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ULTRAVIOLET STUDY OF WOLF-RAYET STARS*

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ABSTRACT

Ultraviolet spectra of population I WR stars obtained from IUE archive are used to determine fundamental stellar parameters. Temperatures and so-called transformed radii were derived basing on available contour plots of spectral characteristics for a grid of NLTE models. The effect of the reddening law on stellar far UV 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 galactic WR stars. The remaining fundamental parameters are then derived and HR diagram for program stars is presented.

Key words: Wolf-Rayet stars; atmospheres; fundamental parameters.

1. INTRODUCTION

Since their discovery in 1867 Wolf-Rayet (WR) stars have been intensively studied by both observers and theoreticians. The most characteristic feature of these stars - their dense, opaque and fast moving envelopes - make interpretation of their spectra very difficult. Therefore, details concerning their physics are still not very precise. Neither the strong emission lines in their spectra nor the shape of their continua can be analyzed by standard methods established during many years of research of more or less ,,standard" stars. The observed high reddenings to many of these very distant stars farther inhibits their analysis. These circumstances result in uncertainty of such fundamental stellar parameters as luminosities, temperatures, masses, intrinsic colors and chemical composition.

Ultraviolet observations of WR stars, prior to IUE, have generally been restricted to either broad-band photometric or low resolution spectrophotometric measurements. With the advent of the IUE satellite a large number of WR stars, both in the Galaxy and the Magellanic Clouds, have become accessible to detailed analyses.

The aim of our study was to give an exhaustive description of ultraviolet Wolf-Rayet stars spectra. So far the spectra were used for e.g.:

- searching for correlations among the strength and widths of emission lines of different ions (Niedzielski and Rochowicz 1994)
- spectral classification in the ultraviolet (Rochowicz 1995)
- determining terminal wind velocities (Rochowicz and Niedzielski 1995)
- analyzing ionization structure of WR envelopes (Rochowicz 1997)

Fundamental parameters of Wolf-Rayet stars are derived here based on available contour plots of spectral characteristics for a grid of NLTE models. Only a brief announcement is presented here, more detailed report will be published elsewhere.

2. OBSERVATIONAL MATERIAL AND REDUCTION

The ultraviolet spectra of 94 WR stars 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 spectra. Altogether 56 objects in the Galaxy and 38 in the LMC were found, for which at least single SWP and LWR (or LWP) low resolution images are accessible - note that this is about one third of the number of known galactic and LMC WR stars. The set of stars we study is representative according to spectral subtype and brightness (it is almost complete to 12 magnitude for galactic stars). See Niedzielski and Rochowicz (1994) for the list of program stars and associated IUE images as well as for the details of reduction.

The reduction procedures and the measurements were performed using the software facilities (ReWiA) of the Institute of Astronomy in Toruń. Continuum was fitted using splines to bye-eye selected line free points from the spectra after careful estimation of its shape for different spectral subclasses.

The line widths (EW, FWHM) and fluxes were measured by fitting Gaussian profiles to the emission lines

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*based on IUE Archive data from Vilspa

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(or separate Gaussians to the blends) using FIT procedure of ReWiA. We assume that our values are accurate to some 20 per cent. An intercomparison of independent measures of the spectra for several stars gave us a formal σ of ± 0.06 in the log of the EW.

The original data (EW, line fluxes and FWHM values) for stars under study are available electronically at the CDS via anonymous ftp (130.79.128.5).

3. STANDARD MODEL INFERENCES

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:

$$R_t = R_* \left[\frac{v_\infty}{2500 \text{ km s}^{-1}} \Big/ \frac{\dot{M}}{10^{-4} \text{ M}_\odot \text{ yr}^{-1}} \right]^{2/3} \qquad (1)$$

It greatly facilitates the spectral analyses. Contour plots of spectral characteristics are available in several papers (Koesterke and 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 transformed radius. Mass-loss rate and radius can be disentangled from transformed radius if the absolute visual magnitude and terminal velocity are given:

$$\log \left(\frac{\dot{M}}{M_\odot \text{ yr}^{-1}} \right) = 0.3 \; (M_v^t - M_v) + \log \left(\frac{v_\infty}{2500} \right) - 4.0 \qquad (2)$$

$$R_* = R_t \; 10^{0.2 \; (M_v^t - M_v)} \qquad (3)$$

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) basing on the measurements of optical lines. We have performed similar analyses basing on ultraviolet spectra.

3.1. Temperatures

Deriving temperatures (T_* [kK], col. 5 of Table 1) for WN stars we used contour plots of HeII λ1640 equivalent width and peak intensity and of UV continuum slope. For WC stars contour plots of equivalent widths for HeII λ1640, CIV λ1550 and CIII λ2297 were used.

3.2. Terminal velocities

Prinja (1994) proposed a method of determination of terminal wind velocities (v_∞) in hot stars from low resolution IUE spectra. Rochowicz and Niedzielski (1995) investigated its application to WR stars. Using new empirical relation we presented v_∞ for a sample of 85 galactic and LMC stars, 19 of them determined for the first time. The comparison with other determinations showed that this simple method is accurate to within 10-20 per cent. Our values (last column of Table 1) were used for further calculations.

These results (T_* and v_∞) 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.

4. INTERSTELLAR REDDENING

Population 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 basing 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 standard extinction law, usually that of Seaton, a priori. On the other hand, as it was shown by Krelowski and 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^m5 in the far UV spectral range. Similar result was reached recently while analysing the shape of the UV extinction curve towards WR stars (Niedzielski 1995). Therefore mean galactic extinction of Krelowski and Papaj (1992) should be used for dereddening instead of Seaton's.

Using this revised extinction law and χ^2 minimization technique to systematically null the 220 nm interstellar absorption feature we obtained color excesses and intrinsic colors for galactic stars.

Dereddening of LMC stars spectra is much more complicated. The light passes through two different interstellar media – of the parent and our Galaxy. The extinction law for LMC is still discussed (Bessel 1991) and „mean extinction" is not applicable in certain directions (e.g. for 30 Doradus region, rich in WR stars). We decided to take into account only these objects, for which the reddening can be neglected (total $E_{b-v} < 0.^m03$).

5. ABSOLUTE MAGNITUDES

Deriving the distances of WR stars remains uncertain. One usually relies on a relationship calibrated for the stars in open clusters and associations.

Table 1. Fundamental parameters for WR stars.

No.	Type	M_v [mag]	R_* $[R_\odot]$	T_* [kK]	$\log L/L_\odot$	$\log \dot{M}$ $[M_\odot/\mathrm{yr}]$	$\log v_\infty$ [km/s]
WR 2	WN 2	-2.7	2.1	73	5.0		
WR 3	WN 3+a(SB1)	-3.3	3.1	79	5.5		
WR 4	WC 5	-3.2	2.6	64	5.0	-4.4	3.5
WR 5	WC 6	-5.0	1.4	87	6.0	-4.1	3.4
WR 6	WN 5(SB1)	-4.2	1.2	80	5.8	-4.3	3.3
WR 10	WN 4.5	-4.4	7.9	30	4.7	-4.1	3.2
WR 12	WN 7(SB1)	-6.0	14.1	38	5.6	-4.4	3.1
WR 14	WC 6	-3.9	3.9	80	5.7	-4.5	3.4
WR 17	WC 5	-2.8	1.4	98	5.2	-4.6	3.4
WR 22	WN 7+a(SB1)	-6.1	19.9	30	5.5	-3.8	3.2
WR 24	WN 7+a	-5.8	17.4	28	5.2	-3.6	3.3
WR 25	WN 7+a	-5.3	12.0	40	5.5	-4.4	3.3
WR 33	WC 5	-4.0	2.7	84	5.5	-4.0	3.5
WR 52	WC 5	-4.1	3.5	72	5.5	-4.2	3.4
WR 53	WC 8	-5.9	13.2	48	5.9	-4.3	3.1
WR 57	WC 7	-3.8	5.1	51	5.2	-4.9	3.3
WR 61	WN 4.5	-4.5	6.8	36	4.8	-4.1	3.2
WR 69	WC 9	-7.0	24.6	41	6.2	-3.9	3.1
WR 71	WN 6(SB1)	-4.5	8.1	33	4.8	-4.2	3.2
WR 75	WN 6	-5.3	8.1	60	5.9	-4.0	3.1
WR 78	WN 7	-7.1	30.3	31	5.9	-3.6	3.1
WR 92	WC 9	-6.5	20.4	39	5.9	-4.1	3.1
WR 103	WC 9(SB1?)	-6.7	23.9	37	6.0	-4.0	3.1
WR 110	WN 6	-5.3	8.5	60	5.9	-3.9	3.4
WR 111	WC 5	-3.6	3.0	63	5.1	-4.3	3.4
WR 128	WN 4(SB1)	-3.7	5.5	40	4.8	-4.6	3.3
WR 134	WN 6(SB1)	-4.8	5.0	70	5.7	-3.8	3.3
WR 135	WC 8	-4.1	5.9	47	5.2	-4.6	3.2
WR 136	WN 6(SB1)	-5.5	6.8	72	6.0	-3.7	3.2
WR 138	WN 6+a(SB1)	-5.8	15.5	36	5.5	-4.1	3.1
WR 141	WN 6(SB1)	-4.4	7.1	36	4.9	-4.1	3.2
WR 148	WN 7(SB1)	-6.0	18.2	31	5.4	-3.9	3.2
WR 152	WN 3	-3.1	3.8	42	4.6	-4.7	3.3
WR 154	WC 6	-2.7	1.9	77	5.0	-4.9	3.3
WR 155	WN 7(SB1)	-6.4	21.3	32	5.6	-3.8	3.2
Br 7	WC 5	-3.3	2.2	82	5.3	-4.5	3.4
Br 13	WN 8	-5.7	14.1	33	5.3	-4.0	3.0
Br 24	WN 7	-5.2	11.7	32	5.1	-3.9	3.1
Br 29	WN 3/WCE	-3.8	3.8	45	4.7	-3.9	3.3
Br 50	WC 5	-4.2	3.2	79	5.5	-4.1	3.5
Br 93	WC 6-7	-2.0	1.0	90	4.8	-4.7	3.5
Br 100	WN 3-4	-3.8	3.5	42	4.5	-3.9	3.3

However (Lundström and Stenholm 1984) only 16 WR stars are at least probable open cluster members (and 25 objects in the case of associations). Some of them are binaries, thus the fundamental calibration of absolute magnitude (M_v) with spectral type (Sp) is still corrected, which often means complicated (cf. Hamann et al. 1993).

Basing on monochromatic photometry of Torres-Dodgen and Massey (1988) and our color excesses we were able to construct the linear relation only for WN stars (in open clusters and associations). We adopt it for the other galactic WN stars.

An independent calibration which we used for the remaining galactic stars was the so-called Baldwin effect (Morris et al. 1993): the relation between equivalent width (of HeII λ 1640 line) and absolute continuum flux, also constructed for the stars in open clusters and associations.

Absolute magnitudes for LMC stars were obtained using the value of $18.^m5$ for the distance modulus of the Large Magellanic Cloud (Panagia et al. 1991).

6. FINAL RESULTS

The values obtained for temperature, terminal velocity and absolute magnitude (M_v, col. 3 of Table 1) were adopted to calculate mass loss rate ($\dot{M}$), radius (R_*) and luminosity (L). The physical parameters of WR stars derived in this study are summarized in Table 1.

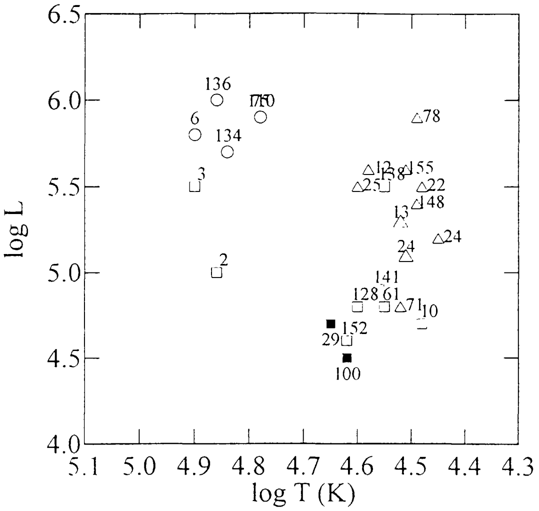

Figure 1. HR diagram for analyzed galactic (open symbols) and LMC (shaded symbols) WN stars. Symbols denote spectral type of stars (see e.g. Hamann et al. 1993): triangles – WNL, squares – WNE-w, circles – WNE-s.

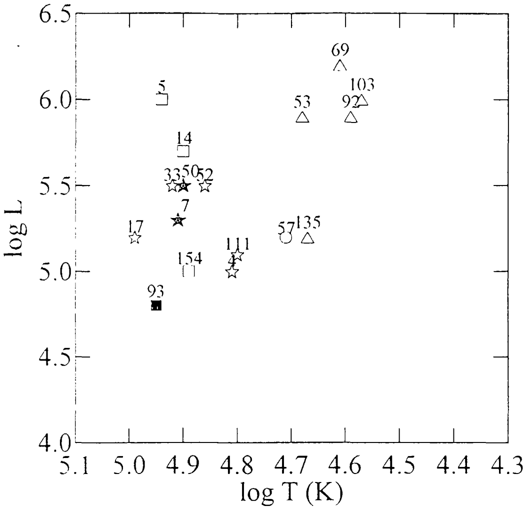

Figure 2. HR diagram for analyzed galactic (open symbols) and LMC (shaded symbols) WC stars. Symbols denote spectral type of stars (see e.g. Hamann et al. 1993): stars – WC5, squares – WC6, circles – WC7, triangles – WC8-9.

We were also able to construct a Hertzsprung-Russell diagram for WN (Figure 1) and WC stars (Figure 2). 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 more luminous; most WN stars form a vertical strip at lower temperatures, while WC stars concentrate towards upper left part of the diagram.

7. CONCLUSIONS

In several papers we presented a large, representative sample of ultraviolet low resolution spectra of single galactic and LMC Wolf-Rayet stars, basing on the IUE Archive. The presented material enables us to draw the following conclusions:

1. The spectral effects of changing physical conditions in WR envelopes are well seen in their UV spectra.
2. In many aspects the WC stars, in spite of their extremely complicated spectra, seem to form a more uniform group – the WN spectra show large variety within one subtype.
3. The influence of the envelope on the line radiation plays a key role in WR stars. The study of ionization structure of WR stars atmospheres is currently under way.
4. Ultraviolet spectra of galactic and LMC stars are not identical, and for the detailed comparison the careful dereddening of magellanic stars spectra is necessary.
5. Similar analysis of high resolution IUE spectra of WR stars will help to understand more subtle effects which play a crucial role in the atmospheres of hot and luminous stars.

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