Massive Stars in Interacting Binaries
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Wolf-Rayet spectra: how to tell binaries from singles

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Abstract. Many Wolf-Rayet stars are suspected to be binaries because their spectra are considered as looking composite. Corresponding criteria are the weakness of the lines ("diluted emission lines, d.e.l."), or the presence of absorption features. However, single WR stars can provide an amazing variety of spectra, depending on their parameters. Many of the "composite" spectra can be reproduced with single-star models. Synthetic spectra from the Potsdam Wolf-Rayet (PoWR) code have been employed to test the Galactic WN stars. It turns out that neither the weakness of emission lines (d.e.l.) nor the presence of absorption features give unique evidence for binarity. However, the spectral energy distribution over a wide range (UV, optical, IR) should reveal the spectral contamination from a companion. We checked eight d.e.l. suspects and 29 further WN stars, but found significant UV/optical contamination only in one case of a well-known binary. Thus the fraction of Galactic WN binaries might have been over-estimated so far.

1. Introduction

The VII$^{\text{th}}$ Catalogue of Galactic Wolf-Rayet Stars (van der Hucht 2001) comprises 127 stars of the nitrogen sequence (WN). From these stars, 49 are included in the catalog's list (Table 18) of "WN-type binaries and probable binaries". However, the evidences for binarity are rather weak in many cases. Especially, for 21 stars in that table the binary designation is based on the *diluted emission lines* (d.e.l.) argument, which is in four cases supported by the presence of absorption features ("a") , and in five further cases backed by additional evidences like "SB1?". As long as these arguments are not confirmed, the fraction of binaries among the Galactic WN population should be considered as being highly uncertain. In the present paper we investigate, if and how composite spectra can be identified.

2. Diluted emission lines, absorption features

The d.e.l. argument is illustrated in Fig. 1. For instance, attributing 50% of the continuum to a companion results in two times stronger emission lines in the normalized WR spectrum. Keeping the absolute brightness of the WR component fixed, the spectral analysis yields a two times higher mass-loss rate. When the brightness of the WR component is reduced according to its fraction of the system's brightness, one derives a correspondingly smaller WR luminosity while the effect on $\dot{M}$ almost cancels out.

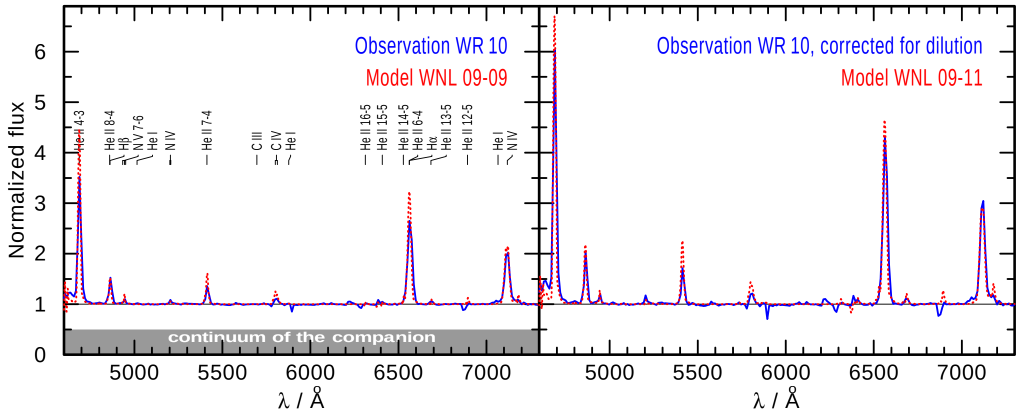

Figure 1. The "diluted emission line" (d.e.l.) effect. The left panel shows the observed, rectified spectrum of WR 10 (full line), which can be reproduced by a WN-late model from our PoWR grid (dotted). Now assume that actually half of the continuum is contributed by a companion (shaded). Then the rectified WR spectrum alone has twice as strong emission lines (right panel, full line). It can also be fitted by a grid model spectrum (dotted).

The identification of diluted emission line spectra relies on the assumption that WN stars of a given spectral type have a "typical" line strength. However, this is not corroborated by the empirical data. Figure 2 shows the (single) Galactic WN stars in the diagnostic $R_t - T_*$–diagram. These distance-independent

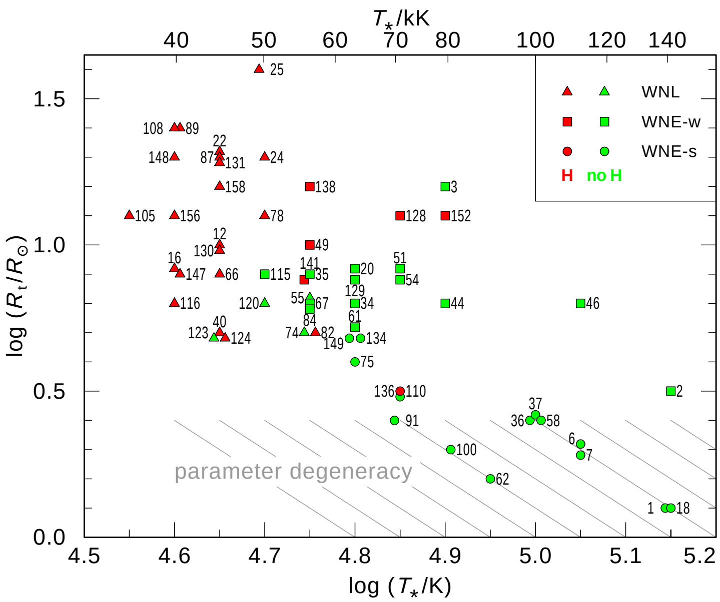

Figure 2. Analyzed (single) Galactic WN stars (labels: WR number) in the diagnostic $R_t - T_*$–diagram. For very dense winds, the parameters are degenerate along the inclined grey lines.

parameters determine the normalized spectrum, where the so-called transformed radius R_t especially influences the strength of the lines ($R_t \propto R_* \, (v_\infty / \dot{M})^{2/3}$, see e.g. Hamann & Gräfener 2004). The diagram clearly displays a two-parametric manifold; at a given stellar temperature T_*, WN stars with strong and with weak lines co-exist. Therefore the d.e.l. criterion is not conclusive for identifying composite spectra.

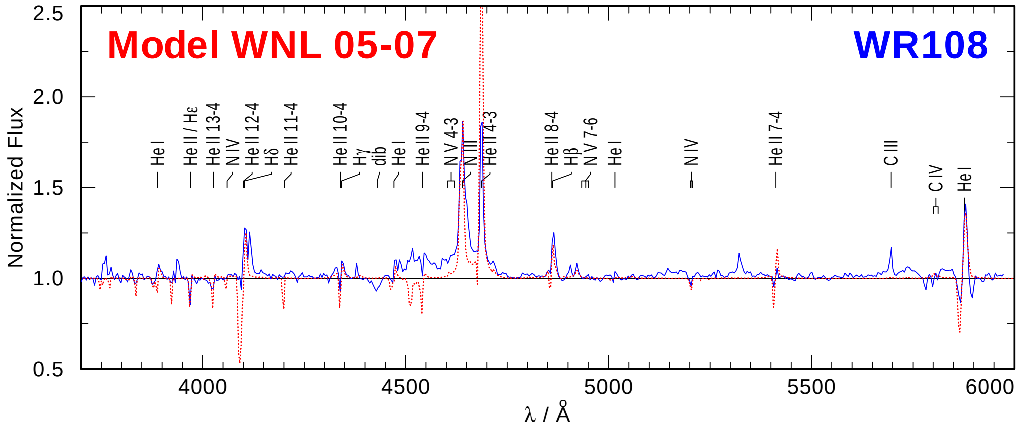

Figure 3. Observed spectrum (full line) of WR 108, in the catalog list of binaries (van der Hucht 2001) blamed with an "a" for absorption features which are attributed to an O-star companion. The model spectrum shown for comparison (dotted) exhibits even stronger absorptions just from a single-star atmosphere.

The occurrence of absorption features in a Wolf-Rayet emission line spectrum has been taken as another indication of binarity. This is evident if those features clearly follow the pattern of a known spectral type, and especially when they show a periodic Doppler shift in antiphase to the WR emission lines (SB2 systems). However, in general the weak absorption lines of, say, an O star are outshined by the bright emission lines of the WR companion, and are therefore hard to detect when both stars are of comparable brightness. On the other hand, WN atmospheres can easily produce absorption features by their own, as demonstrated in Fig. 3. Thus the mere existence of absorption features is not a compelling evidence for binarity either.

3. Spectral energy distribution

When analyzing a WR spectrum, we determine the atmospheric parameters from fitting the line spectrum. Generally we find that the best-fitting model then automatically also matches the spectral energy distribution (SED) over the whole observed wavelength range very well, if the color excess E_{b-v} is properly adjusted. Such a good fit of the SED is virtually excluding that the spectrum is composite. If a companion star would contribute significantly to the observed continuum, this will generally alter the shape of the SED. It is very unlikely that (possibly peculiar) interstellar reddening would exactly compensate for that effect.

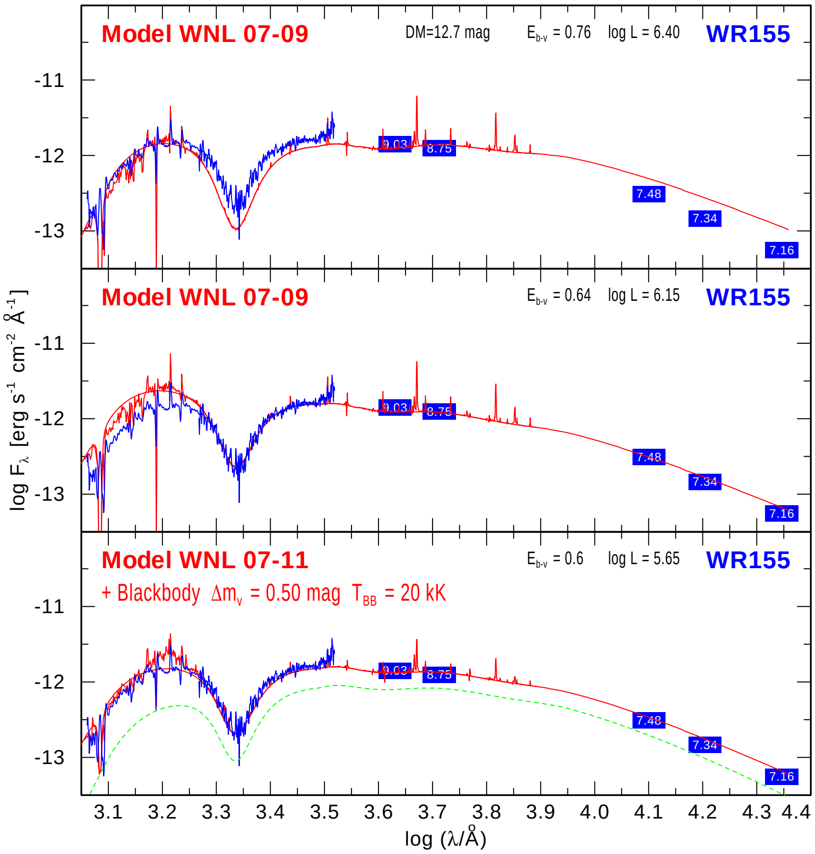

Figure 4. IUE spectrum (noisy line) and optical/IR photometry (dark blocks) of the well-known SB2 system WR 155 (=CQ Ceph). Model spectra (smooth lines) for a single star cannot match the SED, neither for a larger (top panel) nor for a smaller (middle panel) value of E_{b-v}. However, assuming a *composite* spectrum (WN, plus blackbody = dashed line) provides a good fit (bottom panel).

For example, the SB2 system WR 155 (= CQ Ceph) has been classified as a WN6 + O9 II-Ib system, where the O star is slightly brighter (by 0.25 ... 1.0 mag) than the WN star (Marchenko et al. 1995). In the top panel of Fig. 4, the reddening parameter is chosen such that the model reproduces the short-UV IUE observation, as well as the b and v narrow-band photometry. However, with this E_{b-v} a much stronger interstellar absorption bump at 2200 Å is predicted than observed. Alternatively, we might choose a smaller reddening in order to reproduce the 2200 Å feature and the IR-visual slope (middle panel). However, then the flux between 1200 and 2000 Å should be higher. The discrepancy can be solved when assuming that the observed SED is composite. For simplicity, we adopt for the companion a Planck spectrum. With a blackbody temperature of 20 kK and a visual brightness ratio of $m_v^{\rm WR} - m_v^{\rm O} = 0.5$ mag (Smith v), the entire SED can be matched (bottom panel of Fig. 4). The interstellar reddening law applied here is from Cardelli et al. (1988), who adopt a rather strong absorption

Table 1. Inspected d.e.l. suspects

WR	spectral type	binary status	composite SED ? UV/visual	IR
25	WN6h+O4f	d.e.l.	no	yes
44	WN4+OB?	d.e.l.	no	?
46	WN3p+OB?	d.e.l., SB1?	no	no
85	WN6h+OB?	d.e.l., VB	no	yes
108	WN9h+OB	a, d.e.l.	no	no
148	WN8h+B3IV/BH	SB1, d.e.l.	no	no
156	WN8h+OB?	d.e.l.	no	no
158	WN7h+Be?	d.e.l.	no	no

at short-UV wavelengths; less short-UV absorption, which is more typical for the Galaxy (see Fitzpatrick 1999), makes the single-star fit even more discrepant.

Note that for a given distance modulus the composed-SED model yields the smallest luminosity of the WR component. Moreover, a WN model with smaller transformed radius has to be chosen for the line fit because of the dilution effect.

After this successful test of the method, we inspected all stars from van der Hucht's list of WN binaries for which IUE and optical spectra are available to us. Surprisingly, not any of the eight stars (Table 1) shows an indication of being composite, in the way WR 155 does. On the contrary, the SEDs from single-star WN models always fit perfectly to the IUE observation and visual photometry.

In two or three stars, however, an excess of IR flux is observed (photometry from the 2MASS catalog). One example is WR 25 (Fig. 5), as already noticed by Crowther et al. (1995) who adopted an anomalous interstellar reddening law as explanation. Alternatively, a cool giant companion star could also do the job. Possibly the exceptional X-ray brightness of WR 25 might be related to its binarity. A similar IR excess is found in the spectrum of WR 85 and, less pronounced, WR 44.

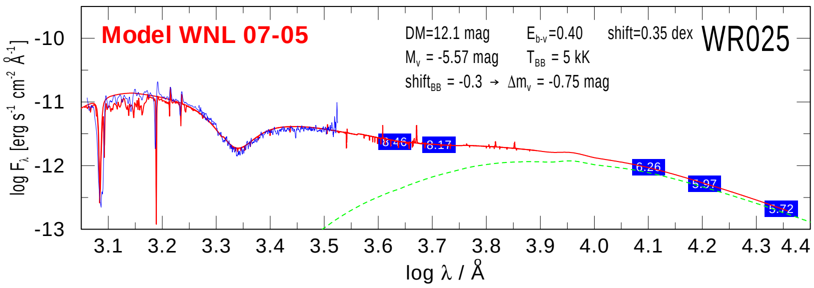

Figure 5. Spectral energy distribution of WR 25. The optical and UV is well matched by a single-star model. The photometric excess in the IR is reproduced with the help of an adopted cool companion (dashed line).

With the same method we have checked all other WN stars for which we have IUE and visual spectra (Table 2). Apart from the known binary WR 155 discussed above, we found no case where the observed UV/visual flux differs

Table 2. Further WN stars checked for composite SEDs

WR	spectral type	binary status	composite SED ? UV/visual	IR
1	WN4	SB1?	no	no
2	WN2	VB	no	no
3	WN3+04	SB2	no	no
6	WN4	SB1?	no	no
7	WN4		no	no
10	WN5ha(+A2V)	VB	no	no
12	WN8h+?	SB1, no d.e.l.	no	?
16	WN8h		no	no
18	WN4		no	no
22	WN7h+09III-V	SB2	no	no
40	WN8h		no	no
55	WN7		no	no
58	WN4/WCE		no	no
61	WN5		no	no
75	WN6		no	no
78	WN7h		no	no
110	WN5-6		no	?
123	WN8	SB1?, no d.e.l.	?	?
124	WN8h	SB1?, no d.e.l.	no	no
128	WN4(h)+OB?	SB2?	no	no
134	WN6	SB1?, no d.e.l.	no	no
136	WN6(h)	SB1?, no d.e.l.	no	no
138	WN5+B?	SB2,VB	no	no
141	WN5+O5V-III	SB2	no	no
155	WN6+O9II-Ib	SB2	yes	yes
157	WN5(+B1II)	VB	?	?

significantly from the single-star models. The fit is very accurate in most cases. Only WR 123 (a variable star) and WR 157 show deficient flux in the short-wavelength UV, but the quality of the IUE data is poor in both cases. Four stars show a slight excess of IR flux (question marks in Table 2), but due to strong reddening of their spectra we do not consider this as conclusive.

Summarizing, we state that none of the checked eight WN stars which have been suspected to display "diluted emission lines" shows evidence for a composite spectral energy distribution. As far as no other evidence for their binarity is found, they might be in fact single stars. Thus the fraction of binaries among the Galactic WN sample might be smaller than hitherto assumed.

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