CONTINUUM AND EMISSION LINE OBSERVATIONS OF WOLF-RAYET STARS: SINGLE AND "WR+ABS" OBJECTS

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Abstract. The UV – IR properties of the continuous energy distribution of single WR stars in the Galaxy and LMC are reviewed. The observed, dereddened distributions may be approximated as a power law $F_\lambda \sim \lambda^{-\alpha}$ with a non-Rayleigh Jeans range of α directly associated with the emission of excess flux over the full wavelength range and across all spectral subtypes. The observational results are compared to published NLTE models, where we find an important discrepancy in the frequency distribution of α for Galactic WN stars. A dependency of emission line equivalent widths on the continuum flux at line center is discussed; the systematic offset of the absorption line (but otherwise presumed single) objects is examined, and the observed behavior is compared to models and explained with simple theory.

Key words: stars: atmospheres – stars: fundamental parameters – stars: Wolf-Rayet

1. Introduction

In this paper we review observed line strength and continuum properties of Wolf-Rayet stars (apparently single and "non-binary" absorption line objects) in the Galaxy and Magellanic Clouds, with emphases on the continuum shapes over a broad wavelength baseline and on the relationship between continuum emission and emission line equivalent widths. The observations covering *IUE* ultraviolet, optical, and near-IR wavelengths are taken primarily from the spectrophotometry described in Morris *et al.* (1993a); they are supplemented by IR published photometry where available. The spectra are of "moderate" resolution (generally 6 – 10 Å), allowing us to avoid direct considerations of variability or wind asymmetry effects, and are thus suitable for comparison to NLTE model predictions by the "Kiel group" (Hamann & Schmutz 1987; Schmutz *et al.* 1989, 1994) for presumed spherical, steady-state WR star atmospheres. This "Standard Model" is reviewed by Hamann (1991 and these proceedings) and Hillier (1991), but see also Schmutz (1991) for a closely related comparison between observed and model continuum properties, and Schmutz (these proceedings) and Hillier (these proceedings) for further discussion of modern improvements (*e.g.* inclusion of line-blanketing) to the models. These models are based on a pure helium analysis and are thus applicable to WN stars, but not to WC stars because of the substantial carbon and oxygen content in their winds (Hillier 1989; Hamann *et al.* 1992). Since no suitable NLTE models which include C and

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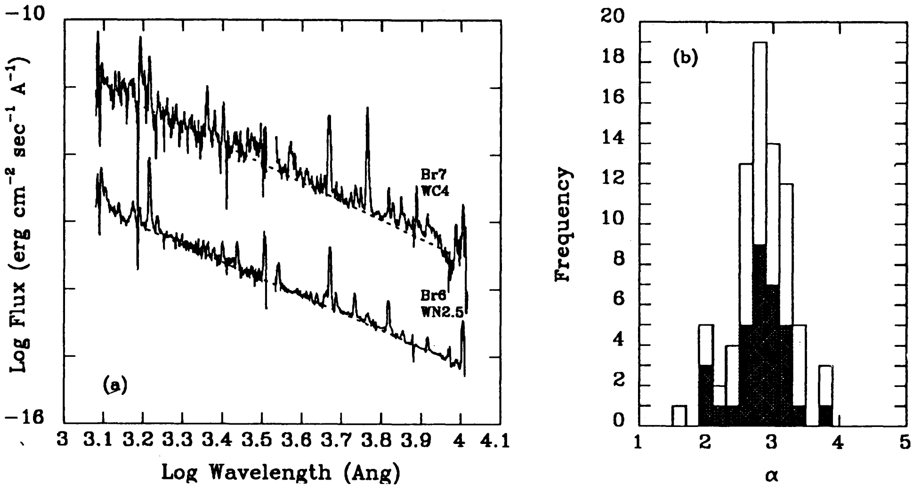

Fig. 1. (a) Observed (uncorrected) distributions of the LMC WR stars HD 32109 (WN2.5) and HD 32125 (WC4). (b) Frequency distribution of α for single WN and WC stars, where shading indicates the LMC group. The average and FWHM values are 2.85 and 0.40.

O are presently available to us, we do not discuss an observations–models comparison for WC stars.

2. Character of the Wolf-Rayet energy distribution

2.1 Observations

Figure 1a shows a situation that is very typical of single WR stars in the Galaxy and Magellanic Clouds: the intrinsic continuum distribution from $\sim$ 0.15 μm to IR wavelengths can be represented by a power law of the form $F_\lambda \sim \lambda^{-\alpha}$ to a high degree of accuracy. This conclusion is easiest to reach for the stars in the LMC, where (in general) interstellar reddening is low. A simple least-squares regression fit to continuum points chosen by eye from the upper distribution of Figure 1a, for example, yields an extremely small uncertainty on the spectral index, $\alpha = 2.45 \pm 0.02$. The same test on other lightly reddened stars in the LMC (outside of 30 Doradus, for example) and the Galaxy (*e.g.* HD 50896) similarly yields excellent fits ($\sigma_\alpha \simeq 0.01 - 0.05$).

Applying this representation to more heavily reddened WR stars has allowed us to determine spectral indices α and color excesses $E(B-V)$ by "nulling" the interstellar absorption feature at 2175 Å. An accurate numerical procedure (χ^2-minimization) for doing this was presented by Vacca & Torres-Dodgen (1990), with application to *IUE* UV spectra. Morris *et al.* (1993a) adopted the technique for 78 single stars over the extended wavelength baseline, finding excellent agreement with Vacca & Torres-Dodgen in $E(B-V)$ values, but often substantially different values of α, a result which stems from both the increased statistical uncertainty of a shorter baseline,

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and the fact that sources of non-thermal continuum radiation are selectively stronger at visual and IR wavelengths (Lamers & Morris 1994).

The distribution of spectral index values for the combined set of WN and WC stars is shown in Figure 1b. Spectral index values are concentrated near 2.85, with no apparent difference between the Galaxy and LMC. The WC stars are only slightly steeper systematically than the WN stars, but this difference may be statistically insignificant. Actually, the WC stars should be expected to have somewhat *shallower* slopes if their broad lines (*e.g.* Conti & Massey 1989) are any indication that they have thicker winds. There is no distinguishing the slopes of WN stars abundant in hydrogen where this has been determined by Conti *et al.* (1983). Observationally, there is no clear correlation between α and spectral type, but the models will show a different result (Section 2.2).

2.2 The models

Model continuum predictions by Schmutz *et al.* (1994) provide theoretical support for describing the continua of WR stars as power laws, as shown in Figure 2a. Utilizing a $\beta = 1$ velocity law, these model helium distributions were produced self consistently from the helium line equivalent width predictions of Schmutz *et al.* (1989), mapped out with two parameters from the effective temperature, radius, mass-loss rate, and terminal wind velocity ($T_\star$, $R_\star$, $\dot{M}$, and v_∞) by introducing a "transformed" radius $R_t = R_\star \times (v_\infty/\dot{M})^{2/3}$, with v_∞ and $\dot{M}$ in units of 2500 km s^{-1} and 10^{-4} M$_\odot$ yr^{-1}. Further discussion of the transformation law and the precise definitions of $R_\star$ and $T_\star$ is found in Schmutz *et al.* (1989).

Since continuum fitting methods are inadequate for determining the effective temperatures of hot stars (*e.g.* Hummer *et al.* 1988), the best way to directly compare model and observed continua is to determine R_t and $T_\star$ from He I/II line observations and then select the corresponding distribution (*cf.* Schmutz 1991).

Resorting again to the spectral index to summarize the comparisons, Figure 2b illustrates the predicted distribution of α using the parameters determined for Galactic WN stars by Hamann *et al.* (1993, hereafter HKW). A distinct gap between strong-lined (WNE-s, where "E" refers to spectral types WN2 – WN6) and weak-lined (WNE-w and WNL, where "L" identifies WN7 – WN9) stars is obvious. This behavior is consistent with conclusions by HKW that the WNE-s stars, hottest in the WN subclass, have the most extended atmospheres as they the exhibit flattest continua; *i.e.* the Rayleigh-Jeans limit is not appropriate for even the hottest WR because of increased continuum flux radiated from thick winds. The average slope of 2.7 for this group agrees somewhat unexpectedly with what is predicted for a spherical, isothermal wind flowing at constant velocity, which for WR stars occurs in the IR–radio continuum (Wright & Barlow 1975). The weak-lined

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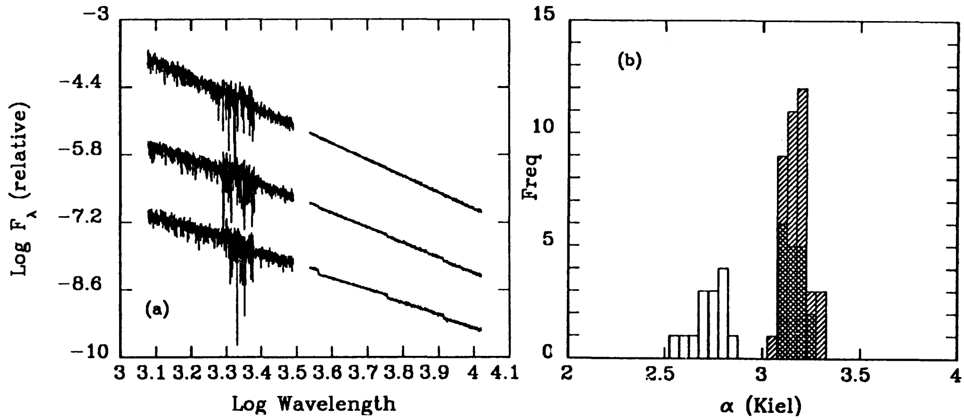

Fig. 2. (a) Model energy distributions taken from grid of Schmutz *et al.* (1994)., coadded with typical observational noise. From top to bottom, the corresponding temperatures and "transformed" radii are (90 kK, 10 $R_\odot$), (35 kK, 10 $R_\odot$), and (90 kK, 3 $R_\odot$). (b) Distribution of α measured from the model continua for values of R_t and $T_\star$ given by HKW for Galactic WN stars. Open boxes represent strong-lined stars, cross-hatching indicates the weak-lined stars, double cross-hatching are the WNE-w stars. Averages and FWHM values are: strong - 2.73±0.08; weak - 3.17±0.06.

stars do not appear to have such extended atmospheres and will therefore have steeper continua at visual and near-IR wavelengths. We note that a blackbody in the range $T_\star = 30 - 35$ kK will have $\alpha \simeq 3.3 - 3.5$, so it cannot be concluded that an hydrostatic photosphere can be observed in these stars.

The observed frequency distribution of α (Figure 1b) is in earnest conflict with the model predictions. The observational analyses are subject to uncertainties of defining the continuum levels and adopting average reddening curves, but the reliability of the observed Gaussian-like frequency distribution is strongest at its centroid ($\alpha \simeq 2.8$ for the WN stars), precisely where the models are unrealized in the analyses. The contradiction is confirmed in the colors when $(b-v)_0$ index values from HKW are compared to those determined by, *e.g.* Schmutz & Vacca (1991) directly.

The physical conclusions drawn from the models are reasonable: we should expect increased amounts of excess (non-thermal) radiation from the densest winds. However, the observed continuum measurements (colors and spectral index values) as well as the smooth variation of observed line properties (*e.g.* equivalent widths and line widths – Conti & Massey 1989, Massey *et al.* 1987; line fluxes – Conti & Morris 1990) and of wind terminal velocities (HKW, Koesterke *et al.* 1991) in moving from strong- to weak-lined stars are not supportive of the bimodal distribution of model continuum slopes. This must create uncertainty in the stellar and wind parameter values determined from WN star spectra utilizing the Kiel models. Lamers & Morris (1994) provide additional discussion.

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3. The correlation between continuum flux and equivalent width: the Wolf-Rayet "Baldwin Effect"

3.1 The observations

Figure 3 illustrates how $W_{\lambda 5411}$ varies inversely with the absolute flux of the continuum at $\lambda 5411$ for single WN stars in the LMC, where the fluxes are better determined with an assured distance and low reddening. Different symbols identify the WNL stars, weak-lined WNE stars ($W_{\lambda 5411} < 40$ Å), strong-lined WNE stars ($W_{\lambda 5411} \geq 40$ Å), and WN+abs objects; see figure caption. The shaded area indicates the range predicted by the Standard Model of the Kiel group, where flux measurements are taken from the model distributions of Schmutz *et al.* (1994). The WN stars show trends (thus far) in NV $\lambda 1240$, CIV $\lambda 1550$, NIV $\lambda 1718$, and all of the easily measured HeII lines between $\lambda 1640$ and $\lambda 10124$ (Morris *et al.* 1993b).

We immediately notice in Figure 3 that the WN+abs stars, all except one of which (Br65, WN7+vis. comp., in the upper left corner) are of the early-type, are systematically offset from the remaining group. Even though these objects are not known to be binaries, their outlying behavior raises the question of whether or not they should be distinguished from otherwise "normal" single stars during a winds analysis. It also raises an interesting possibility for the closest points identifying weak-lined single stars: perhaps these are better fit into the category of WN star with absorption lines (remembering that no strong-lined WN stars have been observed to have absorption lines)? Then six of the seven WNE-w stars plotted here would belong to this group, raising yet one more possibility: are the conditions in the winds of *all* weak-lined stars most similar to those of the WN+abs* stars, as might be expected, for instance, if these are descended from the Of/WN stage? Neglecting the WN+abs stars and the three closest points, we see that the inverse correlation between $W_{\lambda 5411}$ and $L_{\lambda 5411}$ is quite well-defined, taking note of the outlying, very strong-lined object Br6.

Because we have spectrophotometry for only a few single LMC WC stars, all WC4 stars having similar line strengths (Smith *et al.* 1990, Brownsberger 1994), we do not see a WC star Baldwin Effect. Smith *et al.* have shown that CIV (log) $W_{\lambda 5808}$ values closely follow dereddened v magnitudes with -1 slope for 17 LMC WC stars (5 single). The variation occurs among the binaries with all five single stars situated close together at the larger W_{λ},

* Grouping the WNE-w and WN+abs objects together infers that the WNE-s and WNL stars constitute in some respects a more homogeneous group – this differs from arguments based, for example, on atmospheric extension that WNE-w and WNL stars are a more homogeneous group. One can see from the tables of HKW that the WNE-s and WNL stars are predicted to have very similar ranges in mass-loss rates, -4.1 ± 0.2 and -4.3 ± 0.2 dex of $M_{\odot}\ yr^{-1}$, respectively, but the WNE-w stars lose mass systematically slower at -4.8 ± 0.3 dex. Atmospheric extension has obvious physical meaning, but as a fundamental parameter of hot stars, mass-loss has more observable impact on the surrounding medium.

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lower brightness end of the regression. The effect here is one of differential contamination of the WC stars' continua by the companions, and not identified as an intrinsic effect.

No effect is seen among single Galactic WC stars with reasonably certain distance measures. We think this is because most of the non-classification (and unblended) lines are observed to be constant not just in WC4s, but across WCE stars and approximately so across all subtypes (Brownsberger 1994), suggesting that the winds of WR stars are more homogeneous in the later stages of WR evolution. Even WC classification lines show smaller ranges of W_λ than do WN lines where the effect has been seen among the latter. The substantial ranges of line fluxes measured in the LMC WN stars (*e.g.* Conti & Massey 1989; Conti & Morris 1990) exclude the WN effect as being due solely to continuum variations.

3.2 A SIMPLE EXPLANATION FOR THE EFFECT IN THE HeII LINES

That there is any correlation at all between W_λ and L_λ is a bit unexpected from a theoretical viewpoint since the line profiles and continuum fluxes are affected by ρ and ρ^2 processes as well as temperature very differently. Thomson scattering, for example, has been shown (Hillier 1987b) to be responsible for the broadened red wing of the helium lines in HD 50896, but has very little effect on continuum levels in stars with expanding atmospheres (*e.g.* Lamers & Waters 1984).

Even with the effects on the profiles, however, electron scattering and other processes which scale linearly with the wind density must not be important to the net equivalent width or else the transformation law for R_t (Section 2.2), which is fulfilled only for ρ^2 processes, would break down (HKW, Lamers & Morris 1994). Bound-free absorption/emission contributes chiefly with "jumps" in the continuum flux at the HeII edges (Hillier 1987a,b; Schmutz *et al.* 1994). The strengths of the jumps have been used to estimate $(b-v)_0$ in Galactic and LMC WN stars (Schmutz & Vacca 1991), but over an extended baseline we find from observations that they do not substantially disturb the general power law shape of the continuum (Morris *et al.* 1993a).

So now we only consider free-free scattering of electrons from He^{++}. If we further assume for a spherical atmosphere with a $\beta = 1$ velocity law and a simple temperature structure $T(r) = T_\star(1 + R_\star/r)/2$ that the upper levels of the HeII lines are in LTE (which Hillier 1987a and de Koter 1994 show to be reasonable for levels $n \geq 4$ deep in the wind where the departure coefficients are close to unity), then we find for HeII $\lambda5411$ that $W_{\lambda 5411} \sim R_t^{-1.18}$, which is in excellent agreement with a spectral index -1.13 obtained from the Kiel models averaged over curves of constant $T_\star$. This is a strict dependence, with no additional factors of $R_\star$, $\dot{M}$, or v_∞ so that real changes in one parameter must be compensated for by the other two in order to preserve the

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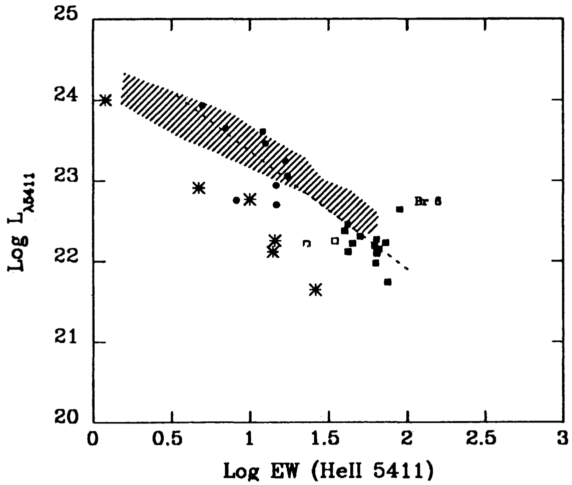

Fig. 3. Log equivalent width (in Å) of HeII λ5411 vs. log continuum luminosity (in ergs s^{-1} Hz^{-1}) at 5411 Å for LMC WN stars. Filled squares are WNL (WN6 – WN9) stars, circles are WNE (WN2 – WN5) stars where open and filled indicate weak- and strong-lined stars (see text for definition), and asterisks indicate the "WN+abs" stars. The shaded area is the theoretical range taken from the grids of Schmutz *et al.* (1989, 1994). Dashed line is an LTE regression averaged over temperature.

scaling law. The dependence on effective temperature is more complicated, but varies roughly as $W_{\lambda 5411} \sim T_\star^{-2.5}$ if the line is treated as being optically thin. This is a much stronger dependence on $T_\star$ than seen in the Kiel models, probably due to the fact that the HeII populations are not truly set at LTE levels but are determined according to recombination theory, which is only weakly dependent on temperature (W. Schmutz, priv comm). The continuum luminosity is found to vary as $L_{\lambda 5411} \sim R_t^{1.73}$, so that at constant $T_\star$ the $\log W_{\lambda 5411}$ vs. $\log L_{\lambda 5411}$ slope should be -1.47, which is actually quite close to the observed slope of -1.56 for the group of stars in Figure 3 that does not include the WN+abs objects or the three closest points.

Although such calculations are exceedingly simple compared to a detailed NLTE treatment, they show in lowest order how this WR Baldwin Effect can arise: the principal factor is differences in wind density among stars, where only ρ^2 processes are the most important. When the wind density is increased, the radius where the continuum is formed moves further into the wind, increasing the continuum flux. Line emission is also increased, but by less than the continuum since the emitting volume for line radiation is decreased as the outer boundary for line emission moves outward much slower than the inner boundary (a consequence of radially decreasing density). As the line emission increases less than the continuum emission, the equivalent widths run inversely with continuum luminosity.

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DISCUSSION:

Lindsey Smith: We (Smith, Shara, Moffat) have made an attempt to improve WN classification (see poster paper). We separate the spectra first by line width - nearly equivalent

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to Hamann et al's separation by strength. Within each group, the spectral sequence with ionization level becomes very smooth - a dramatic improvement.

Morris: It's quite encouraging that the classification scheme is being improved by including spectral properties that take into account not only temperature, but wind density as well. I realize that your method does reveal that the groups of strong- and weak-lined stars do exhibit spectroscopic differences, but I've tried to indicate here that the transition between weak and strong winds should be smooth, not bimodal. I would expect the newer scheme you are developing to show that as well, once you have included the complete stellar dataset.

Conti: I'd like to emphasise that the power law indices, α, and the line widths (FWHM) in WN stars show a continuum of values. The models are bimodal in these two distributions. Thus there seems to be a clear disagreement between what is observed and what is being predicted.

Morris: Regardless of how well the classification os WN stars can be modified to encompass the most important wind parameters, we cannot deny that the observations sharply contrast with the idea of degenerate continuum slopes among the two groups of stars, suggesting that this gap is artificial.

Crowther: There exists considerable evidence that there is a peculiar (anomalously weak) UV reddening towards stars in Tr14, Tr16 (Tapia et al, 1988, Smith 1987). The poor fit to WR 25 can be explained in this way and the extinction curve towards WR25 can be determined assuming its intrinsic energy distribution is typical of other WN7 + abs stars and making comparison with other "less reddened" stars of this subtype (see Crowther et al. 1994, submitted).

Morris: Yes, I agree that the reddening towards these regions is certainly anomalous, though this is really only inferred for the UV from the Tapia et al. optical and IR photometry, so we are not yet certain about the shape of the extinction curve for Tr16. We think it would be dangerous to use other WR stars of similar subtype (such as the other two WN7 + abs. stars in Carina) to derive the extinction for WR 25 since (1) observationally we don't see stars of similar subtype having the same slope or luminosity and (2) one still has to deal with the reddening of the comparison star. WR 24, for example, is not highly reddened, but the difference between using a "Galactic average" extinction curve and one determined by Fitzpatrick and Massa (1990) for Tr14 - 20 will mean a lot to the extinction bump and the far-UV towards WR 25. We think WR 24 has more of a Tr14 extinction curve, even though Tapia et al. indicated the extinction towards Carina as a whole to be more or less normal up to $E(B-V) \approx 0.4$ mag.

van der Hucht: Could the excess seen in the energy distribution of WR 138 be similar to that in WR 25: could it in both cases have to do with O-type binary components?

Morris: Yes, in fact I think that this is very likely the case at least for WR 138. Of course, the profiles of the excesses are quite different, but that of WR 138 resembles what we see in other systems which we know to be WR+O. As far as I know, however, no variations in the absorption line or emission line radial velocities have been observed.

Koenigsberger: I would like to invert Karel's question and ask whether there might not be a disk in WR 138? The photospheric absorptions are highly broadened in this system (Massey 1981) and there are other indications of rapid rotation (Koenigsberger 1990, Rev.Mex.).

Morris: That is an interesting hypothesis that if we cannot say that the excess is definitely due to a companion, then perhaps a disk. The profile of this excess is not like what is seen in the distributions of Be stars, for example, which I believe are continuous into the IR. But as you say, the broad absorption lines and large Vsini you mention would seem to make this plausible. I made a more direct connection to WR 25 not only because of the profile, but also the large X-ray luminosity of this object.

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