High-mass X-ray Binaries: Illuminating the Passage from Massive Binaries to Merging Compact Objects
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Spectroscopy of complete populations of Wolf-Rayet binaries in the Magellanic Clouds

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Abstract. Classical Wolf-Rayet stars are evolved, hydrogen depleted massive stars that exhibit strong mass-loss. In theory, these stars can form either by intrinsic mass loss (stellar winds or eruptions), or via mass-removal in binaries. The Wolf-Rayet stars in the Magellanic Clouds are often thought to have originated through binary interaction due to the low ambient metallicity and, correspondingly, reduced wind mass-loss. We performed a complete spectral analysis of all known WR binaries of the nitrogen sequence in the Small and Large Magellanic Clouds, as well as additional orbital analyses, and constrained the evolutionary histories of these stars. We find that the bulk of Wolf-Rayet stars are luminous enough to be explained by single-star evolution. In contrast to prediction, we do not find clear evidence for a large population of low-luminosity Wolf-Rayet stars that could only form via binary interaction, suggesting a discrepancy between predictions and observations.

Keywords. stars: Wolf-Rayet, binaries: spectroscopic, Magellanic Clouds, stars: evolution

1. Introduction

Wolf-Rayet (WR) stars define a spectral class of stars with emission-dominated spectra (e.g., Smith *et al.* 1996, Crowther *et al.* 2000) associated with strong, radiatively driven winds. Classical WR stars are understood to represent an evolved and relatively short-lived phase (≈0.5 Myr) of massive stars that have stripped a substantial part of their hydrogen-rich outer layers. However, very massive stars may already exhibit WR-like spectra at birth.

Studying WR stars is essential for understanding the evolution of massive stars, the energy budget of galaxies, and the upper-mass limit of stars. WR stars easily dominate entire populations of massive stars in terms of their mechanical and radiative energy input (e.g., Doran *et al.* 2013, Ramachandran *et al.* 2018). Furthermore, as WR stars are the expected immediate progenitors of stellar-mass black holes (BHs), their attributes (e.g., mass-loss rates, masses) prior to core-collapse largely determine the properties of the BH remnant. Therefore, uncertainties with respect to WR stars directly translate to inaccurate predictions of rates and properties of gravitational wave (GW) events (e.g., de Mink *et al.* 2014, Eldridge *et al.* 2016).

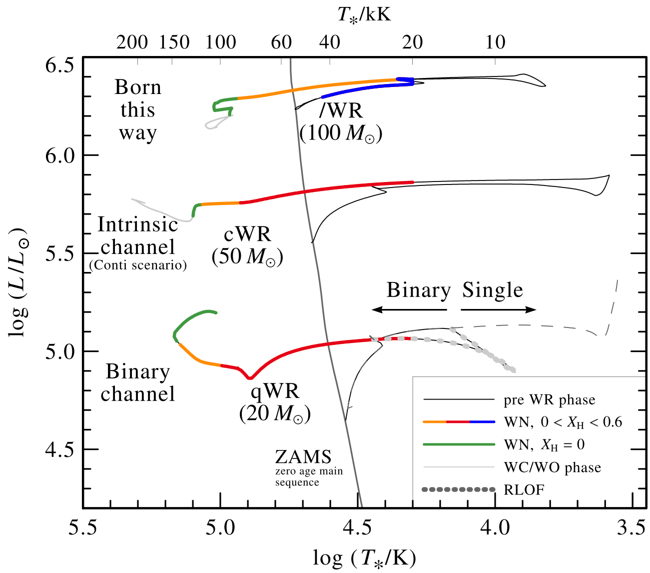

Figure 1. Evolution tracks calculated with the BPASS code for single stars with initial masses $M_i = 100, 50$, and $20\,M_\odot$, as well as a binary evolution track for the primary star with initial mass, period, and mass ratio of $M_i = 20\,M_\odot$, $P_i = 25\,d$, and $q_i = 0.3$, respectively (coloured part of lower track). The tracks illustrate the three formation channels for WR stars: the binary channel (lower tracks), the intrinsic channel (middle track), and the "born this way" channel (upper track).

In principle, WR stars may form via three channels:

(a) **Classical WR stars (cWR)** form through *intrinsic* mass-loss, either via stellar winds or eruptions (Conti 1976, Smith *et al.* 2006). They are evolved, hydrogen depleted (or hydrogen free) massive stars. Only stars that are sufficiently massive will reach the cWR phase. The minimum mass necessary is a strong function of the metallicity Z, and is estimated to be $\approx$20 $M_\odot$ at solar metallicity and $\approx 45 - 60\,M_\odot$ at $\approx 1/5\,Z_\odot$ (Crowther 2006, Hainich *et al.* 2014), keeping in mind that the latter values suffer from large uncertainties.

(b) **Binary product WR stars (stripped stars, quasi-WR, qWR)** are hydrogen depleted stars that lie close to the Eddington limit after having lost their hydrogen-rich envelope through *binary interaction*, either via Roche lobe Overflow (RLOF) or via common-envelope (CE) evolution (Paczynski 1973, Vanbeveren *et al.* 1998).

(c) **"Born this way" stars (/WR, WNh)** are born with such high masses ($\gtrsim 60\,M_\odot$ at solar metallicity) that they possess strong, WR-like stellar winds already at birth. Typically, spectra of such stars show P-Cygni like Hβ profiles, and they are therefore often associated with "slash stars" (Crowther 2011) or WNh stars, although very young and massive stars may also exhibit pure Hβ emission and may thus be classified as WR stars. Because they are not evolved, they are not necessarily hydrogen depleted.

These three WR-types are illustrated in Fig. 1 using evolution tracks calculated with the BPASS† (Binary Population and Spectral Synthesis) code (Eldridge *et al.* 2008, Eldridge *et al.* 2017). While the spectroscopic definition of WR stars is fairly unambiguous (e.g., Smith *et al.* 1996, Crowther 2011), it is usually not straightforward to identify a WR star's evolutionary channel from its spectrum.

One of the central problems in this context is to correctly estimate the frequency of stripped stars, or qWR stars, in a host galaxy as a function of Z. Several studies give

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direct evidence that the vast majority of massive stars will interact with a companion star during their lifetime (Sana *et al.* 2012). Among the WR stars, about 40 % are observed to be binaries (e.g., van der Hucht 2001).

Considering the strong tendency of the initial mass function (IMF) to form lower-mass stars and the frequency of interacting binaries, stripped WR stars (qWR stars) should be abundant in our Universe - much more abundant than classical WR stars - bearing large implications on the energy budget of galaxies (e.g., Götberg *et al.* 2018). However, to-date, only one star, HD 45166, is considered a good candidate for a stripped WR star (Oliveira *et al.* 2003, Groh *et al.* 2008). Several low-mass ($\approx 1\,M_\odot$) O-type subdwarfs (sdO) believed to originate from binary mass-transfer have been discovered near B-type stars (the putative mass-accretors), but their masses are too low to support a strong stellar wind and a corresponding WR-star appearance (e.g., Wang *et al.* 2018). While other peculiar WR stars have been suggested to originate from binary interactions (Schootemeijer & Langer 2017, Neugent *et al.* 2017), there is an obvious dissonance between the predicted abundance of qWR stars and their observed number. In fact, it is not even certain that a stripped star would portray a wind that is strong enough to impart on the star the appearance of a WR star: While theoretical predictions for the mass-loss rates of qWR stars exist (Vink *et al.* 2017), empirical $\dot{M}$ estimates for qWR stars are still lacking.

It is by now empirically (Mokiem *et al.* 2007, Nugis *et al.* 2007, Hainich *et al.* 2015) as well as theoretically (Kudritzki *et al.* 1987, Vink *et al.* 2001) established that the intrinsic mass-loss rates of massive stars decrease with decreasing surface metallicity, $\dot{M} \propto Z^\alpha$, with $0.5 \lesssim \alpha \lesssim 1$. This immediately implies that it is harder for stars at low metallicity to intrinsically peel off their outer layers and become cWR stars. In other words, the intrinsic formation channel - if dominated by mass-loss by continous stellar winds - becomes increasingly inefficient with decreasing metallicity. In contrast, the binary formation channel is, at least to first order, independent of the metallicity†. One therefore concludes that the binary channel should become increasingly dominant in the formation of observed WR populations at low metallicity.

Motivated by such predictions, Bartzakos *et al.* (2001), Foellmi *et al.* (2003a), Foellmi *et al.* (2003b), and Schnurr *et al.* (2008), conducted a large spectroscopic survey in the Small and Large Magellanic Cloud (SMC and LMC, respectively) with the goal of measuring the binary fraction in their WR populations. The LMC and SMC are both known to have a subsolar metallicity of a factor $\sim 1/3$ and $\sim 1/5$ solar, respectively (Dufour *et al.* 1982, Larsen *et al.* 2000). Following the reasoning of the previous paragraph, it is expected that the fraction of WR stars formed via the binary channel will be relatively large in the LMC, and even larger in the SMC. Relying on models by Maeder *et al.* (1994), Bartzakos *et al.* (2001) argued that virtually *all* WR stars in the SMC are expected to have been formed in binaries. This prediction remains valid even with the most recent generation of stellar evolution codes (e.g., Georgy *et al.* 2015). It was therefore surprising that the measured WR binary fraction in the SMC is only ≈40% (Foellmi *et al.* 2003a), comparable to the Galactic fraction. A similar, slightly lower binary fraction is obtained for the LMC (Foellmi *et al.* 2003b). This revealed a clear discrepancy between theory and observation which must be explained.

To explore the formation channels of the WR stars in the Magellanic Clouds, we performed spectral analyses and, when possible, orbital analyses of all known WR stars and binaries of the nitrogen sequence (WN) in the Magellanic Clouds. The results for

† At low metallicity, the radiation pressure is lower, and thus so are the stellar radii for a given initial mass and age, which in turn reduces the likelihood of binary interaction, primarily for case A mass-transfer (i.e. mass-transfer during the main sequence). However, this effect is negligible compared to the sensitivity of $\dot{M}$ to Z.

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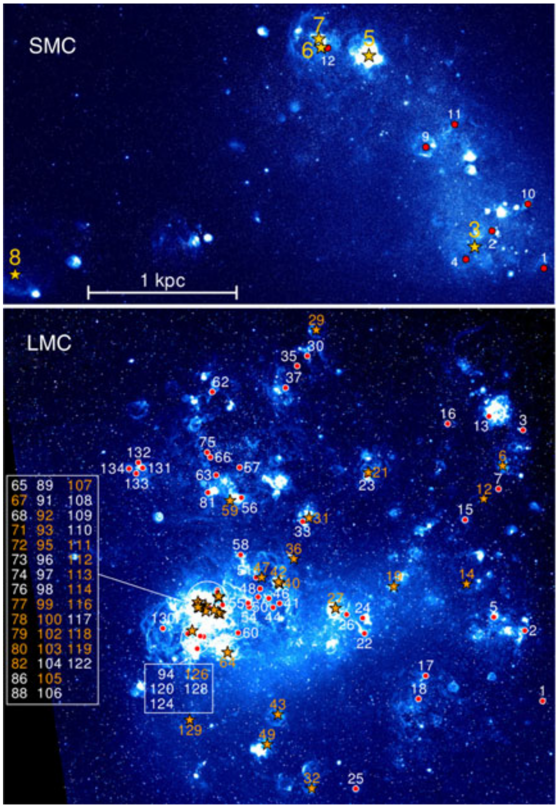

Figure 2. Upper panel: A narrow band O [III] nebular emission image of the SMC Smith *et al.* (2005) with all known WN stars and binaries marked. Nomenclature follows the catalogues Azzopardi & Breysacher (1979) and Breysacher *et al.* (1999) for the SMC and LMC, respectively. Yellow stars correspond to confirmed binary systems. Lower panel: same as the upper panel, but for the LMC in the Hα band.

the single WR stars were published by Hainich *et al.* (2014, 2015), while the binary samples were analyzed by Shenar *et al.* (2016) for the SMC and Shenar *et al.* (in prep.) for the LMC. The very massive WR+WR system BAT99 119 (R 145) in the LMC was analyzed by Shenar *et al.* (2017), while the WR quadruple/quintuple system SMC AB 6 was analyzed in Shenar *et al.* (2018). In these proceedings, we focus on the WR binaries.

2. Target selection and observations

A census of the known WR stars in the Magellanic Clouds is given by Massey *et al.* (2014) and Neugent *et al.* (2018). The positions of of all known single and binary WN stars and binaries in the SMC and LMC are displayed in Fig. 2.

The SMC sample comprises the five confirmed WR binaries SMC AB 3, 5, 6, 7, and 8, where SMC AB 5 was recently found to be a quadruple or quintuple system (Shenar *et al.* 2018). Among the 109 WR stars listed in the fourth catalog of WN stars in the LMC (Breysacher *et al.* 1999, BAT99 hereafter), Hainich *et al.* (2014) identified 43 that are either known binary/multiple systems or binary candidates. These 43 objects constitute our sample. 19 of these objects were confirmed via periodic RV variation to be binary/multiple systems, and six are considered binary candidates on the basis of RV variations for which no period could be found. Other binary candidates were identified based on their X-ray properties. A comprehensive list can be found in Hainich *et al.* (2014).

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The observational dataset largely relied on the dataset used in the studies by Foellmi *et al.* (2003a), Foellmi *et al.* (2003b), and Schnurr *et al.* (2008). In some cases, archival ESO data could be retrieved. UV and far-UV data from the International Ultraviolet Explorer (IUE) and Hubble Space Telescope (HST) could also be retrieved for some of our targets. For a detailed account of the observing material, we refer to the aforementioned studies, as well as to Hainich *et al.* (2014, 2015) and Shenar *et al.* (2016, 2017, 2018).

3. Methods

The spectral analysis is performed with the non-LTE Potsdam Wolf-Rayet (PoWR) model atmosphere code, especially suitable for hot stars with expanding atmospheres†. It iteratively solves the co-moving frame radiative transfer and the statistical balance equations in spherical symmetry under the constraint of energy conservation. A more detailed description of the assumptions and methods used in the code is given by Gräfener *et al.* (2002), Hamann *et al.* (2004), and Sander *et al.* (2015). By comparing synthetic spectra generated by PoWR to observations, the stellar parameters can be derived.

By analyzing the spectra with the PoWR tool, we can derive the effective temperatures T_*, luminosities $\log L$, radii R_*, mass-loss rates $\dot{M}$, and other parameters of interest. Quantities marked with an asterisk refer to a Rosseland optical depth of τ_{Ross}=20, which is defined to be the inner boundary of our models. When possible, spectral disentanglement was utilized for binaries to separate the spectra into their constituents. Otherwise, composite spectra were analyzed by adding up model spectra corresponding to the various components of the systems. For a complete account of the methodology of binary analysis, we refer the reader to Shenar *et al.* (2016, 2017, 2018). In Fig. 3, we show an example for a binary analysis of the system BAT99 6.

4. Results

Figure 4 summarizes the positions of all WR binary components in the Magellanic Clouds on a Hertzsprung Russell diagram (HRD). The surface hydrogen mass fractions of the WR stars are color-coded. The same Figure also includes evolution tracks for non-rotating single stars calculated for LMC and SMC metallicity with the BPASS code.

In Shenar *et al.* (2016), we provide a detailed comparison to binary evolution tracks for each of the WR binaries in the SMC. This was done by comparing the full set of observables (e.g., periods, masses, temperatures, luminosities, rotation...) to evolution tracks calculated with the BPASS code. Through this, we derived initial masses and periods, as well as ages, for each of the binaries.

While we generally find that binary interaction can better explain the properties of the observed WR binary population in the SMC, all WR components are found to have very large initial masses ($M_{\mathrm{i}} \gtrsim 60\,M_{\odot}$). With such initial masses, it seems likely that the WR components would have entered the WR phase regardless of binary interaction. This stands in strong contrast to the prediction that all WR stars in the SMC must have formed via binary interaction.

Moreover, there is an apparent lack of WR components with luminosities lower than $\approx$5.8 dex. Such WR stars are expected to be abundant - much more abundant than their massive counterparts - given the tendency of the IMF to form lower-mass stars and the frequency of interacting binaries. However, none can be found in the SMC. One may think that stars at such luminosities at SMC metallicity do not retrain the appearance of a WR star. However, single WR stars in the SMC (e.g. SMC AB 2), with luminosities of $\approx$5.5 dex, do have the appearance of a WR star.

† PoWR models of Wolf-Rayet stars can be downloaded at http://www.astro.physik.uni-potsdam.de/PoWR

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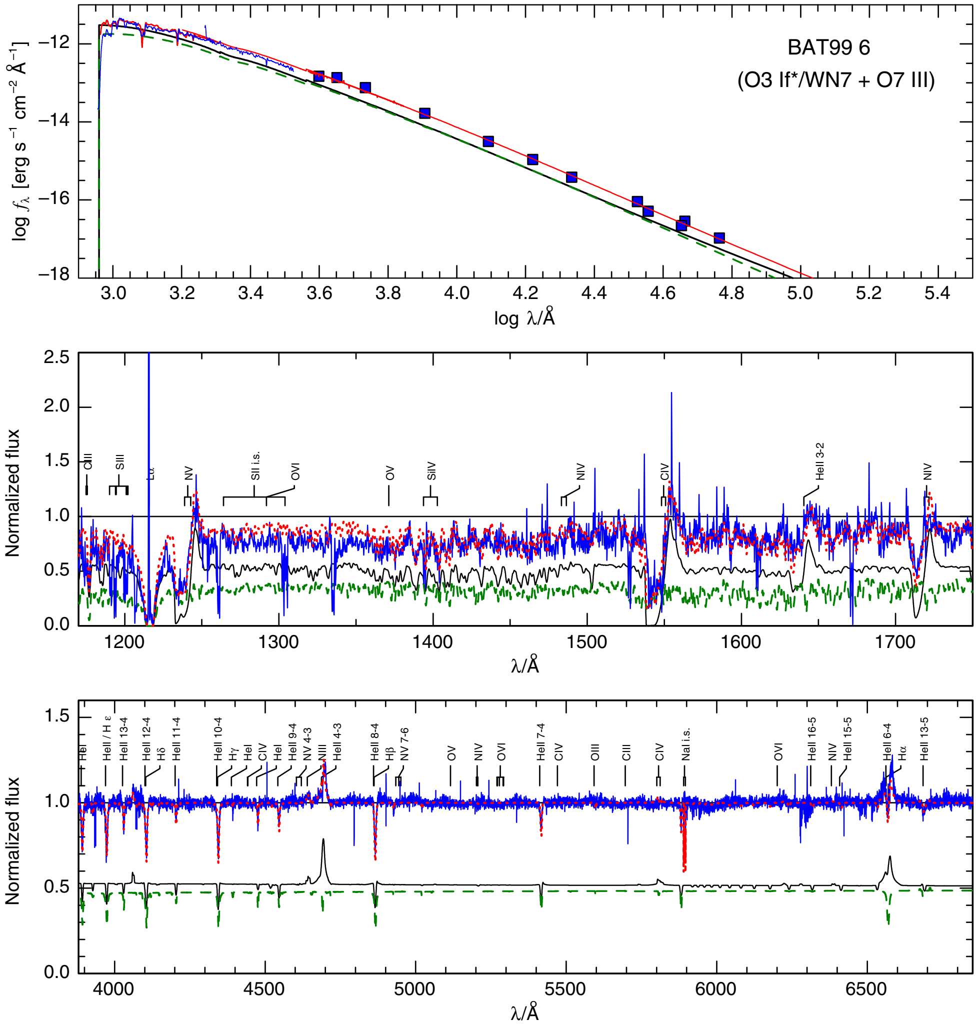

Figure 3. A spectral analysis of the system BAT99 6. The observed photometry and spectra (archival IUE, FEROS) of BAT99 6 are shown in blue. The composite synthetic spectrum (red dotted line) is the sum of the WR (black solid line) and O (green dashed line) models. The relative offsets of the model continua correspond to the light ratio between the two stars.

A similar result is obtained for the LMC sample, this time offering much better statistics. While the detailed evolutionary analyses of each binary are still underway (Shenar *et al.* in prep.), it is evident from the right panel of Fig. 4 that the majority of observed WR stars in the LMC can be explained with single-star evolution. While this does not mean that binary interaction did not take place, it again raises the question as to the lack of low-luminosity WR stars that are supposedly the product of binary interaction. This time, the LMC sample does offer a few interesting candidates (most interestingly BAT99 72), but this population again appears much smaller than predicted.

It has been suggested that many of these stars may remain very difficult to detect since they are expected to be the companions of massive, visually-brighter OB-type stars (e.g., Paczynski 1973, Schootemeijer *et al.* 2018). However, whether this can truly explain the apparent lack of qWR stars, compared to their anticipated abundance, needs to be further tested.

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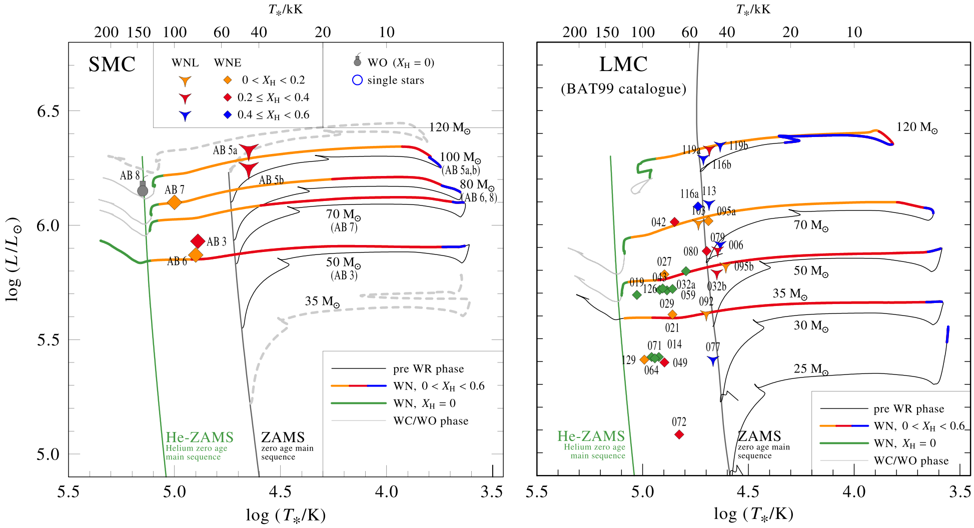

Figure 4. Comparison between observed HRD positions of our the WR components in WR binaries in the SMC (left panel) and LMC (right panel), adopted from Shenar *et al.* (2016, 2017, 2018 in prep.). Also shown are evolution tracks calculated with the BPASS code for non-rotating single stars at SMC (left panel) and LMC (right panel) metallicity for various initial masses. It is evident that the majority of WR components are luminous enough to be explained with single-star evolution.

5. Summary

We performed a spectral analysis of all known single and binary WR stars in the SMC and LMC. Our results were published in Hainich *et al.* (2014, 2015) and Shenar *et al.* (2016, 2017, 2018), with the LMC binary sample soon to be published (Shenar *et al.* in prep.). These studies provide all stellar parameters that could be derived for the WR stars in the Magellanic Clouds and, if present, for their companions. When possible, orbital analyses were performed to derive further constraints on the orbits and masses of the systems.

We generally find that the vast majority of WR components in binaries in the Magellanic Clouds are sufficiently luminous to be explained by single-star evolution. There is a very obvious lack of WR stars at low luminosities ($\log L \lesssim 5.7$ $[L_\odot]$). Such stars are expected to be very abundant given the bias of the IMF towards lower masses and the prevalence of interacting binaries. However, only few such stars are actually observed in the LMC and none in the SMC.

Observational biases offer a possible way out of this contradiction: stripped qWR stars are expected to reside near visually-brighter and more luminous mass accretors, which may render the detection of their stripped companions difficult (Paczynski 1973). However, since we do observe many WR binaries with bright OB-type stars, it is not obvious that there should be an observational cut-off precisely at luminosities these stars are expected to possess. For now, we do not find clear indications that binary interaction dominates the formation of WR stars at the low metallicity environment of the Magellanic Clouds.

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Discussion

Kawai: Do you observe rotations in WR stars? It is important as WR stars could be progenitors of γ-Ray bursts.

Shenar: From the upper limits that could be derived, no significant rotation (above 200 km/s) could be derived. There are a few peculiar WR stars with very round emission lines (Shenar *et al.* 2014, A&A, 562, 118), but whether this is the result of rotation or not is still not clear.

Marchant: How do you find the best-fitting evolutionary status? When you compare your results to evolution tracks, you should use Bayesian statistics to account for the likelihood of your targets to be in the inferred positions on the tracks.

Shenar: I use a simple χ^2-fitting with a grid of models. I agree that the inferred HRD-positions may be affected by Bayesian statistics. However, the most important result - the initial mass - is virtually independent of the fitting method.