ANALYSES OF WOLF-RAYET ULTRAVIOLET SPECTRA

KRZYSZTOF ROCHOWICZ
Institute of Astronomy
ul. Chopina 12/18
PL-87-100 Torun, Poland

Abstract. Ultraviolet spectra of population I WR stars obtained from IUE archive are used to determine fundamental stellar parameters. Terminal velocities for 85 galactic and LMC Wolf-Rayet stars were obtained by means of the empirical relation between spectral quantities easily measured in low resolution and high-resolution terminal velocity measurements. Temperatures and so-called transformed radii were derived based on available contour plots of spectral characteristics for a grid of NLTE models. The effect of the reddening law on stellar far ultraviolet continua is emphasized and the revised extinction curve towards WR stars is used for dereddening. For the sample of stars attributed to open clusters or associations we construct the stellar distance scale and adopt it for the other WR stars. The remaining fundamental parameters are derived and HR diagram for population I WR stars is presented.

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

Our perception of Pop. I Wolf-Rayet stars has undergone a remarkable transformation over the past two decades largely through the advent of new observations spanning a wide range of the electromagnetic spectrum, from X-rays to radio wavelengths. One expects the ultraviolet to be particularly important for WR studies since these stars are hot and emit the bulk of their radiation shortward of the visible region, and exhibit substantial mass loss and stellar winds which can be readily probed using UV P-Cygni profiles. Additionally, the UV provides numerous important line diagnostics for quantitative atmospheric analyses principally through the availability of resonance and low excitation transitions in common ions. Ultraviolet observations of WR stars prior to IUE satellite consisted of broad-band photometric or low resolution spectrophotometric observations of a relatively small sample of galactic objects. IUE has brought a large number of WR stars both in the Galaxy and in the Magellanic Clouds under detailed scrutiny in both its high- and low-resolution mode, spectroscopically placing this class on the same footing in the UV as has been available in the optical.

The ultraviolet spectra of WR stars used here were obtained from the Vilspa IUE archive. We have tried to select as many single stars as possible in the Galaxy and the LMC to get the complete, flux-calibrated ultraviolet spectra. Altogether 56 stars in the Galaxy and 38 in the LMC were found, for which at least single spectra are accessible (note that this is about one third of the number of known galactic and LMC WR stars and about one half of the single objects). The spectra are of „moderate" resolution (0.6 nm), 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" for presumed spherical, steady-state WR star atmospheres.

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The observational material used here is described in detail in Niedzielski & Rochowicz (1994), where we also discuss general spectral characteristics on the basis of both shape of the spectra and correlations of line equivalent widths and line widths with spectral subtype and between different lines of many ions. The asymptotic or terminal velocity is a fundamental parameter in quantitative descriptions of the wind from a hot star. We use the simple method of determining terminal wind velocities from low resolution IUE spectra (see Rochowicz & Niedzielski, 1995).

A "standard" model of WR atmosphere is defined by its basic parameters: radius, temperature, mass-loss rate and terminal velocity. Synthetic spectra from Wolf-Rayet model atmospheres of different mass-loss rates, stellar radii and terminal velocities yield the same emission line equivalent widths, if they agree in their "transformed radius" defined below:

$$R_t = R_* \left[\frac{v_\infty}{2500\,\mathrm{km\,s^{-1}}} \Big/ \frac{\dot{M}}{10^{-4}\,M_\odot\,\mathrm{a^{-1}}} \right]^{2/3} \tag{1}$$

It greatly facilitates the spectral analyses. Contour plots of spectral characteristics are available in several papers (Koesterke & Hamann (1995) and references therein). Those contours which correspond to the observed values of a star can be selected, and the intersection point yields directly temperature and the transformed radius. Mass-loss rate and radius can be disentangled from the transformed radius if the absolute visual magnitude and terminal velocity are given:

$$\lg\left(\frac{\dot{M}}{M_\odot\,\mathrm{a^{-1}}}\right) = 0.3\,(M_v^t - M_v) + \lg\left(\frac{v_\infty}{2500\,\mathrm{km\,s^{-1}}}\right) - 4.0 \tag{2}$$

where M_v^t denotes the absolute visual magnitude for $R_* = R_t$. This technique was used for spectral analyses of Wolf-Rayet stars in a series of papers (Hamann *et al.* (1993) and references therein) based on the measurements of optical lines. We have performed similar analyses based on ultraviolet spectra.

For WN stars we used the contour plots of the He II 164.0 nm line equivalent width and peak intensity and of the UV continuum slope. For WC stars the contour plots of equivalent widths for the He II 164.0 nm, C IV 155.0 nm and C III 229.7 nm lines were used.

In Fig. 1 our program stars are allocated in the $\lg T_*$ - $\lg R_t$ diagram, identified by their WR (open symbols) or Br (dark symbols) numbers. The spectroscopic subclasses are distinguished by different symbols as in the papers of Hamann *et al.* Late type stars of both subclasses have lower temperatures and large transformed radii; there is a clear separation between WC 5-6 and WC 7-9 stars, while for WN subclass there is a close relationship between WNL and WNE-weak lined stars, two exceptions being WR 2 and WR 3.

These results are purely spectroscopic and do not depend on the knowledge of the stellar distance. Now we proceed to those parameters which involve the absolute dimensions of the stars.

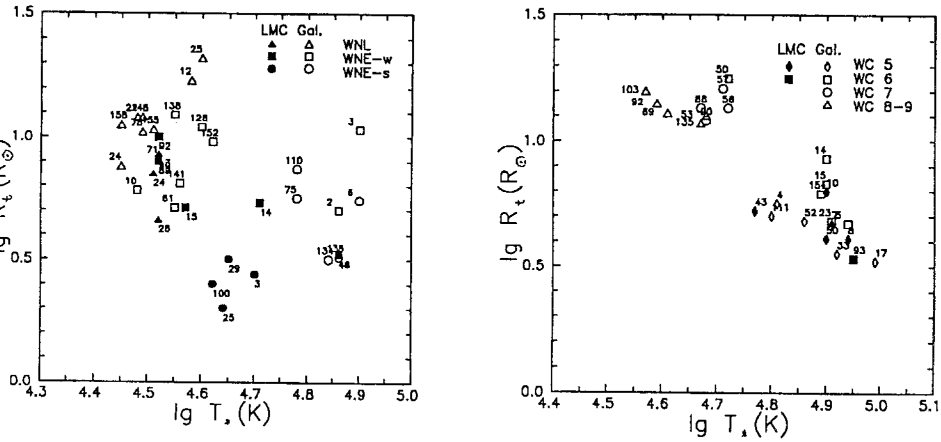

Figure 1. Analyzed WN (left) and WC (right) stars in the lg T_* - lg R_t plane. Data from Rochowicz (in preparation).

Pop. I Wolf-Rayet stars are very bright objects and therefore are observed at high distances. Their close coupling to the galactic plane results, however, in extreme reddening. The shape of the extinction curve derived from preliminary studies based on a few stars was found to be in very good agreement with Seaton (1979). Although several peculiarities in the reddening law towards some WR stars were reported, all papers devoted to dereddening of WR spectra assumed a standard extinction law, usually that of Seaton, a priori. On the other hand, as it was shown by Krelowski & Papaj (1992), the ultraviolet shape of the mean galactic extinction curve depends strongly on the stars used. For a well defined sample including distant bright stars, their mean galactic extinction curve differs from that of Seaton by about 0.5^{m} in the far UV spectral range. A similar result was reached recently while analysing the shape of the UV extinction curve towards WR stars (Niedzielski 1995). Therefore the mean galactic extinction of Krelowski & Papaj (1992) should be used for dereddening instead of Seaton's.

Using this revised extinction law and χ^2 minimization technique to systematically remove the 220 nm interstellar absorption feature we obtained color excesses and intrinsic colors. Then for the sample of stars associated with open clusters or associations we constructed the stellar distance scale and adopted it as calibration based on two relations: visual absolute magnitude versus subtype (for WN stars only) and line equivalent widths versus continuum luminosity, the so-called Baldwin effect. Linear best fits yielded distances for the remaining galactic stars. Later on we calculated the other parameters, such as radii, luminosities, mass loss rates and thus we were able to construct a Hertzsprung-Russell diagram for our program stars.

The overall picture is consistent with what was recently demonstrated by the Kiel group, although we have found a group of strong-lined early WN stars to be

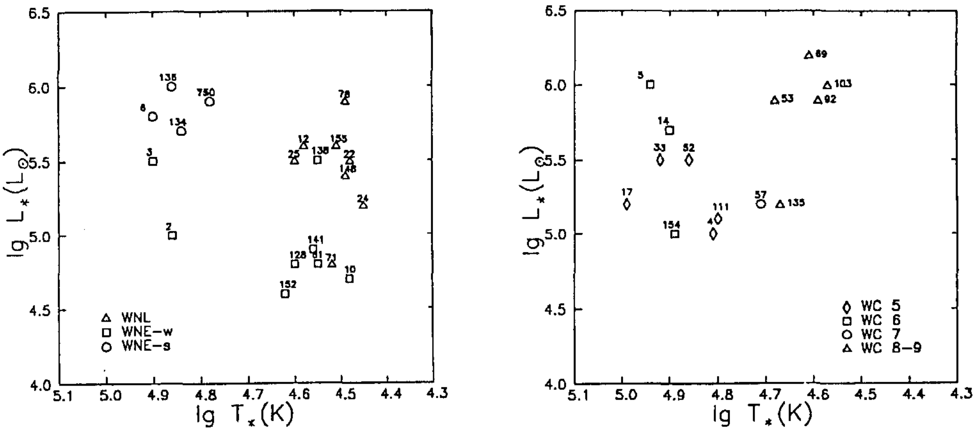

Figure 2. HR diagram for analyzed galactic WN (left) and WC (right) stars. Data from Rochowicz (in preparation).

more luminous; most WN stars form a vertical strip at lower temperatures, while WC stars concentrate towards upper left part of the diagram.

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