mean value for all of these galaxies, Bartzakos et al. (2001) found a ‘universal’ value of \(\phi = 0.021 \pm 0.006\). Therefore, an estimate of the binary frequency of the WR population for each galaxy may be found, following:

\[
WR_{RLOF}/WR = \frac{WR_{RLOF}/O}{WR/O}.
\]

Because new WR stars have been found in the MCs since the publication of these two papers (Morgan, Vassiliadis & Dopta 1991; Breysacher, Azzopardi & Testor 1999; Massey & Duffy 2001), we have updated the values found by Bartzakos et al. (2001). The results are summarized in Table 1. Since our main purpose is to study the Magellanic Clouds, we did not change the values for our Galaxy, which otherwise would deserve a more careful analysis because of the metallicity gradient. We should stress that the values in Table 1 give only an estimate of the binary frequency, since the discovery of new WR stars in most of the Local Group galaxies will increase the mean value of \(\phi\) computed above. This also means that this value of \(\phi\) is a lower limit of the binary frequency. Table 1 shows that a binary frequency of virtually 100 per cent is expected theoretically in the SMC.

We emphasize that these limits are strongly dependent on the exponent used in the relation between \(Z\) and the mass loss \(M\) rate. An exponent other than \(\frac{1}{2}\) would modify the values computed for the theoretical binary frequency, since it would influence the theoretical minimum mass of formation of WR stars. Nevertheless, what we want to show here is the significantly higher binary frequency expected theoretically at the metallicity of the SMC than that at solar metallicity. Therefore, the influence of metallicity remains whatever the exponent (unless it is equal to 0), although the 100 per cent value must be taken with caution.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>(Z)</th>
<th>(WR/O)</th>
<th>(WR_{RLOF}/WR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMC</td>
<td>0.002</td>
<td>0.021</td>
<td>0.98 ± 0.32</td>
</tr>
<tr>
<td>LMC</td>
<td>0.006</td>
<td>0.05</td>
<td>0.41 ± 0.13</td>
</tr>
<tr>
<td>Milky Way</td>
<td>0.02</td>
<td>0.104</td>
<td>0.20 ± 0.06</td>
</tr>
</tbody>
</table>


Table 1. Theoretical binary frequency for our Galaxy, the LMC and the SMC. See the text for details.
As discussed in Maeder & Meynet (1994), the ratio \( \phi \) can be divided into three parts, corresponding to the three subclasses of the WR sequences: WNL, WNE and WC. One extreme possibility is to suppose that the WR stars born in close binary systems are equally distributed in different subtypes (i.e. \( \phi_L = \phi_C = \phi_E = \frac{1}{3} \phi \)). This possibility is ruled out by the observations in the SMC. Indeed, if all WR stars in the SMC belong to binary systems, one would have an equal number of WNL, WNE and WC stars, which is not the case. Another extreme possibility is to suppose that the binary channel leads mainly to one given subtype. Since most of the WR stars in the SMC are WNE, we are inclined to believe that the situation looks more like \( \phi_L = \phi_C = 0 \) and \( \phi_E = \phi \). Furthermore, models of interacting massive binaries (see Section 4) show that for most binary systems, RLOF would occur during the expansion phase of the primary (i.e. the supergiant stage). Consequently, we expect that the hydrogen-rich envelope is mostly removed from the primary by RLOF and the star will appear more often as a WNE than as a WNL star. Therefore, among the different WR subtypes, the WNE stars are the best candidates for a past occurrence of the RLOF.

As noted at the beginning of this introduction, rotation is expected theoretically to have major effects on the evolution of massive stars (Maeder & Meynet 2001). In particular, the enhanced internal mixing and mass loss by stellar winds, during the main-sequence phase, make the formation of a WR star easier. Playing against the influence of \( Z \) on mass loss mentioned above, rotation, if present, reduces the minimum mass required to form single WR stars.

Many authors have argued that binary interaction is needed not only for massive star evolution, but can also explain other important issues: the space velocity distribution of single pulsars (e.g. de Donder & Vanbeveren 1999), black hole formation and supernovae (e.g. Wellstein & Langer 1999), starburst characteristics (e.g. Schaerer & Vacca 1998), age determination of starbursts (e.g. de Donder, Vanbeveren & van Bever 1997), OB runaways van Rensbergen, Vanbeveren & de Loore (1996). All of these reasons have accumulated over the years, waiting for a large spectroscopic survey of a complete WR population in a given galaxy of the Local Group. Although we will show in the next paper (Paper II) that the LMC is probably the best location to address these questions, the SMC also provides a relevant situation, since its even lower metallicity increases the sensitivity to the effects of metallicity on the evolution of massive stars, and strengthens the expected role of binaries, despite the small numbers.

We present here the results of a large spectroscopic campaign using various 2-m class telescopes (and a 4-m telescope for the faintest stars) to detect binaries via radial velocity (RV) variations mainly among the hotter WN stars (WNE = WN2–5) stars in the MCs. Combined with a similar study for the WC stars of Bartzakos et al. (2001), along with additional sources from the literature for known binaries, our study covers the whole WR population of the SMC. In the LMC, all WNE and WC stars are now investigated for binaries, and the results for this galaxy will be the subject of Paper II. To strengthen our discussion on the binary character of SMC WR stars we also retrieved publicly available photometric and X-ray data.

The present paper is organized as follows. In Section 2, we present the details of the observations and discuss the statistical analysis and calibration of our data sets. In Section 3 we present the different results for each WR star in the SMC in the three data sets: spectroscopic, photometric and X-rays. In Section 4 we discuss the combined results and clarify the situation of the WR population in the SMC. Section 5 gives a summary and our conclusions, which will be further developed in the paper dedicated to the LMC.

2 OBSERVATIONS

Our data for both MCs consist of: (i) a large spectroscopic campaign on various telescopes, (ii) photometric data retrieved from the OGLE and MACHO data bases and (iii) X-ray data from the ROSAT and Chandra satellites. We start by describing the spectroscopic data set, since it represents the core of this work. Radial velocity variations will be used as the prime indicator of the binary status. We will use the photometric and X-ray data to strengthen our assignment of the binary status.

2.1 The spectroscopic campaign

We carried out long-slit spectroscopy with low spectral dispersion to keep the exposure times reasonable, as the stellar visual magnitudes range from 12 to 17. 2-m class telescopes were employed for the brighter stars, while a 4-m telescope was used for the fainter ones. During each observing run we tried to obtain on average one spectrum for each star every two nights. Wavelength calibrations were taken before and after the object exposures in order to obtain reliable radial velocities.

The SMC sample consists of all the known WN stars (10 targets) and the LMC sample consists of all WNE stars, excluding the bright WN5h stars mainly in the 30 Dor region (61 targets, listed in Paper II). The LMC sample was divided into two subsamples: LMC I (36 stars) with magnitude \( V \leq 15 \) mag and LMC II (25 stars) with \( V > 15 \) mag. Over 1500 spectra were obtained on a total of 78 observing nights. Although the wavelength coverage differed from one run to another, we always kept the strongest emission line (He II \( \lambda 4686 \)) close to the centre of the wavelength range.

2.2 Observing runs

Our campaign consists of six observing runs on 2-m class telescopes and two runs on the 4-m CTIO telescope, over a total span of 3 years. Runs are grouped into ‘epochs’, since some of them are adjacent in time. The details of each run are given in Table 2. We discuss here the whole data set (i.e. including the LMC data), because the reduction and analysis of the SMC and LMC data taken as a whole were performed in the same manner.

Runs 1–4, which were exclusively dedicated to the SMC and LMC I samples, constitute the main body of our spectroscopic data set. The spectral dispersion was chosen as a compromise between radial velocity precision and securing sufficient time coverage of each star. Runs 3 and 6 had slightly higher spectral dispersion, because the corresponding grating had a more efficient throughput compared with the gratings with a dispersion equivalent to those used in other runs. To ensure completeness, run 5 at the 4-m CTIO telescope was dedicated to the fainter subsample in the LMC (LMC II). However, only four contiguous nights were allocated.

Since two WN stars in the original SMC programme were fainter than \( V = 15 \) (SMC-WR1, WR9) and two WN stars were discovered after the project was started (SMC-WR10 and WR11, Massey & Duffy 2001, see below), we devoted more time to them during the later runs. Therefore, runs 6 and 7 were dedicated partly to these SMC stars. These two runs have the same instrumental parameters as the previous runs. In order to strengthen our preliminary results both on these SMC stars and on LMC II stars, we obtained a pair of three contiguous nights separated by a week at the 4-m CTIO telescope (run 8). We chose a twice higher spectral dispersion.
2.4.2 RV measurements

Heliocentric radial velocities were measured using two different methods: bisectors and cross-correlation. It is essential to have two

(1 Å pixel$^{-1}$ instead of 1.6–2.5 Å pixel$^{-1}$, see Table 2) to increase our RV precision.

Although no standard RV stars were observed during runs 1–5, we observed two such stars during the last three runs in order to calibrate our RVs. Among the SMC binaries with a published orbit, we chose to observe SMC-WR6 intensively as a control star, i.e. to verify that we are able to recover a published orbital solution with our data (Hutchings et al. 1984). Since SMC-WR6 has a short period (∼6 d), we could cover more than one orbital period during the longest run (run 4, epoch 3; see Table 2).

Fig. 1 shows the signal-to-noise (S/N) ratio of each spectrum versus the magnitude of the given star. This shows that most stars fainter than $V \sim 13$ have a similar S/N $\sim 50$, while brighter stars were easily observed with higher values. Experience shows that for spectra with strong emission lines such as WR stars, a S/N ratio $\geqslant 15$ is the minimum necessary for measuring RVs in most cases.

Besides adequate spectral resolution and S/N ratio, the key parameter to find spectroscopic binaries is time coverage. The third epoch provides the best time coverage since we obtained observing time at CASLEO, followed immediately with SAAO, each of these two runs being split into two parts. A total interval of approximately 40 d was obtained for this epoch, with 28 nights of observation. SMC stars observed during epoch 4 have a total time coverage of approximately 49 d, but with a smaller number of observing nights. Run 8 provides a 12-d time coverage with higher RV precision for the SMC and LMC II subsamples.

2.3 The SMC sample

The SMC contains 11 known WR stars, which comprise presumably an essentially complete sample, although two stars were found only recently by Massey & Duffy (2001) (see their discussion of completeness). Table 3 gives the identifications, coordinates, $v$ magnitudes and spectral types (see Section 3.8). Throughout this paper, we also use their nomenclature, which respects previous numbers but does not follow the more normal scheme of names increasing with right ascension. A homogeneous set of finding charts of the 11 known WR stars in the SMC can be found in Massey & Duffy (2001).

Our sample includes all 10 WN stars in the SMC. We observed intensively SMC-WR1, WR2, WR3, WR4, WR6, WR9, WR10 and WR11. Since WR5 and WR7 are known binaries, we obtained only a few spectra for these two stars in order to gain a homogeneous set of spectra for all 10 known WN stars in the SMC.

2.4 The data

2.4.1 Reduction

All spectra were extracted and reduced using standard IRAF tasks. A set of spectral continuum windows was defined individually for each star, and used to rectify the spectra. Special care was taken to homogenize all the relevant information in the headers of the files, since each observatory provides different keywords. This ensures a reliable measurement of the heliocentric velocity, and the heliocentric Julian date.

2.4.2 RV measurements

Heliocentric radial velocities were measured using two different methods: bisectors and cross-correlation. It is essential to have two
very different techniques such as this, given the fact that many WR stars show intrinsic line-profile variations that could influence the RVs.

The bisector method consists of measuring the centre of horizontal levels between the two wings of the line for a large number of levels (usually 100). Then we compute the simple mean of all the central values of these levels, and subtract from this mean the rest wavelength of the considered line. We avoid the extreme wings of the line because of the possible proximity with another strong emission line. The top can also be influenced by excess emission coming from different effects not related to orbital motion (e.g. the wind–wind collision (WWC) zone, if binary). Apart from a few special cases we always used a fraction of the line height comprised between 0.3 and 0.7 of the total height of the line (the peak of which is

Table 3. Wolf-Rayet Stars in the SMC.

<table>
<thead>
<tr>
<th>Star</th>
<th>Other ID</th>
<th>Ref.</th>
<th>α (J2000.0)</th>
<th>δ (J2000.0)</th>
<th>V</th>
<th>$M_v$</th>
<th>Spectral type</th>
</tr>
</thead>
<tbody>
<tr>
<td>SMC-WR1</td>
<td>AB1, AV2a</td>
<td>1</td>
<td>0:43:42.23</td>
<td>−73:28:54.9</td>
<td>15.14</td>
<td>−4.6</td>
<td>WN3ha</td>
</tr>
<tr>
<td>SMC-WR2</td>
<td>AB2, AV39a</td>
<td>1</td>
<td>0:48:30.76</td>
<td>−73:15:44.7</td>
<td>14.23</td>
<td>−5.2</td>
<td>WN5ha</td>
</tr>
<tr>
<td>SMC-WR3</td>
<td>AB3, AV60a</td>
<td>1</td>
<td>0:49:59.45</td>
<td>−73:22:13.6</td>
<td>14.48</td>
<td>−5.1</td>
<td>WN3h+O9:</td>
</tr>
<tr>
<td>SMC-WR4</td>
<td>AB4, AV81, Sk 41</td>
<td>1</td>
<td>0:50:43.06</td>
<td>−73:27:07.8</td>
<td>13.35</td>
<td>−6.2</td>
<td>WN6h</td>
</tr>
<tr>
<td>SMC-WR5</td>
<td>AB5, HD5980</td>
<td>1</td>
<td>0:59:30.62</td>
<td>−72:09:10.2</td>
<td>11.08</td>
<td>−8.9</td>
<td>WN6h</td>
</tr>
<tr>
<td>SMC-WR6</td>
<td>AB6, AV332, Sk 108</td>
<td>1</td>
<td>1:03:25.73</td>
<td>−72:06:46.8</td>
<td>12.30</td>
<td>−7.1</td>
<td>WN4+:O6.5I:</td>
</tr>
<tr>
<td>SMC-WR7</td>
<td>AB7, AV336a</td>
<td>1</td>
<td>1:03:36.62</td>
<td>−72:03:20.7</td>
<td>12.93</td>
<td>−6.8</td>
<td>WN4+O6(f)</td>
</tr>
<tr>
<td>SMC-WR8</td>
<td>AB8, Sk 188</td>
<td>1</td>
<td>1:31:04.29</td>
<td>−73:25:03.9</td>
<td>12.81</td>
<td>−6.6</td>
<td>WO4+O4V</td>
</tr>
<tr>
<td>SMC-WR9</td>
<td>MG9</td>
<td>2</td>
<td>0:54:29.30</td>
<td>−72:44:34.1</td>
<td>15.23</td>
<td>−4.3</td>
<td>WN3ha</td>
</tr>
<tr>
<td>SMC-WR10</td>
<td></td>
<td>3</td>
<td>0:45:28.78</td>
<td>−73:04:45.2</td>
<td>15.76</td>
<td>−3.6</td>
<td>WN3ha</td>
</tr>
<tr>
<td>SMC-WR11</td>
<td></td>
<td>3</td>
<td>0:52:07.36</td>
<td>−72:35:37.4</td>
<td>15.7:</td>
<td>−4.8</td>
<td>WN4ha</td>
</tr>
</tbody>
</table>

References: (1) Azzopardi & Breysacher (1980), (2) Morgan et al. (1991), (3) Massey & Duffy (2001). Here we give our own spectral classification (apart from the star SMC-WR8, which is taken from Bartzakos et al. 2001). This classification, and previous ones from various authors, are discussed in Section 3.8. The apparent and absolute magnitude are taken from Massey & Duffy (2001). We use their values since they provide a uniform determination of $M_v$ for all SMC WR stars, although we note that different values were also found by Crowther (2000) (see Section 4). Originally, Massey & Duffy assigned a magnitude $v = 14.97$ to WR11, but it appeared clearly fainter in our observations. We estimate its magnitude between 15.5 and 16. The absolute magnitude has been corrected accordingly.
normalized to 1, the continuum being at 0). We always used the by far strongest line in the WR spectrum, He II $\lambda$4686. However, we tested the results with the next strongest, isolated, but significantly weaker line, He II $\lambda$5411, if present in the spectrum, and found consistent results, although with significantly larger uncertainties.

For the cross-correlation method, we grouped the data into runs 1–7 and run 8, since the latter has a ∼ twice higher resolution. In the following, ‘low resolution’ corresponds to the data of runs 1–7, and ‘high resolution’ to data of run 8. Before the computations, we subtracted unity from all the spectra (leading to a continuum at 0), in order to avoid any problem of apodization.

First, we defined, for each star individually, a region of correlation centred around the line He II $\lambda$4686. This region may differ significantly from one star to another, depending on the presence or not of useful and well-defined lines above the noise that occur around He II $\lambda$4686.

We measured RV shifts using the spectrum with the highest S/N ratio as a template. For low-resolution spectra, this template was chosen from the SAAO run 4, since this run has the best quality. Some SMC stars were not observed during this run (SMC-WR5, WR7) and therefore have a template chosen from SAAO run 2. For the high-resolution spectra, we chose a template in the run 8 data.

For a given star and a given resolution (low or high) we measured the RV shifts using the IRAF task FXCOR. Then, we shifted back all the spectra to the same rest wavelength, using the results of the cross-correlation. We then defined 3 regions free of lines in the spectra, from which we computed the S/N ratio. Finally, we calculated a mean spectrum, weighted by the corresponding S/N ratios. We then recomputed new RVs with the same task, using this weighted mean spectrum as a new template.

As a result of this way of combining the spectra, the weighted mean spectrum has the highest dispersion available based on the spectra it was computed from. During the cross-correlation, this reference spectrum was rebinned (as an option of the IRAF task FXCOR) to that of the object spectrum (and not the opposite: the object spectrum rebinned to the dispersion of the template). This method ensures that for spectra with a lower dispersion than that of the template, information is not artificially created. We used the bisector method to measure the centre of the He II $\lambda$4686 line in the template spectrum, thus providing an absolute RV for each spectrum.

This iterative method was used for each star. The S/N ratio of the final mean template is generally between 150 and 300 per pixel, in the continuum. This method has the advantage of being less sensitive to any line-profile variations, because they tend to be averaged out in the mean spectrum. We also performed a second iteration, using the new RVs to shift all the spectra to the rest wavelength, and computed a second and better template. This task was performed on a few stars and appears not to increase our precision significantly, so was deemed unnecessary for the remaining stars. When compared, RVs from the bisectors and cross-correlations give consistent results, although the bisector method leads to larger uncertainties. In the following sections, the RVs presented are always those obtained from the cross-correlation method.

### 2.4.3 Poor quality data

An overall inspection of each spectrum was made in order to detect poor quality data that could compromise the final results. We have thus removed a few spectra according to the following criteria: (i) a cosmic ray is found on the He II $\lambda$4686 line; (ii) the S/N ratio is less than 15; and (iii) the spectrum is diluted by the presence of a bright but visually separated companion owing to bad seeing.

The first nights of runs 2 and 4, both from SAAO, appear to have poor wavelength calibrations for most of the stars observed during these nights, leading to systematically larger RVs by approximately 70 km s$^{-1}$ compared with the mean RVs of the remaining run. A cross-check with calibrations of other SAAO nights provided no clues for the origin of this effect. All the spectra of these two nights were removed.

Among the 1547 spectra of our data set, 84 were removed (i.e. 5.5 per cent of the total).

### 2.5 Calibration of the data set

In order to maximize the time spent on the programme stars, no standard RV stars were observed during any of the first five runs. Systematic RV shifts between different runs are expected because of the use of different instruments at different telescopes. To determine these shifts, we used the numerous repeated spectra of constant-RV stars found a posteriori, as described below. This is an important step, since the binary status of many stars depends on the stability of the data from different observatories. Standard RV stars were observed during the final three runs.

#### 2.5.1 Runs 1–4: systematic RV shift between CASLEO and SAAO

A systematic shift between runs 1 and 3 at CASLEO is expected, because the instrument was upgraded in between these two runs, and also because different calibration lamps were used. We do not expect a noticeable shift between runs 2 and 4 at SAAO, however, since the instrument seemed very stable. We use run 4 (SAAO) as a reference, since it has the best quality and the largest number of spectra per star. Since we are primarily looking for periodic RV variations, we are not, in the first instance, interested in the absolute systemic velocities of the stars.

To correct the systematic RV shifts between these runs, we first isolated those stars in the list of the SMC and LMC I samples that were most likely to be single. More precisely, a few stars show very large RV variations (∼ 100 km s$^{-1}$), and were removed from the list. A few stars show repeated RV variations between 50 and 100 km s$^{-1}$, and were also removed from the list. Two LMC I stars (and only these two) have a very bright visual B-type supergiant companion. This causes the WR spectral lines to be very diluted and hence the RV measurements to be very uncertain. These two stars were therefore also removed from the list. The remaining list contains 29 reliable stars of constant RV.

For each star in this list, we computed its mean RV during run 4, and the difference between its RV for each night it was observed and the mean computed above. If all the stars in this list were perfectly constant and single and our measurements contained no systematic shifts between observatories, the RV differences for each star for each given night should be equal to zero. The result is displayed in Fig. 2 (upper panel), where the abscissa is the night number and the ordinate is the RV difference centred on 0.

Using the same list of stars, we computed the mean RV for each star individually, for each of the four runs, as long as the star has at least three spectra per run. Then we calculated the differences between runs 1–4. All the differences were then averaged, providing the systematic RV shifts between the runs and the observatories. The results are summarized in Table 4.

Not surprisingly, we found no significant systematic shift ($1.2 \pm 3.4$ km s$^{-1}$) between runs 2 and 4 made at SAAO. However, we obtained a systematic shift of $−36.7 \pm 3.2$ km s$^{-1}$ between run 3 and SAAO, and $−59.4 \pm 5.1$ km s$^{-1}$ between run 1 and SAAO.
Figure 2. Overall depiction of the quality of our data set for runs 1–4. The abscissa refers to night numbers; the ordinate refers to the difference between the RV of a star for a given night and the mean RV for run 4. Upper panel: the whole data set before correction of the systemic RV shifts. Bottom panel: the ‘reduced’ data set after correction.

Table 4. Stars and their mean RVs used to determine the systematic shifts between observatories for runs 1–4.

<table>
<thead>
<tr>
<th>Star</th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RV (km s(^{-1}))</td>
<td>σ (km s(^{-1}))</td>
<td>Δ(\text{run} \times \text{run} - 1) (km s(^{-1}))</td>
<td>Δ(\text{run} \times \text{run} - 2) (km s(^{-1}))</td>
</tr>
<tr>
<td>SMC-WR2</td>
<td>225.4</td>
<td>36.9</td>
<td>-49.6 ±15.4</td>
<td>181.5 ±26.2</td>
</tr>
<tr>
<td>SMC-WR4</td>
<td>243.8</td>
<td>35.3</td>
<td>-55.6 ±17.6</td>
<td>204.1 ±23.9</td>
</tr>
<tr>
<td>BAT99-7</td>
<td>367.5</td>
<td>24.5</td>
<td>-64.1 ±14.4</td>
<td>296.3 ±30.1</td>
</tr>
<tr>
<td>BAT99-17</td>
<td>323.5</td>
<td>26.3</td>
<td>-19.6 ±15.4</td>
<td>280.4 ±19.4</td>
</tr>
<tr>
<td>BAT99-21</td>
<td>400.6</td>
<td>20.7</td>
<td>-82.4 ±13.2</td>
<td>315.8 ±20.4</td>
</tr>
<tr>
<td>BAT99-26</td>
<td>358.1</td>
<td>46.3</td>
<td>-64.7 ±23.9</td>
<td>281.7 ±23.0</td>
</tr>
<tr>
<td>BAT99-47</td>
<td>350.1</td>
<td>35.2</td>
<td>-73.8 ±21.1</td>
<td>288.9 ±13.7</td>
</tr>
<tr>
<td>BAT99-50</td>
<td>355.8</td>
<td>53.4</td>
<td>-31.8 ±31.2</td>
<td>343.3 ±44.0</td>
</tr>
<tr>
<td>BAT99-67</td>
<td>413.5</td>
<td>22.9</td>
<td>-75.2 ±13.5</td>
<td>378.2 ±27.4</td>
</tr>
<tr>
<td>BAT99-117</td>
<td>459.9</td>
<td>39.1</td>
<td>-63.4 ±20.1</td>
<td>398.5 ±10.9</td>
</tr>
<tr>
<td>BAT99-122</td>
<td>385.7</td>
<td>17.4</td>
<td>-80.4 ±11.4</td>
<td>335.4 ±21.2</td>
</tr>
<tr>
<td>BAT99-131</td>
<td>408.1</td>
<td>20.5</td>
<td>-52.8 ±13.3</td>
<td>359.4 ±7.9</td>
</tr>
<tr>
<td>Averages:</td>
<td>-59.4 ±5.1</td>
<td>-1.2 ±3.4</td>
<td>-36.7 ±3.2</td>
<td></td>
</tr>
</tbody>
</table>

Notes: For each of the runs 1–4, the mean RV and its standard deviation (in km s\(^{-1}\)) are indicated. The differences (Δ), computed with run 4 as reference, and the corresponding standard deviation, are indicated for each of runs 1–3. The means of the differences are indicated in the final line. LMC names are taken from the BAT99 catalog (Breysacher et al. 1999).
Although run 1 has an overall inferior quality and a smaller number of spectra compared with the three other runs, we chose to keep this run anyway, in order to maximize the number of useful spectra per star for an eventual orbital solution. However, special care will be taken if RV variations are detected mainly caused by run 1.

All the RVs of runs 1 and 3 for all stars (in the SMC and LMC I subsamples, binary or not) were globally adjusted in RV accordingly to their respective systematic shifts. The results are shown in Fig. 2 (bottom panel). It is clear that all four data subsets are now in the same ‘rest frame’. We then computed the quality of our data set for each run, taking the standard deviation of all differences after correction shown in Fig. 2. We found $\sigma = 36.5, 28.7, 17.1$ and 17.8 km s$^{-1}$, respectively.

This procedure has a caveat: long-period binaries (with a period of hundreds of days) may certainly bias this correction. Nevertheless, we expect their influence to be small and thus not to compromise our calibration. This can be illustrated by the following example. For a binary with a (circular) orbit, with a period of 2 yr and an amplitude of $K = 40$ km s$^{-1}$, the difference of RV between one run and another run 1 yr later could be as much as 80 km s$^{-1}$. However, this would occur only if the times of the two runs correspond to successive quadratures of the orbit, i.e. when the WR star has a maximal/minimal velocity relative to the observer. In general, the star will be observed at two positions in its orbit different from quadrature and the amplitude of the velocity variation will be smaller. An inclination angle departing from 90° will also reduce this effect.

Therefore, we can expect with confidence that the influence of possible unrecognized long-period binaries has a negligible effect on the calibration of our data set.

### 2.5.2 RV calibration of runs 5–8 for SMC and LMC II data

While no standard RV star was observed during run 5, we did observe $\zeta$ Dor (= HD 33262, spectral type F7V) as a standard RV star during runs 6 and 7, and IC418 (= HD 35914, planetary nebula) during run 8. The RVs of $\zeta$ Dor and IC418 were computed following the identical method as for the WR stars. Their RVs appear to be stable and constant. A standard deviation of 19.1 and 6.2 km s$^{-1}$ was found for the two objects, respectively. The almost three times better quality of IC418 data is a result in part to the twice as high dispersion, and in part to narrow emission lines.

We performed the same procedure as described above to determine a systematic shift between runs 5 (CTIO 4 m), 6 (CTIO 1.5 m), 7 (SAAO) and 8 (CTIO 4 m). Although runs 6 and 7 have relatively few spectra (approximately 10 spectra each), no significant systematic shifts were found. Runs 5–7 have an equivalent quality compared with previous runs ($\sigma \approx 24$ km s$^{-1}$), while run 8 has much better quality, because of its better spectral resolution: $\sigma = 9.6$ km s$^{-1}$.

Since it has a magnitude at the cross-over value of 15.0, we observed the LMC star BAT99-41 both on 2-m and 4-m telescopes (precisely, during runs 3–5 and 8). Although weak, this is the link between the data of runs 1–4 and runs 5–8. Fortunately, it appears that this star shows constant RVs. We measured the mean RV of runs 1–4, and runs 5–8. We found 303 ± 26 (σ), and 320 ± 22 (σ) km s$^{-1}$, respectively. Therefore, the data of all runs can be compared. Besides BAT99-41, only four stars (SMC-WR1, WR9, WR10 and WR11) were observed both in runs 1–4 and 5–8 and thus need a uniform data set to be created.

### 2.6 The photometric data

We have made use of two sets of photometric data: (i) from the Optical Gravitational Lensing Experiment (OGLE, cf. Udalski et al. 1998) and (ii) the Massive Compact Halo Object (MACHO) experiment (Alcock et al. 1996). A. Udalski has kindly provided us with OGLE data for the SMC WR stars falling within their observing fields. MACHO data were retrieved from the public archive accessible from the website (http://www.macho.mcmaster.ca/). Table 5 summarizes the identifications of the data subsets for each SMC star. The retrieved output of the MACHO data base provides a list ordered by increasing separation between the coordinates of the star and the entries of the MACHO data base. We always chose the first entry, which usually has a separation of less than 1 arcsec. However, for WR6 and WR11 the corresponding second entries (IDs 206.16834.11 and 208.16086.11, respectively) appeared to have a magnitude closer to the expected magnitude of the star. After comparison with OGLE data, it appears that the second entry for SMC-WR6 is the correct one, and has therefore been used for the analysis.

We performed the same analysis with the two data sets for SMC-WR11, and found identical results. We did not retrieve photometric data for SMC-WR5, since its photometric variability has already been studied specifically (e.g. Sterken & Breysacher 1997, using their own data; we note, however, that no MACHO data are available for this star, since it is probably too bright). For SMC-WR9, the second data set listed in Table 5 is uncertain according to A. Udalski, since this star is faint ($v = 15.7$). However, after analysis, this data set was found to be consistent with the first data set; mean values of the magnitudes are 15.87 ± 0.02. No OGLE nor MACHO data were available for the WC/WO star WR8, since it lies outside both observing fields.

### Table 5. Summary of available photometric data from the OGLE and MACHO data bases. The ID(s) of the star is given for each data set.

<table>
<thead>
<tr>
<th>Star</th>
<th>OGLE ID</th>
<th>MACHO ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR1</td>
<td>SMC-SC3.63387</td>
<td>213.15560.24</td>
</tr>
<tr>
<td>WR2</td>
<td>SMC-SC4.163528 &amp; SC5.26514</td>
<td>212.15848.1125</td>
</tr>
<tr>
<td>WR3</td>
<td>SMC-SC5.95184</td>
<td>212.15960.9</td>
</tr>
<tr>
<td>WR4</td>
<td>SMC-SC5.166018</td>
<td>212.16016.6</td>
</tr>
<tr>
<td>WR6</td>
<td>SMC-SC10.33875 &amp; SC9.175315</td>
<td>206.16384.11</td>
</tr>
<tr>
<td>WR7</td>
<td>SMC-SC10.37124</td>
<td>No data</td>
</tr>
<tr>
<td>WR9</td>
<td>SMC-SC6.311199 &amp; SC7.47183</td>
<td>No data</td>
</tr>
<tr>
<td>WR10</td>
<td>SMC-SC3.217541 &amp; SC4.26140</td>
<td>212.15680.41</td>
</tr>
<tr>
<td>WR11</td>
<td>SMC-SC6.81637</td>
<td>208.16086.14</td>
</tr>
</tbody>
</table>

### 2.7 The X-ray data

One of us (MAG) has retrieved publicly available data sets from the ROSAT and Chandra archives containing X-ray observations of WR stars in the SMC. These include observations for 10 out of the 11 WR stars in the SMC that are summarized in Table 6. Further details of these observations will be provided in a subsequent paper (Guerrero et al. in preparation), but it is noted here that the Chandra archives are accessible at the World Wide Web site http://heasarc.gsfc.nasa.gov/W3Browse supported by the High Energy Astrophysics Space Science Archive Research Centre (HEASARC) of the NASA Goddard Space Flight Centre. The Chandra archive is available using the Chandra Search and Retrieval Interface (ChaSeR) at the Chandra X-ray Observatory site (http://asc.harvard.edu).
observations of SMC-WR6 and WR7 are composed of multiple observations with short exposure times, typically ∼10 ks.

3 RESULTS

3.1 Radial velocities

Fig. 3 shows the radial velocities obtained for each star observed in the SMC during the first three epochs (runs 1–4). Fig. 4 shows the SMC RVs obtained during epoch 4 for SMC-WR1, WR9, WR10 and WR11 only. All figures have the same ordinate scale to allow a comparison only between the stars.

The short-period binaries are quite obvious to detect. They are SMC-WR3, WR5, WR6 and WR7. The other stars need a more careful analysis concerning their binary status. SMC-WR1, WR2, WR4 and WR10 seem to be single, although small RV variations appear to be visible. SMC-WR9 shows RV variations, but its faint magnitude (v = 15.7) suggests that these might be instrumental. SMC-WR11 also shows small RV variations, but is also a very faint star (corrected magnitude 15.7; see the comments in Table 3).

The case of WR5 is special. No significant RV variability was originally detected in our data, but the RVs we computed are dominated by the He II λ4686 line. Moffat et al. (1998) have shown that this line does not follow the binary motion of WR5. It appears that one of the lines that follows the binary motion best is He II λ4200 (Niemela, Barba & Morrell 1999). Therefore, we recomputed the RVs, taking a spectral window for cross-correlation, including only this line. The corresponding RVs are shown in Fig. 3 (middle left panel).

3.2 Period search and orbital solutions

Before discussing our search for periodic RV variability, we need to determine our detection threshold. Obviously, this threshold is strongly affected by the data of the lowest quality. With and without data from epoch 1, the scatter in RV for the first three epochs computed above (see Fig. 2) is ∼25 and ∼20 km s⁻¹, respectively. Following Massey & Conti (1980), detection of RV variability can be claimed if the scatter exceeds √2 times these values, i.e. 35 and 28 km s⁻¹, respectively. As shown below, only one star (WR9) lies close to this latter limit; all other stars lie either well above or below the limit.

For each star we computed a Fourier transform (FT) with the corresponding set of RVs, with frequencies ranging from 0.0005 to 0.5 d⁻¹. A detection threshold was calculated individually for each star and fixed at three times the simple mean of the noise in the power spectrum, which is equivalent to a 99 per cent confidence level (Billéres 1998; see also Scargle 1982). For each frequency with a power above the threshold, a period search (i.e. a search for orbital parameters) was performed using the program ELEMENTS described in detail by Marchenko, Moffat & Koenigsberger (1994), with the same weight assigned to all data points. More precisely, we performed 21 computations (10 with smaller frequencies, 10 with larger frequencies and the central frequency itself) around each of these frequencies, since the program ELEMENTS is very sensitive to the input period guess. If two contiguous frequencies had a power above the threshold, the intermediate period guess was computed in order to cover the interval between the two frequencies smoothly. Otherwise a step of 0.0004 d⁻¹ was chosen. This program allows us to perform an orbital solution search with or without improvement of the input guess period. If one (or more) orbital solution is found with improvement of the input period, no more searches were done. In contrast, if no orbital solutions were found, we performed the orbital solution search with a period fixed at the guess period value. This reduces by one the number of free parameters in the program. We emphasize the necessity of this rigorous procedure, since it proved to be especially important for the discussion of the 61 stars in the LMC (see Paper II).

We therefore have four possibilities: (i) no detected frequency in the FT; (ii) one (or more) detected frequency in the FT but no orbital solution found; (iii) same as (ii) but one (or more) orbital solution found without improvement of the guess period; and (iv) same as (iii) but with improvement. For the SMC stars, the results of this procedure are given in Table 7.

Not surprisingly, the previously known binaries SMC-WR3, WR5, WR6 and WR7 are indeed detected by this procedure. SMC-WR1, WR2, WR4, WR10 and WR11 (although with a smaller number of spectra for these two latter stars compared with the others) show no significant signatures of periodic RV variations. They are therefore either true single stars, short-period binaries with a small inclination angle and/or large eccentricity, or long-period binaries. They are discussed more carefully below. SMC-WR9 shows suspicious variability, and needs further analysis. Before discussing each star individually, we consider first the control star SMC-WR6.

3.3 SMC-WR6: the control star

SMC-WR6 (also known as AB6, AV332, Sk 108, R31) is a known double-line spectroscopic binary (Moffat 1982; Hutchings et al. 1984). Since the RVs of absorption lines were measurable in our data (although with significant uncertainties), we performed a combined period search for both emission-line and absorption-line RVs. The Hγ absorption line only was used as it is the best defined absorption line in most of our spectra. The best orbital solution found for SMC-WR6 is given in Table 8, and the other solutions given by Moffat (1982) and Hutchings et al. (1984), both based on photographic spectra. The orbital solution for both components is shown in Fig. 5. At this stage we are only interested in verifying that our data are consistent with previously published orbital solutions. The evolutionary stage of SMC-WR6 will be discussed later (see Section 4).

A few points need to be mentioned concerning these orbital solutions. (i) The period found in our study agrees well with that of Hutchings et al. (1984), which is more accurate than that of Moffat (1982). (ii) We also found a non-zero eccentricity, which was also detected by the study of Hutchings et al. and considered suspicious by Moffat (1982). This point will be discussed more carefully in
Section 4 (and the masses of both components given in both studies).

(iii) We note the good agreement of the $K$ amplitude found in our study with those of others. The error of the absorption-line amplitude is larger than that of the emission-line amplitude because of the method used to construct our cross-correlation template. Indeed, the template spectrum, which is used to measure RVs for both emission and absorption lines, is built following a first measurement of the RVs of the emission lines. As the absorption lines are antiphased [which is the case, see Hutchings et al. (1984) for a detailed discussion], they tend to be averaged out, and their intensity is significantly reduced in the final template spectrum. Therefore, the measurement of RVs on these lines will be less accurate. Although possible, no further analysis has been done to recover the true RVs of the companion. (iv) The value of $T_0$ given in the present study and that of Moffat, which is the time of passage of the WR star in front for Hutchings et al. is the time at periastron, as opposed to the value of Moffat, which is the time of passage of the WR star in front for...
a circular orbit. Finally, our value of the systemic velocity for this star is slightly different from that of Hutchings et al. and of Moffat. Indeed, as noted above, this is caused by the procedure used to calibrate our data sets between the different observatories (see Section 2.6). Therefore, our value is not especially reliable.

Nevertheless, we are able to conclude that the orbital solution found for SMC-WR6 in the present work lends considerable credibility to the calibration of our data.

### 3.4 Binary status of SMC WR stars from RVs

We discuss here carefully the RVs for each remaining star of our SMC sample. As noted above, one must allow for the inferior quality of the CASLEO data of run 1 (=epoch 1) before making any conclusions on the binary nature of any star.

**SMC-WR1.** The RVs are consistent with a single star. The increased scatter in the first epoch is certainly caused by instrumental effects. The RVs in the fourth epoch (see Fig. 4) show constant RV within the errors. We also note that small RV variations were observed by Moffat (1988), based on four contiguous nights, and who wrote that this star could be a relatively long-period binary ($\gg 4$ d).

**SMC-WR2.** The RVs are consistent with a single star, as noted already by Conti, Garmany & Massey (1989) and Moffat (1988), who also noted again negligible RV variations over the course of four successive nights. Again, RVs from the first epoch show relatively large scatter, which is smaller in later epochs, especially the third. We note, however, that some frequencies in the FT have a power that is very close to the FT threshold. Therefore, we artificially decreased this threshold and performed a more detailed period search centred on the few frequencies found. We did find a few orbital solutions, but all of these solutions show either a $K$ amplitude significantly smaller than our detection limit, a very eccentric orbit dominated by epoch 1 data or both. From the RV point of view only, this star appears, confidently, not to be a short-period binary.

**SMC-WR3.** This star is a double-line binary according to Moffat (1988), but no previous orbital solution was found in the literature. The orbital parameters of SMC-WR3 and its orbital solution found are given in Table 9 and Fig. 5, respectively. They agree with estimations given by Moffat (1988). The small value found for the eccentricity is consistent with an almost circular orbit, the value obtained being certainly influenced by the finite number of spectra. Unfortunately, individual spectra are not of sufficient quality to allow a measurement of the RV of absorption lines. As for SMC-WR6, we emphasize that the value given for the systemic velocity $\gamma$ is only a poor estimate of the true value.

**SMC-WR4.** The RVs are consistent with a single star. Moffat (1988) classified this star as single based on RVs from photographic spectra obtained on two 10-d intervals separated by a year. According to this author, the very similar spectra and RVs of this star with those of WR2 strengthen its single-star status. A detailed study of the spectrum of this star can be found in Crowther (2000), who denoted WR4 as the only known single WR star in the SMC.

**SMC-WR5 (HD5980).** This star is very peculiar since it experienced an LBV-like outburst in 1994 (Barba et al. 1995; Barba & Niemela 1995). Long-term changes during the period 1978–1991 are described by Koenigsberger et al. (1994). The spectral type of the WR component changed from WN3 in 1988 to WN11h during the outburst in 1994 (Niemela et al. 1999), to WN6(h) after the outburst in 1997 (Crowther 2000). Much of this change, especially when the system was fainter, arose in the strong wind–wind collision shock zone of the 19-d binary, according to Moffat et al. (1998). Evidence for a multiple system is given by Koenigsberger et al. (2000). The orbit found in the present study, based on He ii $\lambda 4542$ RVs, has a period of 23 d, and does not correspond to other solutions. Therefore, we consider our solution not to be reliable enough to discuss

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**Table 7.** Results of period and orbital solution searches on the He ii 4686 RVs. The best period is given when an orbital solution is found.

<table>
<thead>
<tr>
<th>Star</th>
<th>Result</th>
<th>Best P</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR1</td>
<td>No frequencies</td>
<td></td>
</tr>
<tr>
<td>WR2</td>
<td>No frequencies</td>
<td></td>
</tr>
<tr>
<td>WR3</td>
<td>Orbit with improvement</td>
<td>10.0 d</td>
</tr>
<tr>
<td>WR4</td>
<td>No frequencies</td>
<td></td>
</tr>
<tr>
<td>WR5</td>
<td>Orbit with improvement</td>
<td>23.3 d</td>
</tr>
<tr>
<td>WR6</td>
<td>Orbit with improvement</td>
<td>6.5 d</td>
</tr>
<tr>
<td>WR7</td>
<td>Orbit with improvement</td>
<td>20.5 d</td>
</tr>
<tr>
<td>WR9</td>
<td>Orbit without improvement</td>
<td>34.2 d</td>
</tr>
<tr>
<td>WR10</td>
<td>No frequencies</td>
<td></td>
</tr>
<tr>
<td>WR11</td>
<td>No frequencies</td>
<td></td>
</tr>
</tbody>
</table>

---

Figure 4. RVs of WR1, WR9, WR10 and WR11 during the final epoch (runs 6–8). The data on the right with much smaller uncertainties show the RVs obtained with 1 Å pixel$^{-1}$ dispersion (run 8).
Table 8. Orbital solutions for SMC-WR6. See the text for the description of each solution.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$P$ (d)</td>
<td>6.5364 ± 0.0007</td>
<td>6.861 ± 0.005</td>
<td>6.5380 ± 0.0008</td>
</tr>
<tr>
<td>$e$</td>
<td>0.10 ± 0.03</td>
<td>0.00 ± 0.005</td>
<td>0.18 ± 0.06</td>
</tr>
<tr>
<td>$K_r$ emission (km s$^{-1}$)</td>
<td>290 ± 10</td>
<td>334 ± 42</td>
<td>350 ± 37</td>
</tr>
<tr>
<td>$K_r$ absorption (km s$^{-1}$)</td>
<td>66.3 ± 10.3</td>
<td>58 ± 7</td>
<td>64 ± 5</td>
</tr>
<tr>
<td>$T_0$ (HJD − 245 1100.0)</td>
<td>821.4 ± 0.2</td>
<td>818.47 ± 0.14</td>
<td>824.2 ± 0.6</td>
</tr>
<tr>
<td>$\gamma$ (km s$^{-1}$)</td>
<td>199 ± 3</td>
<td>221 ± 30</td>
<td>267 ± 26</td>
</tr>
<tr>
<td>$\omega$ (deg)</td>
<td>103 ± 20</td>
<td>1.8 ± 0.6</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Here we give the best orbital solution from our study and from Moffat (1982), and the best (eccentric) orbital solution given in Hutchings et al. (1984). Values of $T_0$ for published solutions are extrapolated to facilitate a comparison with the present study. Present values of $\gamma$ and $\omega$ are obtained for a spectral window centred on He II $\lambda$4686 (precisely from 4570 to 4800 Å). See the text for details of each solution.

Figure 5. Orbits of four SMC WR binaries, confirmed and marginal. For WR6 and WR7, the RVs of absorption lines are indicated (open circles). All figures have the same scale to allow an easier comparison. The ephemeris are based on the present study.
in detail the properties of this interesting star, which anyway is beyond the scope of this paper. A detailed analysis can be found in the papers cited above.

**SMC-WR7.** This star is a binary according to Moffat (1988). A detailed study of WR7 can be found in Niemela et al. (2002). Since the RVs of absorption lines were measurable in our data (although more accurate data are needed to confirm this result, we expect 0.8 additional binaries in the region below the curve with \( i = 30^\circ \). However, since our detection limit is approximately 30 km s\(^{-1}\), it is statistically unlikely that we missed a binary star, at least with a period of less than \( \sim 30 \) d. Even if we did miss one binary, we can be confident that we have detected the significant majority of binaries. Different eccentricity values do not change this result.

### 3.5 Binary frequency and statistical correction

The preliminary conclusion that can be drawn from the RV point of view is that the binary frequency of the WR population seems smaller than the expected 98 ± 32 per cent (see Table 1), since we detected only five certain binaries (including the WC/WO star WR8) among 11 WR stars. Since our survey is obviously limited, we may have missed a few short-medium period binaries for mainly two reasons: the inclination angle is low and/or the eccentricity is large. We need to evaluate statistically the possible influence of these two effects on the observed binary frequency.

Let us build a theoretical binary. We choose \( M_1 = 10 M_\odot \) and \( M_2 = 30 M_\odot \), which are typical values for WNE and O stars in WNE+O systems (exact values are not important here anyway). From the WR mass function, we have \( K_1 = 212.7 M_2 (M_1 + M_2)^{1/3} P^{-1/2} \left(1 - e^2 \right)^{-3/2} \) for \( M_1 \) and \( M_2 \) in \( M_\odot \) and \( P \) in days. We compute the \( K_1 \) amplitude as a function of the period \( P \) between 1 and 1000 d, for \( e = 0 \) and two different values of the inclination of the system. The result is shown in Fig. 6, where we add a threshold of 30 km s\(^{-1}\). The positions of all SMC binaries (including WR8) are shown.

From a statistically random sample of inclinations for any given \( P \), we expect

\[
\frac{\int_{0}^{90} \sin(i) \, di}{\int_{0}^{90} \sin(i) \, di} = \frac{\cos(30^\circ)}{[1 - \cos(30^\circ)]} = 6.5
\]

n times as many binaries to lie between the two curves \((i = 90^\circ \) and \( 30^\circ \)) as between \((i = 30^\circ \) and \( 0^\circ \)). All five reliable SMC WR binaries effectively lie in the upper region. If these five binaries represent 6.5/7.5 = 87 per cent of the WR binary population, we therefore expect 0.8 additional binaries in the region below the curve with \( i = 30^\circ \). However, since our detection limit is approximately 30 km s\(^{-1}\), it is statistically unlikely that we missed a binary star, at least with a period of less than \( \sim 30 \) d. Even if we did miss one binary, we can be confident that we have detected the significant majority of binaries. Different eccentricity values do not change this result.

### 3.6 Analysis of the photometric data

All stars that have photometric data appeared to be slightly variable (of the order of \( \sigma \approx 0.02 \)–0.1 mag). To confirm this apparent variability, we looked for periodic variability among the photometric data using FTs to detect possible eclipses and/or intrinsic periodic variability. We performed FTs separately on OGLE, MACHO red-band and MACHO blue-band data. (See Alcock et al. 1999 for a detailed description of the instrumental procedure and calibration in the MACHO project.)

For binaries (including the marginal case of WR9), we folded the photometric data with the inverse frequencies found from both FTs (i.e. FT on the RVs, and on the photometric data). Photometric data are expected to confirm or modify which RV-orbit solution

\[^2\] This argument is elaborated and applied to other stars in Section 3.8.
Figure 6. Upper panel: RV amplitude of the WR component ($K_1$) versus the period $P$ for two different values of the orbital inclination $i$. Bottom panel: $K_1 P^{1/3}$ versus the period $P$. Masses of 10 and 30 M$_\odot$ are assigned to the WR and O components, respectively. The eccentricity is fixed to 0. The dotted line represents a threshold of 30 km s$^{-1}$. Values for WR8 are taken from Bartzakos et al. (2001) and from Schweickhardt & Schmutz (1999) for WR5. The proximity of WR9 with the detection limit is better seen in the bottom panel.

Figure 7. Light curves from OGLE and MACHO data for WR1 and WR2.

is the best, in the case of significant periodic light variations. For single stars, we performed a folding of the light curve with inverse frequencies found from FTs on photometric data only. The light curves are shown in Figs 7–10.

We found no eclipses whatsoever for the SMC WR binaries, including WR9. Although WR7 appears to show coherent photometric variations in Fig. 9, a formal analysis failed to reveal anything significant. Interestingly, we found significant periodic variability only in the blue-band of the MACHO data for the single star SMC–WR4, with a period of 6.55 d. The light curve is nearly sinusoidal, unlike the sharper dips expected for atmospheric or photospheric eclipses. The red band of MACHO seems to show the same behaviour, but is not as clear. The OGLE data seem not to follow this period, but the scatter of the data points is larger. To test this periodicity, we performed a folding of the data with 1000 different periods ranging from 1 to 100 d with a constant step-size in frequency. For all of these foldings, we computed the scatter ($\sigma$) around the mean value, after binning the data with 0.05 phase bins. If the data do not show a periodic signal at a given period, the scatter of the binned points remains low. In contrast, if a periodic signal is well defined for a given period, the corresponding scatter will be higher. It appears that the 6.55-d signal of WR4 is significant at the 3.2$\sigma$ level (i.e. with a scatter 3.2 times larger than the mean scatter for no periodic signal).
Figure 8. Folded light curves from OGLE and MACHO data for WR3 and WR4 with the corresponding period: orbital period $P = 10.053$ d for WR3, with $T_0$ taken from the orbital solution. For WR4: $P = 6.55$ d, and the origin was arbitrary chosen at the time of our first spectra, i.e. $T_0$(HJD) = 245 1114.6093481.

The light curves of each star (except WR5 which is a known deep double-eclipser; see Moffat et al. 1998) are shown in Figs 7–10. For binaries and WR4 the data have been folded with the corresponding period. We used the period $P = 6.55$ d for WR4 and the orbital period found in the present study for the binaries, except for WR7 for which we took the orbital period of Niemela et al. (2002) see below.

Figure 9. Folded light curves from OGLE and MACHO data for WR6, WR7 and WR9. The data have been folded with periods 6.5364, 19.56 and 37.57 d, respectively, with $T_0$ taken from the respective orbital solution. The period of WR7 is taken from Niemela et al. (2002).

Since no evidence was found for eclipses in the binaries, this result can be used to constrain the orbital inclinations and hence the masses of the stars. Since potential eclipses in WR binaries are not always photospheric (as in WR5), but are more often wind-eclipses (cf. Lamontagne et al. 1996), i.e. spatially larger regions of the WR wind electrons scatter the light from the O star when it passes behind, the result found above (i.e. no eclipses) points toward inclination angles significantly below 90°. Therefore, any estimation of the masses of the stars are only lower limits.

3.7 Analysis of the X-ray data

The ROSAT PSPC observations of SMC-WR1, WR2, WR3, WR4, WR9, WR10 and WR11 (see Table 6) were searched for X-ray
have further processed their observations. First, we have reduced
the impact of charge transfer inefficiencies (CTI) in the ACIS-I ob-
servations using the CTI corrector (Townsley et al. 2000).
Subsequent data reduction and analysis were performed using the
Chandra X-ray Centre software CIAO v2.2.1 and HEASARC
XTOOLS and XSPEC v11.0.1 routines (Arnaud 1996). The data reduction
included the reprocessing of the ACIS-S3 observations to ensure that
the most up-to-date calibration files were used, along with the appli-
cation of standard filters and the removal of time intervals when the
background count rate was 20 per cent above the quiescent mean
value (Markevitch 2001). Finally, the reprocessed level 2 event files
from observations with the same instrument (ACIS-I or ACIS-S3)
were merged to increase the signal-to-noise ratio.

We have extracted source and background spectra for each of
these stars and constructed the appropriate response matrices and
effective area files to allow its spectral analysis (the so-called re-
distribution matrix file, RMF, and ancillary response file, ARF).
SMC-WR5 is embedded in a region of diffuse, soft X-ray emission
that may contaminate the source spectrum. This was excluded from
a small, 2 arcsec radius, region centred on the star to minimize
the contribution of the diffuse emission. Furthermore, the diffuse
emission was subtracted using a larger surrounding annular region
with inner and outer radii of 3.5 and 7 arcsec, respectively. The
use of other background regions did not introduce any noticeable
differences in the background-subtracted spectrum of SMC-WR5.
SMC-WR6 and WR7 are not affected by this problem, thus the
formal source regions had a larger radius of 7 arcsec, and the back-
ground annular regions was larger too, with inner and outer radii of
25 and 37 arcsec, respectively.

The observations of SMC-WR6 and WR7 are composed of mul-
tiple short exposure-time observations. We computed the RMF and
ARF files for each of the individual observations and averaged them
using weighting factors equal to the exposure time (corrected to the
periods affected by high background emission). Finally, the spectra
were grouped to contain a minimum of 16–25 counts per energy
channel, thereby allowing \( \chi^2 \) statistics to be used. The background-
subtracted spectra are plotted in Fig. 11. (The total number of
background-subtracted counts are listed in Table 6.)

The background-subtracted spectra have been used to determine
the temperature and the hydrogen column density of the interven-
ting material, \( N_H \). The spectra have been modelled using the XSPEC
MEKAL optically thin plasma emission model (Kaastra & Mewe
1993; Liedahl, Osterheld & Goldstein 1995) and the photoelectric
absorption models of Balucinska-Church & McCammon (1992).
The chemical abundances for the X-ray-emitting plasma and for the

<table>
<thead>
<tr>
<th>Star</th>
<th>( kT ) (keV)</th>
<th>( N_H ) (cm(^{-2}))</th>
<th>( A_V ) (mag)</th>
<th>X-ray lum. (0.5–5 keV) (erg s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR1</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;1 \times 10(^{33})</td>
</tr>
<tr>
<td>WR2</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;1 \times 10(^{33})</td>
</tr>
<tr>
<td>WR3</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;1 \times 10(^{33})</td>
</tr>
<tr>
<td>WR4</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;2 \times 10(^{33})</td>
</tr>
<tr>
<td>WR5</td>
<td>7.4(^{+3.4}_{-2.2})</td>
<td>5.9 \times 10(^{21})</td>
<td>0.36(^{+1/4}_{-0.19})</td>
<td>1.2 \times 10(^{34})</td>
</tr>
<tr>
<td>WR6</td>
<td>1.9 \pm 0.3</td>
<td>&lt;1.0 \times 10(^{21})</td>
<td>&lt;0.06</td>
<td>4.2 \times 10(^{33})</td>
</tr>
<tr>
<td>WR7</td>
<td>2.1 \pm 0.3</td>
<td>2.8 \times 10(^{21})</td>
<td>0.17(^{+0.10}_{-0.08})</td>
<td>5.5 \times 10(^{33})</td>
</tr>
<tr>
<td>WR9</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;2 \times 10(^{33})</td>
</tr>
<tr>
<td>WR10</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;2 \times 10(^{33})</td>
</tr>
<tr>
<td>WR11</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>&lt;2 \times 10(^{33})</td>
</tr>
</tbody>
</table>

Table 12. Temperature, hydrogen column density, deduced extinction and
unabsorbed X-ray luminosity obtained for the different WR stars in the SMC.

emission, but none was detected. These observations were still used
to determine 3\( \sigma \) upper limits of the count rate from these stars in
the PSPC energy band (0.1–2.4 keV). Assuming a Raymond–Smith
thermal plasma emission model with reasonable parameters \( (kT =
2 \text{ keV}, \text{hydrogen column density equivalent to } A_V = 0.1 \text{ mag,}
\text{and chemical abundances } 0.1 \text{ solar}) \), these count rates have allowed us
to derive upper limits for the X-ray luminosities of these stars in the
0.5–5.0 keV band (see Table 12).

The three WR stars in the SMC with Chandra observations,
namely SMC-WR5, WR6 and WR7, are clearly detected. In or-
der to analyse the spectroscopic information of these three stars, we

Figure 10. Light curves from OGLE and MACHO data for WR10 and
WR11.
absorbing intervening material was set to 0.1 solar, as appropriate to the SMC. The parameters of the best-fitting models are given in Table 12. The visual extinction, $A_V$, has been computed from the fitted $N_H$ using Bouchet et al.'s (1985) values for the SMC of visual extinction to excess colour, $R = A_V / E(B-V) = 2.7 \pm 0.2$, and the gas-to-dust ratio, $N_H / E(B-V) = 4.5 \pm 0.8 \times 10^{22} \text{ cm}^{-2} \text{ mag}^{-1}$.

The best-fitting models for SMC-WR6 and WR7 indicate a very similar plasma temperature, $\sim 22 \pm 3 \times 10^6 \text{ K}$ for SMC-WR6 and $\sim 27 \pm 3 \times 10^6 \text{ K}$ for SMC-WR7. The X-ray luminosities of these two stars in the 0.5–5.0 keV band are also similar, $L_X \sim 4 \times 10^{33} \text{ erg s}^{-1}$, i.e. two to four times larger than the upper limits of $L_X$ of the WR stars in the SMC that are not detected. The spectrum of SMC-WR5 does not provide a tight constraint on the column density and plasma temperature because only ACIS-I observations are available and their calibration is not accurate below 0.9 keV. Without information on this energy band, which is very sensitive to the intervening column density, the spectral fit is degenerate and models with a higher temperature and smaller $N_H$, or lower temperature and larger $N_H$ both provide an appropriate description of the observed spectrum. Nevertheless, its spectral shape suggests that the X-ray-emitting plasma in SMC-WR5 is much hotter and more highly extinct than in SMC-WR6 and WR7. Its X-ray luminosity is also higher, $\sim 1.0 \times 10^{33} \text{ erg s}^{-1}$, thus being the most luminous X-ray WR star in the SMC and among the most X-ray luminous known WR stars (van der Hucht 2002).

In Table 12, there is a clear dichotomy in $L_X$ between the binaries and the single stars. The exceptional case of WR3 is interesting since it has an orbital period between that of WR6 and WR7. The reason why it does not show a similar X-ray luminosity perhaps resides in the fact that, besides its faintness, the WR component in WR3 has an earlier subtype (WN3 instead of WN4 for WR6 and WR7, respectively), while its companion has a later O subtype. Additionally, absorption lines from the companion in WR3 are almost impossible to detect, revealing that this companion should be very faint. In this case, the wind of the WR star is somewhat less dense than that of other WN subtypes, and that of the companion is probably very weak. This would produce a small opening angle of a relatively weak shock-cone. Therefore, heating in the wind–wind collision zone is less efficient, leading to a lower X-ray flux (see, e.g., Usov 1992).

### 3.8 Spectral types of the SMC WR stars

A montage with the weighted mean spectrum based on all the available spectra for each SMC star in our sample is shown in Fig. 12. The spectra of binary stars were shifted to the same rest wavelength according to their respective emission-line RVs. In order to obtain a precise spectral type for the two new and faint WR stars in the SMC, we obtained a mean of three spectra for both stars from the 3.5-m ESO-NTT telescope in the blue range (3900–4900 Å). These
Figure 12. Montage of the rectified mean SMC WR spectra in order of WN subtype. The relative intensity of the different spectra has been preserved and the separation between successive vertical tick marks corresponds to one continuum unit.

The basic spectral type is therefore WN3. As in previous classifications we note the presence of absorption lines of the Pickering He ii and Balmer series.

We measured the radial velocities (with Gaussian fits) of four non-blended absorption lines (see Table 14). Being clearly blueshifted compared with the mean RV of the SMC (\(\sim 160 \text{ km s}^{-1}\)), these absorption lines must be formed in the wind of the WR star itself (or in a wide OB-type companion; however, blueshifted absorption lines are only seen in luminous supergiants, which is not the case here). Otherwise, if WR1 were a binary with such blueshifted absorption lines arising in an O-type companion, they would eventually shift to an equal amount on the red side of the systemic velocity in a period of several days. Such rapid motion would be easy to see, in particular, in the WR component. The fact that the RVs of the WR star remain essentially constant over all observed time-scales from a day to months, strongly supports the suggestion that the

observations were obtained in 2002 at the beginning of February with the spectrograph EMMI. A spectral dispersion of 0.9 Å pixel\(^{-1}\) was chosen. The spectra were combined to increase the signal-to-noise ratio. They are shown in Fig. 13.

A recent homogeneous assignment of spectral types for all SMC WR stars can be found in Massey & Duffy (2001). We review here the spectral characteristics of the SMC WN stars, compared with the previous assignments of Moffat (1988), Conti et al. (1989), Crowther (2000) and Massey & Duffy (2001). New and previous spectral types are given in Table 13. For our classifications, we follow the scheme defined by Smith, Shara & Moffat (1996) for WN stars and Walborn & Fitzpatrick (1990) for O stars.

SMC-WRI. As noted by Massey & Duffy (2001) and Moffat (1988), this star has strong He ii \(\lambda 4686\) and N v \(\lambda 4603, 4619\) emission lines, but no detectable N iv \(\lambda 4058\) or N iii \(\lambda 4634, 4642\) emission. He ii \(\lambda 5411\) emission is much stronger than that of He i \(\lambda 5876\).
absorption lines are formed deep in the relatively weak WR wind, at modestly blueshifted RV along the line of sight to the stellar core. Based on the oscillating Pickering series, we determine a final type for SMC-WR1 of WN3ha, i.e. WN3 with intrinsic hydrogen in the wind, seen both in emission and absorption. SMC-WR1 therefore resembles very closely the anticentre Galactic single star WR3, with newly determined type WN3ha (Marchenko et al. 2002, in preparation).

**SMC-WR2.** As noted by previous studies (Conti et al. 1989; Massey & Duffy 2001), this star has narrow emission at HeII $\lambda 4686$. The blended lines N iii $\lambda\lambda 4634, 4642$ are present in emission. The various ratios allow us to assign a WN5 spectral type. Massey & Duffy (2001) detected He, which is also present in our spectra, but is too weak to consider this star as a transition between WN and WC subtypes. Absorption lines are present: H\$\epsilon\$, H\$\gamma\$, H\$\delta\$, He II $\lambda\lambda 4200, 4542$, etc. and also P Cygni N V $\lambda\lambda 4603, 4619$. The ratio $4861/\sqrt{4541\times 5411} - 1$ (see Smith et al. 1996) is equal to $\sim 6$ in our spectra, revealing the presence of hydrogen in the WR wind. We measured the RVs of H\$\gamma\$ and He II $\lambda 4542$ (the shapes of other emission lines are not well defined) in the mean.

**Table 13.** Spectral types of SMC WR stars.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>WR1</td>
<td>WN3+O4:</td>
<td>WN3+abs</td>
<td>WN3+O4</td>
<td>WN3+abs</td>
<td>WN3ha</td>
</tr>
<tr>
<td>WR2</td>
<td>O3III*/WN6-A</td>
<td>WN4.5Of</td>
<td>WN4.5+abs</td>
<td>WN5ha</td>
<td></td>
</tr>
<tr>
<td>WR3</td>
<td>WN3+O4:</td>
<td>WN3+abs</td>
<td>WN4+O4</td>
<td>WN3+abs</td>
<td>WN3h+O9:</td>
</tr>
<tr>
<td>WR4</td>
<td>WN6-A</td>
<td>WN4.5</td>
<td>WN5h</td>
<td>WN6p</td>
<td>WN6h$^b$</td>
</tr>
<tr>
<td>WR5</td>
<td>WN4+O7I:</td>
<td>WN4+abs</td>
<td>WN6h$^a$</td>
<td>WN5</td>
<td></td>
</tr>
<tr>
<td>WR6</td>
<td>WN3+O6.5I:</td>
<td>WN3+abs</td>
<td>WN3+O6.5I</td>
<td>WN4+O6.5I</td>
<td>WN4+O6.5I:</td>
</tr>
<tr>
<td>WR7</td>
<td>WN3+O7I:</td>
<td>WN3+abs</td>
<td>WN3+O7</td>
<td>WN2+abs</td>
<td>WN4+O6(f)</td>
</tr>
<tr>
<td>WR8</td>
<td>WO4+O4V</td>
<td>WO4+abs</td>
<td>WO3+O4V</td>
<td>WO4+abs</td>
<td></td>
</tr>
<tr>
<td>WR9</td>
<td></td>
<td>WN3+abs</td>
<td>WN3+abs</td>
<td>WN3ha</td>
<td></td>
</tr>
<tr>
<td>WR10</td>
<td></td>
<td>WN3+abs</td>
<td>WN3+abs</td>
<td>WN3ha</td>
<td></td>
</tr>
<tr>
<td>WR11</td>
<td></td>
<td>WN3+abs</td>
<td>WN3+abs</td>
<td>WN4h:a</td>
<td></td>
</tr>
</tbody>
</table>

Notes: $^a$We give here only the last (post-outburst) spectral type assigned by Crowther (2000). $^b$WR5 is known to have varied its spectral type dramatically over the past three decades. The classification found in the present study is based on spectra taken in 1998 and 1999 (runs 1 and 2, see Table 2).
that the spectra, even from a 4-m class telescope do not allow us to confirm the presence of a companion. As shown below, line-profile variations and absolute magnitude point toward a single-star status. We are inclined to classify this star as being single, with a spectral type of WN3ha.

SMC-WR10. As noted by Massey & Duffy (2001), the spectrum has no N IV λ4058 or N iii λλ4634, 4642 emission. We observe strong N v λλ4603, 4619 emission. Absorption lines are present: Hδ, He ii λ4200, Hγ and He ii λ4542. We measured the RVs of these lines in the NTT spectrum, since it has the best quality, and found them to be constant and blueshifted (see Table 14). Therefore, the absorption component of the spectrum originates in the WR wind itself. We classify this star as WN3ha.

SMC-WR11. This star also clearly shows an absorption component. N iv λλ4603, 4619 is clearly in emission. In contrast to Massey & Duffy (2001), we do see N iv λ4058 in emission, particularly in the NTT spectrum. However, N iii λλ4634, 4642 is lacking. We therefore adopt a WN4 subclass. Hδ, He ii λ4200, Hγ and He ii λ4542 are in absorption. We measured the RVs of these lines and found them to be constant, although not strongly blueshifted (see Table 14). Spectra from the NTT give equivalent results. We classify this star as WN4ha.

Interestingly, our spectra reveal the clear presence of hydrogen in most, if not all spectra of the WR stars in the SMC. For most of these stars, hydrogen arises in the wind of the WR star itself. This important point is discussed below in an evolutionary context. We also stress that, owing to strong superposed absorption lines from the companion, we were unable to distinguish the hydrogen parameter o, (h), h in the Smith et al. (1996) system for the WR winds in the binaries WR6 and WR7. This does not mean that their WR winds do not have hydrogen. Indeed, because of the companion, absorption lines of the WR itself, if present, will be embedded in the secondary spectrum. Only separation of the absorption-line component using high-quality, time-resolved spectra will be able to clarify this problem. Indeed, we easily found hydrogen in the spectra of the binary WR3, where the companion is relatively faint.

3.9 Line-profile variations and wind–wind collisions

To detect possible line profile variations (LPVs), we constructed a temporal variance spectrum (TVS; see Fullerton, Gies & Bolton 1996) for each WR star in our sample. TVS is a method that compares the deviations observed in spectral features with those of adjacent continuum regions in a statistically rigorous way. It accounts for pixel-to-pixel and spectrum-to-spectrum differences in the noise distribution. It allows one to obtain a direct estimate of the level of LPVs in a spectral time-series. We performed TVS on the strongest emission line (HeII λ4686), which is very sensitive to wind–wind collision effects, and also on Hδ and He II λ4859 when they are sufficiently well defined above the noise. Interestingly, a double-peaked TVS profile is expected for spectroscopic binaries, where the LPVs are dominated by Doppler shifts of the spectra.

As expected, we found a single-peaked TVS profile for the true single WR stars (WR1, WR2, WR4, WR10, WR11). In addition, the true binaries (WR3, WR5, WR6 and WR7) show a double-peaked profile. However, the uncertain binary WR9 shows a single-peaked profile, adding weight to our suspicion that this star may, in fact, be a single star.

Quantitative estimations of LPV for all WN stars (following equations 15 and 16 in Fullerton et al. 1996) are summarized in

| Table 14. Radial velocities (km s\(^{-1}\)) of hydrogen and helium absorption lines. Balmer lines are blended with close HeII lines, which therefore influence the final value of the RV. This explains the systematic shift toward more negative RVs for the Balmer lines measured. However, the blueshift for most of the lines is clearly observed. |
|-----------------|-------|-------|-------|-------|-------|
|                 | WR1   | WR2   | WR9   | WR10  | WR11  |
| He ii λ4026     | 71    | 11    | −70   | 81    | 58    |
| Hδ              | 84    | −8    | 73    | 172   |       |
| He ii λ4200     | 28    | 45    | −40   | −97   | 80    |
| Hγ              | 48    | 83    | −24   | 27    | 167   |
| He ii λ4542     | −90   | −187  |       |       |       |
| Hδ              |       |       |       |       |       |


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LPVs in binaries probably come mainly from the WWC zone. This zone produces excess emission at the top of the line, which varies periodically from red to blue with amplitudes typically of \( \sim 10^3 \) km s\(^{-1}\) but 90° out of phase with the orbital motion (see, e.g., Marchenko et al. 1994, for the Galactic binary star V444 Cygni). As shown in Fig. 15, we detect the presence of phase-dependent WWC effects in SMC-WR6 but not in WR3. For WR3, the same reason (i.e. the companion is faint, and therefore the WR spectrum is not diluted, and WWC effects are weak) explains why LPVs are significant, but nothing related to WWC appears in the grey-scale plot. As the WWC theory predicts, we see redshifted excess emission at the time the WR is in front and therefore the matter in the shock cone produced by the collision is moving outward from the observer in the case of WR6.

Phase coverage was unfortunately not good enough for WR7 to allow a clear detection, although some indications in the partial grey-scale plot seem to show a small WWC effect.

### 4 DISCUSSION

Table 16 gives an overview of all the characteristics of the WN stars in the SMC discussed in this paper. The following preliminary statements can be reiterated.

(i) **The binary frequency is lower than theoretically expected.** With only four certain short-medium period binaries among the 10 WN stars in the SMC, the binary frequency lies around 40 per cent instead of 100 per cent (even if this latter value must be taken with care, see the introduction). Even accounting for possible binaries missed because of large inclination angles or high eccentricity, the observed binary frequency remains below its expected value. If we take the lower boundary of the theoretical binary frequency (66 per cent), a cumulative binomial probability test reveals that the hypothesis of such a binary frequency is disproved by the data at a 95 per cent significance level, with four detected binaries. With five binaries among 10 stars, the hypothesis would be disproved at a 92 per cent significance level.

(ii) **No photometric eclipses were found in the binary systems** beyond the double photometric eclipses already known in the binary WR5. This can provide a constraint on the inclination angle of these systems, and leads to higher estimates of the masses of the stars (see Table 16). For the binary WR9, the hypothesis of such a binary frequency is disproved by the data at a 95 per cent significance level, with four detected binaries. With five binaries among 10 stars, the hypothesis would be disproved at a 92 per cent significance level.

Table 15. For the binaries, all the spectra have first been shifted to the rest wavelength of the WR component, using the corresponding orbital solution. These values represent a normalized quantity of LPV compared with the strength of the considered line. This quantity allows us to make a comparison between different stars.

Given the fact that we have only a moderate spectral resolution with a moderate signal-to-noise ratio for most of the stars, we consider LPVs to be significant in our data only if they appear above a 3σ level. From Table 15, we therefore clearly see that only three stars have strong LPVs: WR3, WR4 and WR5. For the binary WR3 this is an indication of the possible weak effect of wind–wind collision (see below). WR5 is already known to have very strong LPVs.

As for WR4, the LPVs found in our data seem to be significant. A relation between these variations and the periodic signal found in the photometric data will be sought elsewhere.

The binaries WR6 and WR7 show no significant LPVs (i.e. below the 3σ level). This is probably caused by the fact that the wind–wind collision effect arising on the top of the He\( \pi \) \( \lambda \)4686 line is diluted by the spectrum of the bright supergiant companions. The level of LPVs quantified by the TVS method on WR9 is low and adds weight to the single-star status of this star.
below). A periodic signal was found with a period of 6.55 d in the photometry of the single star WR4. This might suggest that WR4 may be a rotating single WR star with large-scale structure in its wind, somewhat like EZ CMa or WR134 in the Galaxy (e.g. Morel et al. 1999).

(iii) X-rays were clearly detected in the three brightest binaries: WR5, WR6 and WR7, with the highest X-ray luminosity for WR5. These X-rays almost certainly have their origin in the WWC phenomenon. Interestingly, the new certain binary WR3, which has a period between that of WR6 and WR7, does not show evidence for strong X-ray production.

(iv) We detected phase-dependent WWC effects in the binary WR6, but not in WR3. This is consistent with the fact that this latter star shows weak absorption lines (the companion is probably very faint) and no X-rays.

(v) A large fraction, if not all WN stars in the SMC, show the presence of hydrogen in their WR spectrum. Although this is easily understandable for the WNL stars WR5 and WR4, it is unexpected...
in the other (mostly WNE) stars. This means that WNE stars in the SMC are fundamentally different from the bulk of WNE stars in our Galaxy, the latter often showing virtually no hydrogen in their spectra. [A strong exception to this is the anticentre Galactic WNE star WR3, recently found to be single and of type WN3ha by Marchenko et al. (in preparation).]

Using all the information collected in different data sets, we are now able to discuss the problem of the formation of WR stars in a low-metallicity environment such as the SMC.

4.1 Binary frequency in the SMC: the effect of metallicity

The main goal of this study was to find out whether binary stars are an important channel for the formation of WR stars in a low-metallicity environment. The SMC obviously suffers from small number statistics; however, this study points towards the conclusion that binaries are, although present, not dominant among the WR stars in the SMC. Six WR stars are probably truly single. Even if they do belong to a long-period binary system, the evolution of the primary that became a WR star could not have been significantly influenced by a possible companion. Stellar-wind type mass-loss was therefore sufficient to allow these stars to appear as WR. The question of whether this wind mass loss is caused by very high initial masses or powered by another effect such as rotation is addressed below.

We note that the binary frequency of the WR population in the SMC (46 per cent), is compatible with that of the Galaxy: 38 per cent (van der Hucht 2001), although our Galaxy suffers from incompleteness and an absence of systematic searches for binaries via RV variations (possibily compensated for by the softer criteria for binaries applied to the Galactic WR stars). This frequency is also compatible with that found by Garmany, Conti & Massey (1980) among Galactic O stars: 36 per cent. These values point towards the conclusion that the binary frequency of WR stars is identical to that of their progenitors and independent of the metallicity. However, as the binary frequency of O stars in the MCs and our Galaxy is still poorly known, this result must be taken with caution.

Moreover, the influence of rotation on the formation of WR stars is hard to evaluate. Maeder & Meynet (2001) have shown that rotation favours the formation of WR stars by two means: an increased internal mixing and an enhanced mass-loss rate, during the MS phase. However, if the distribution of rotational velocities among the progenitors is independent of the metallicity, rotation will have no effect on the corresponding WR population, and the metallicity only, through the mass-loss rate, will statistically modify the conditions of formation of WR stars. In that context, the WR binary frequency is expected to be clearly Z-dependent, since fewer single WR stars will be formed compared with those formed in binaries.

However, if the rotational velocities among the progenitors are statistically higher at low Z, the minimum mass to form single WR stars will be reduced. In that case, the binary frequency will decrease, and may reach a ‘normal’ value, which is in fact hiding the opposite contribution of two different effects.

4.2 Formation of WR stars at low Z: the single stars

To form single WR stars in low-metallicity environments such as the SMC, there are (at least) two main possibilities. (i) These stars were initially very massive, with an initial mass well above the estimated minimum mass of 45 $M_\odot$ by Maeder (1998) for the SMC. (ii) These stars were not initially particularly massive, and another mechanism is needed to explain their formation.

If the single stars were initially very massive, their mass loss by the stellar wind is therefore expected to be strong enough to peel-off their hydrogen-rich envelope and allow them to evolve through the WR stage.

This point of very high initial masses is supported by the results of cluster turn-offs in OB associations in the SMC and the LMC by Massey, Waterhouse & DeGioia-Eastwood (2000). They found that the WR stars in the SMC come from only the highest-mass stars, i.e. $M_i > 70 M_\odot$. They also argued that ‘true’ luminous blue variable (LBV) stars (similar to what is known for the LBV η Car in our Galaxy, i.e. coming from the most massive progenitors) have very high initial masses ($M_i > 85 M_\odot$). If the results of Massey et al. (2000) are correct, this means that the initial masses of single WR stars lie between ~70 and ~85 $M_\odot$, since only WR5 is known to have experienced an LBV outburst.

However, two major difficulties are related to this approach.

(i) Maeder & Meynet (1994) have shown that at low metallicity, the most massive stars enter the WR phase earlier in their evolutionary time-scale than at high metallicity. Therefore, with a higher mass at the entry point of the WR stage, the star spends its WR lifetime mostly as WNL. The models show that this is true for a standard mass-loss rate and for a mass-loss rate of twice the standard value. Therefore, if the single WR stars initially had masses of between 70 and 85 $M_\odot$, they should mostly be WNL and not WNE. However, among the single stars in the SMC, WR1, WR9, WR10 and WR11 are clearly of early subtype (WN3–4). Only WR2 (WN5ha) and especially WR4 (WN6h) seem closer to this scenario.

(ii) Furthermore, WR1, WR9, WR10 and WR11 are intrinsically fainter than WR2 and WR4. The absolute visual magnitudes taken from Massey & Duffy (2001) are shown in Fig. 16.
Figure 16. Total absolute visual magnitude from Massey & Duffy (2001) with WR11 revised as in Table 3 versus WR spectral type, based on the current classifications for the WR stars in the SMC. WR8 has been placed at ‘WN3’ for simplicity, as WO stars have similar absolute magnitudes compared with WN3 stars. Filled symbols are for single stars, open symbols for binaries. We note the observed trend for single stars, which is similar to what is seen for single WN stars in our Galaxy (van der Hucht 2001). WR9 appears to follow this trend, adding weight to its single-star status.

The absolute magnitudes of WR1, WR7, WR10 and WR11, a very strong mass loss is needed. However, even with a mass-loss rate of twice the standard value, the models cannot reproduce such low luminosities with a metallicity of that of the SMC (Maeder & Meynet 1994). Moreover, this strong mass loss is incompatible with the clear presence of hydrogen in the spectra of these stars.

We recall here two important results. First, Crowther (2000) has shown that for identical physical parameters, single WN stars at low Z appear to have an ‘earlier’ spectral subtype than their Galactic counterparts. Secondly, Maeder, Grebel & Mermilliod (1999) have shown that the fraction of Be stars among the total of B stars increases as the metallicity decreases. If the Be phenomenon is indeed related to rotation, this result points towards the fact that the overall rotation rate is higher at lower Z. This interesting result is also supported by the RSG/BSG number ratio (Maeder & Meynet 2001), as noted in the introduction. The question arises: could these two phenomena be related?

Indeed, if the rotation velocity is larger in low-Z environments, the mixing and the mass-loss rate will be enhanced during the MS phase, as noted above. Once the star reaches the WR stage, more helium-burning products will be visible at the surface of the star and a fortiori in the wind. An enhanced abundance of helium in the atmosphere of the star reduces its opacity (Meynet & Maeder 2002). The star is more compact, and therefore bluer. This means that, for a given mass, the star will be also hotter. Since the temperature is directly related to the ionization subclass (see, e.g., Hamann, Koesterke & Wesselowski 1995; Crowther, Smith & Hillier 1995), the star is likely to appear with an ‘earlier’ subtype. This hypothesis (rotation velocity larger at lower metallicity) also has the major advantage of explaining the presence of hydrogen in spectra of early spectral subtype.

If this speculative hypothesis is true, it means that WR2 and WR4 are in fact, from the evolutionary point of view, true late-type WN stars. However, they appear with a WNE, or nearly so, spectral subtype (WR4 is indeed WN6) because of the effects of rotation on their internal structure. On the other hand, WR1, WR9, WR10 and WR11 are certainly ‘truer’ WNE stars, although certainly not as evolved as their Galactic counterparts. In fact, WR2 and WR4 have narrower emission lines [FWHM(He II λ4686) ~15 Å] than WR1, WR9, WR10 and WR11 [FWHM(He II λ4686) ~22 Å]. This means that the latter stars are hotter, and are therefore probably more evolved.

In this context, it is probable that WR2 and WR4 are certainly the more massive stars in the single-star population in the SMC. If the above hypothesis is true, it means that rotation has played a major role in their formation. It does not rule out the possibility of very high-mass progenitors, but this possibility becomes less necessary to explain their formation. Moreover, if rotation has played such a role in the formation of single WR stars in the SMC, it also explains the ‘normal’ binary frequency observed.

To add weight to this hypothesis, we emphasize that if rotation played an important role in the formation of WR stars, and that their progenitors are indeed rapidly rotating stars, these stars will appear overluminous for their actual masses (Maeder & Meynet 2000). Therefore, the estimations of the cluster turn-offs of Massey...
Table 17. Masses (in $M_\odot$) and the corresponding mass ratio $q \equiv M_\odot/M_{\text{WR}}$ of WR6 and WR7 from previous published solutions and the present study.

<table>
<thead>
<tr>
<th>Star</th>
<th>$M_{\text{WR}}$</th>
<th>$M_{\text{OB}}$</th>
<th>$q$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>WR6</td>
<td>$9 \pm 2$</td>
<td>$38 \pm 8$</td>
<td>4.2</td>
<td>Present study</td>
</tr>
<tr>
<td>WR7</td>
<td>$27 \pm 2$</td>
<td>$52 \pm 4$</td>
<td>1.8</td>
<td>2</td>
</tr>
<tr>
<td>WR7</td>
<td>$15 \pm 3$</td>
<td>$55 \pm 12$</td>
<td>3.6</td>
<td>Present study</td>
</tr>
</tbody>
</table>

References: 1, Hutchings et al. (1984). The values quoted are those preferred by the authors. 2, Niemela et al. (2002). We corrected the values of Niemela et al. with an inclination angle of 60°.

et al. (2002), who used the ‘old’ evolutionary paths of Schaller et al. (1992) must be corrected to lower values.

4.3 Masses of the binary components

Before discussing the formation of binary stars in the SMC, we discuss the different determination of the masses of the WN binaries for which one is able to measure the amplitudes of both components: WR6 and WR7.

Since the photometry of both stars shows no eclipses in folding with the orbital period, the inclination angle is significantly less than 90°. In fact, one of us (AFJM) found an inclination angle for WR6 of $65° \pm 7°$ from unpublished polarimetric data. If we adopt an inclination angle of $i = 60°$ for both stars the resulting masses are summarized in Table 17.

The masses of the components in WR6 found in the present study do not agree with those found by Hutchings et al. (1984), who even argued that, using an inclination angle of $i = 60°$, values of less than 9 and 45 $M_\odot$ for the WR and OB component, respectively, are unlikely. This difference clearly arises from the fact that we obtained a smaller RV amplitude $K$ for the WR component. However, our estimation of the mass of the OB component in WR6 is in better correspondence with its spectral subtype. For this reason, we think that our solution is better.

The mass we found for the WR component of WR7 does not agree with that found by Niemela et al. (2002, which was corrected for the given inclination angle in Table 17). However, in this case, our solution is certainly less accurate, since we have a lot fewer spectra than Niemela et al., and we did not take into account the phase shift of $\sim 1$ d between the two components in the orbital solution. Therefore, the solution of Niemela et al. is certainly more reliable.

4.4 Formation of WR stars at low Z: the binaries

As shown above, RLOF is not a dominant mechanism for forming all WR stars at low Z. However, for the observed binaries in the SMC, RLOF could have occurred. The models of interacting massive binaries (Vanbeveren, de Loore & van Rensbergen 1998; Wellstein & Langer 1999) all show that RLOF is a short-duration process, with two phases of very strong mass loss, up to $10^{-3} M_\odot$ yr$^{-1}$ (e.g. Wellstein, Langer & Braun 2001) over roughly $10^6$ yr, followed by a second phase with $M \sim 10^{4.5} - 10^5 M_\odot$ yr$^{-1}$ for roughly $1.5 \times 10^7$ yr. A rough estimate of the total amount of mass lost by the primary is: $\sim 12 M_\odot$.

For short-period massive binaries, there is a priori no reason for RLOF not to occur. However, the authors of these models often argue that there is significant accretion of matter by the secondary star. Arguments in favour of accretion in such systems have been discussed by Wellstein & Langer (1999).

If accretion does occur, in whatever way, i.e. via a direct hit or a keplerian disc (see, e.g., Wellstein et al. 2001), the secondary is rejuvenated. For some moderate-mass stars, a second RLOF can occur, and the matter is transferred back to the primary. This implies increased difficulty in finding signatures of what happened in both stars. We suppose in what follows that only one RLOF occurred, if any. The first consequence of the possible rejuvenation, is the possibility of having binary systems such as WN3+O3, i.e. a hot and evolved WR star at least 3 or 4 Myr old, and a very early-type (i.e. massive) O star, the age of which should apparently be much less than that of the WR star. This apparent contradiction is resolved by interacting massive star models.

However, no such binary systems exist in the SMC. The three binaries for which we have at least a rough idea of the spectral types of the companion are: WR3 (WN3h+O9), WR6 (WN4+O6.5I) and WR7 (WN6+O7). None of the secondaries appear to be significantly younger than their WR counterpart (except for the WC/WO binary system WR8, see below). Additionally, if the formation of the primaries has been influenced by rotation, they are indeed less evolved than their spectral subtypes suggest, as for single stars.

Another problem appearing in RLOF models for SMC WR stars is that no hydrogen is expected to be present, or clearly present in the post-RLOF WR primary (Wellstein et al. 2001). We clearly found significant hydrogen in the WR winds of most of the WN stars.

An important test for interacting massive binary models involves period changes. Depending on the fraction of mass accreted or not, and the fraction of mass lost by the entire system, the period will change, because of the transfer or loss of angular momentum. Following the models of Vanbeveren et al. (1998), the situation can be summarized as follows.

(i) If the primary experiences a LBV stage, the mass ejected during the outburst is expected to leave the system. The period increases, following their equation (4.2) in Vanbeveren et al. (1998), the subscript ‘0’ denotes values at the beginning of RLOF:

$$\frac{P}{P_0} = \left(\frac{M_{1,0} + M_{2,0}}{M_1 + M_2}\right)^2.$$  

(ii) If the primary experiences RLOF and the secondary accretes the totality of the mass lost by the primary ($\beta \equiv 1$), the period increases following their equation (4.4):

$$\frac{P}{P_0} = \left(\frac{M_{1,0} M_{2,0}}{M_1 M_2}\right)^3.$$  

(iii) If the primary experiences RLOF and the secondary does not accrete at all ($\beta \equiv 0$), the period decreases following their equation (4.6):

$$\frac{P}{P_0} = \left(\frac{M_{1,0} M_{2,0}}{M_1 M_2}\right)^{0.42} \exp\left(3.42 \frac{M_1 - M_{1,0}}{M_2}\right).$$

The values quoted here are for the so-called ‘Case B’ RLOF (see, e.g., Wellstein et al. 2001), which is expected to be the most common among interacting massive binaries (Vanbeveren, van Rensbergen & de Loore 1998). We note, however, that for Case A RLOF (the star fills its Roche lobe during core hydrogen burning instead of filling its lobe after core hydrogen burning, following the original definitions by Kippenhahn & Weigert 1967), the situation is similar in terms of mass loss, i.e. lasting $\sim 10$ times longer, but with a smaller mass-loss rate by (at least) an order of magnitude for both phases.
Figure 17. Period change versus the initial mass of the primary for the two extreme case of accretion and for an LBV-type mass loss, for two values of the initial-mass ratio. Vertical dotted lines represent the lower limit of initial primary mass for WR binaries for $q_0 = 0.9$ and $\beta = 1$. See the text for details.

To estimate the amount of mass lost by the primary during RLOF, we used the formulae for the SMC given in Vanbeveren et al. (1998, p. 104). Fig. 17 shows the period changes as a function of the initial mass of the primary, for two values of the initial-mass ratio $q \equiv M_\text{O}/M_\text{WR}$, and for the two RLOF cases of no accretion ($\beta = 0$) and complete accretion ($\beta = 1$) and for a LBV-type mass loss.

We can roughly distinguish two different regimes in Fig. 17: for an initial mass of the primary smaller or larger than $\sim 40 M_\odot$. Above this limit all estimations of the period changes converge toward 1. Therefore, it is hard to use this test as a constraint for the observed WR binaries. Below $\sim 40 M_\odot$ things are different.

(i) For the case of no accretion ($\beta = 0$), $P/P_0$ is between $\sim 0.01$ and 0.1. This means that initial periods of SMC WR binaries that would have followed this scenario would lie between 100 and 1000 d.

(ii) For the case of full accretion ($\beta = 1$), $P/P_0$ is comprised between 1 and more than 5, depending on the initial-mass ratio. For $q_0 = 0.5$, the period does not change significantly, and the SMC WR binaries would have similar initial periods as observed today. In contrast, with an initial-mass ratio of $q_0 = 0.9$, the initial periods of the WR binaries in the SMC would fall into the range of 2–4 d designated as Case A RLOF in interacting binary models (see the footnote above). This case of RLOF does not produce WR+OB binaries, but leads to spiral-in of the secondary into the envelope of the primary, and the two stars probably merge. The corresponding minimum values for the initial mass of the primary for WR binaries in the SMC are indicated by vertical dotted lines in Fig. 17.

(iii) The LBV scenario is valid only for large initial masses, and suppresses a possible RLOF. At Galactic metallicity, an initial-mass limit of the primary of $M_1, i > 60 M_\odot$ is generally assumed in the models cited above (this limit corresponds to the limit for single-star models). At low metallicity, this limit will therefore increase ($M_1, i \sim 85 M_\odot$).

The test of period changes reveals that for an initial mass of the primary above $40 M_\odot$, all scenarios are possible. However, it also shows that the fraction of the space parameter where $M_1, i > 40 M_\odot$, $\beta = 1$ and $q = 0.9$ is unlikely, since in that case, the initial period of the binary systems would not lead to WR+OB systems (Case A).

To further constrain these partial results, we apply the test of the post-RLOF mass ratio, using the same interacting models as cited above. Fig. 18 shows the post-RLOF mass ratio for two values of $\beta$ versus the initial mass of the primary star. The case of LBV-type mass loss is also indicated. An initial-mass ratio $q_0 = 0.9$ is assumed. The position of WR6 (taking the mass ratio found in the present study) and WR7 (the mass ratio from Niemela et al. 2002) are shown by horizontal dotted lines.

This test shows that the initial mass of the primary for WR6 should lie around $20 M_\odot$ for complete accretion ($\beta = 1$), which is not allowed by the test of period changes. For $q_0 = 0.5$ (not shown in Fig. 18), the initial mass of the primary lies around
Figure 18. Post-RLOF mass ratio $q$ versus the initial mass of the primary. An initial-mass ratio of $q = 0.9$ is assumed. See the text for details.

15 $M_{\odot}$. The corresponding initial period would be $\sim 3$ d (i.e. $P/P_0 \sim 2$), which is not allowed by the models either. Moreover, if our estimation of the mass of the WR component is correct, it means that the primary lost only 6 $M_{\odot}$ during RLOF, which is half of what is expected theoretically, not taking into account the additional mass lost between RLOF and the present state.

To summarize, the scenario of full accretion appears to be unlikely for the system WR6, whatever the initial values of the mass of the primary, and the mass ratio. Therefore, the remaining possibility is the scenario of no accretion. In that case, the primary must have an initial mass above the mass of its companion, at least of the value of the present state (i.e. $> 38$ $M_{\odot}$), since it entered the WR stage first.

Although the test of period changes allows such a scenario, the test of post-RLOF mass ratio does not. Following this latter test, the actual mass ratio of the system WR6 should be less than 1.5. Moreover, the orbit of WR6 is slightly eccentric, which is not expected since RLOF with accretion is expected to circularize the orbit.

This analysis points towards the fact that RLOF has not occurred in the binary system WR6. The only remaining possibility is that the primary in WR6 was initially massive enough to become a WR star through the stellar wind mass loss. It could also have experienced an LBV outburst, but the past occurrence of this event should be confirmed by observations.

The present mass ratio of WR7 is consistent with the fact that this binary system is less evolved than WR6. The test of post-RLOF mass ratio leads to an initial mass of the primary of $\sim 45$ $M_{\odot}$ if $\beta = 1$, which is allowed by the first test. We obtain $\sim 32$ $M_{\odot}$ if an initial-mass ratio $q_0 = 0.5$ was assumed (not shown in Fig. 18). Although being apparently smaller than the mass of the secondary, these values are consistent if we take into account that $\sim 12$ $M_{\odot}$ were transferred from the primary to the secondary star.

However, for the $\beta = 0$ scenario, although allowed by the test of period changes, the initial mass of the primary will be significantly less than that of the secondary (for all values of $q_0$), which is contradictory with the fact that it entered the WR stage first.

Following these two tests, it appears that the system WR7 could have experienced an RLOF only if accretion was significant. However, the formation of the WR component in WR7 could have also been caused by stellar wind mass loss. Furthermore, the presence of hydrogen in the wind of the WR star will favour this latter scenario, since no detectable hydrogen is expected to remain in the wind of the primary after RLOF.

We note, however, the interesting case of the WC/WO binary WR8, which has a spectral type of WO4 + O4V and a period of approximately 16 d (Bartzakos et al. 2001). Has this star experienced RLOF? The actual mass ratio of WR8 is $\sim 3.7$. The test of the post-RLOF mass ratio leads to an initial mass of the primary (with $\beta = 1$, as required by the early type of the OB companion) of around 22 $M_{\odot}$. In that case, the test of period changes shows that its initial period should have been three times smaller than what is observed today: $\sim 6$ d. Although closer to the expected Case A RLOF that leads to mergers, this scenario is possible (and even more so if we...
take into account the wind mass loss involved between the RLOF and the present WC/WO state).

This case is particularly interesting regarding the fact that WNE stars were originally expected to be the most sensitive candidates for RLOF evolution.

In all the three cases discussed here (WR6, WR7 and WR8), the LBV scenario cannot be ruled out, since no significant period changes nor post-LBV mass ratio is expected theoretically. A careful analysis of the neighbourhood of these stars would clarify this possibility.

We may also argue that the single stars observed in the SMC could have followed the case where the periods do not change significantly (i.e. $M_{1,i} > 40 M_{\odot}$ and/or $\beta = 1, q = 0.5$) and because of initially long periods we did not detect these stars as binaries. However, at least for WR1, WR9, WR10 and WR11, the arguments against this scenario (i.e. mass loss not sufficient to explain the low luminosity and the presence of hydrogen in the WR wind) remain. Moreover, the test of the post-RLOF mass ratio shows that for high initial-mass primaries, the secondaries should have a mass similar to that of the primaries, and would therefore be visible.

This discussion leads us to claim that if RLOF occurred in SMC WR binaries, it probably did not occur for all of them. A persistent problem is that the interacting binary models often provide observational predictions of the state of the WR component, which are similar to that of single-star models. The test of abundances seems, however, to be the best test available for distinguishing between the two sets of predictions. The combination of the tests of period changes and post-RLOF mass ratio proved to be useful. However, since mass-loss rates are poorly known observationally and theoretically, this combination of tests does not provide definitive conclusions.

5 CONCLUSIONS

We have studied in detail the binary character of each WR star in the SMC. Among the 11 stars known, six stars are probably true single stars (SMC-WR1, WR2, WR4, WR9, WR10 and WR11). We provided the first orbital solution known for SMC-WR3. We emphasize that, although our prime indicator of the binary status shows that WR9 may be a binary, all other indications point towards a single-star status. More data are needed to confirm the status of this star.

We found the clear presence of hydrogen in the winds of most of the WN stars in the SMC. We have shown that no photometric eclipses exist for the binaries, except for WR5. We found, however, a periodic signal of 6.55 d for the single star WR4, which could be caused by large-scale and rotating structures. X-rays are clearly detected in three binaries: WR5, WR6 and WR7; WR5 (HD5980) being one of the most X-ray luminous stars known. The exception of WR3 is understandable given its spectral subtype and the faintness of its companion.

Using these complementary data sets, we have clarified the situation of the WR stars in the SMC. We have shown that WR2 and WR4 are probably, from the evolutionary point of view, late-type stars, but appear with a relatively early subtype probably because of the influence of rotation on their internal structure. The other single stars appear therefore to be the true WNE stars in the SMC, although not as evolved as their Galactic counterparts since they still have easily detectable amounts of hydrogen in their spectra. We were not able to rule out the possibility of very high initial-mass progenitors. However, rotation is found to probably play an important role on the formation of single WR stars in the SMC. Rotation also allows us to explain the ‘normal’ binary frequency (i.e. a frequency similar to what is observed at other metallicities).

For binary stars, we discussed the possible past occurrence of RLOF. The situation is obviously complex, but it is probable that RLOF did not occur in all observed binaries. An RLOF scenario is certainly ruled out for WR6. However, it remains possible for WR7. The WC/WO star WR8 appears to be the best candidate for such an event. The detection of hydrogen in the wind of the WR component in the binaries WR6 and WR7 would be a pivotal test to discriminate between the interacting binary models and the models of formation valid for single stars.

Globally, the binary frequency of the WR stars in the SMC seems to be significantly smaller than the virtual 100 per cent binary frequency expected theoretically. This shows that the binary channel, although important, is not dominant for the formation of WR stars in low-metallicity environments. This could have strong consequences for starburst characteristics (see, e.g., Schaerer & Vacca 1998).

Our overall conclusion is, in some sense, conservative. The SMC has a normal binary frequency of WR stars. SMC WR stars probably do not have very high-mass progenitors, since they are able to appear as WR without huge mass loss. RLOF could have occurred in some binary systems, however, probably not in all systems. Rotation is probably the mechanism to account for the properties of the SMC WR population.

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