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Ultraviolet Ionization Stratification in Wolf-Rayet Winds [1]

by

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ABSTRACT

Ionization stratification can be used to study the structure of WR winds. In an accelerated outflow the stratification is observable through the Doppler effect as an inverse correlation of ionization potential (IP) with line width (FWHM). However, not only the average line widths of different ions, but also the line widths of one series of HeII show stratification. The evidence of both effects is demonstrated here as a part of ongoing study.

The ultraviolet spectra of WR stars obtained from the IUE archive are used to get the IP *vs.* FWHM diagrams as well as the principal quantum number n of HeII $(n-3)$ transitions *vs.* FWHM velocity relations. A systematic insight into stratification in HeII lines is provided on the basis of observations.

Key words: *Stars: Wolf-Rayet – Stars: atmospheres*

1. Introduction

In the case of Wolf-Rayet stars we usually observe not a star itself but a large, dense and fast expanding envelope surrounding the central source. The spectra of WR stars are composed of series of broad and bright emission lines superimposed on a relatively faint continuum, both originating in, or substantially modified by the envelope.

Thus almost everything we know about WR stars concerns the envelopes surrounding them. The knowledge of conditions in envelopes is essential for the studies of WR stars. Among the unsolved problems one of the most important remains the velocity run in the envelope. The aim of this paper is to show that the stratification in ultraviolet emission lines of different ions is an evidence of velocity structure in WR winds.

Ionization stratification of WR winds has been recognized spectroscopically (Beals 1929) based on an observed inverse correlation of emission line width with

[1] Based on archive IUE spectra from Vilspa

ionization potential for both WN and WC stars. For an accelerating outflow, these results imply a decrease in the degree of ionization with increasing radius.

A relationship has also been noted between excitation potential and line width (Willis 1982). The predictions concerning ionization and excitation stratification resulting from the standard model (Hillier 1989) have been confirmed observationally once more by Dalton *et al.* (1995).

So far, empirical studies of WR winds ionization stratification included a few galactic objects only. We would like to extend similar analysis for more representative set of stars both from our Galaxy and from the Large Magellanic Cloud (LMC). The preliminary results based on ultraviolet spectral region are given below. We will demonstrate the evidence of ionization stratification for two WR winds. Only the stratification in HeII $(n-3)$ Fowler series will be discussed in more detail here. The summary of the results for a sample of stars showing a well-defined UV ionization structure will be provided in a subsequent paper.

2. Observational Material and Reduction

The ultraviolet spectra of 94 WR stars were obtained from the Vilspa IUE archive. We tried to select as many single and SB1 type stars as possible in the Galaxy and the LMC to get the complete, flux-calibrated spectra between 1150 and 3250 Å. Altogether 56 (34 of WN and 22 of WC type) stars in the Galaxy and 38 (31 of WN and 7 of WC type) 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 studied stars is representative relative 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 (Borkowski 1992). 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 (FWHM) were measured by fitting Gaussian profiles to the emission lines (or separate Gaussians to the blends) using FIT procedure of ReWiA. We assume that our FWHM values are accurate to some 10–15%. An intercomparison of independent measures of the spectra for several stars gave us a formal σ of ± 0.04 in the log of the FWHM.

The original data (FWHM in Å) for stars under study are available electronically at the CDS via anonymous ftp (130.79.128.5).

3. Line Width *vs.* Ionization Potential

Ionization stratification in an accelerated outflow can be traced on the traditional plot of half-width velocity *vs.* IP (in Fig. 1 for WR23, a WC6 star). It shows that the mean width of the SiIII lines is wider than the mean of the SiIV lines, which is in turn wider than the mean width of the next ion lines, as is expected according to the increasing IPs of these lines.

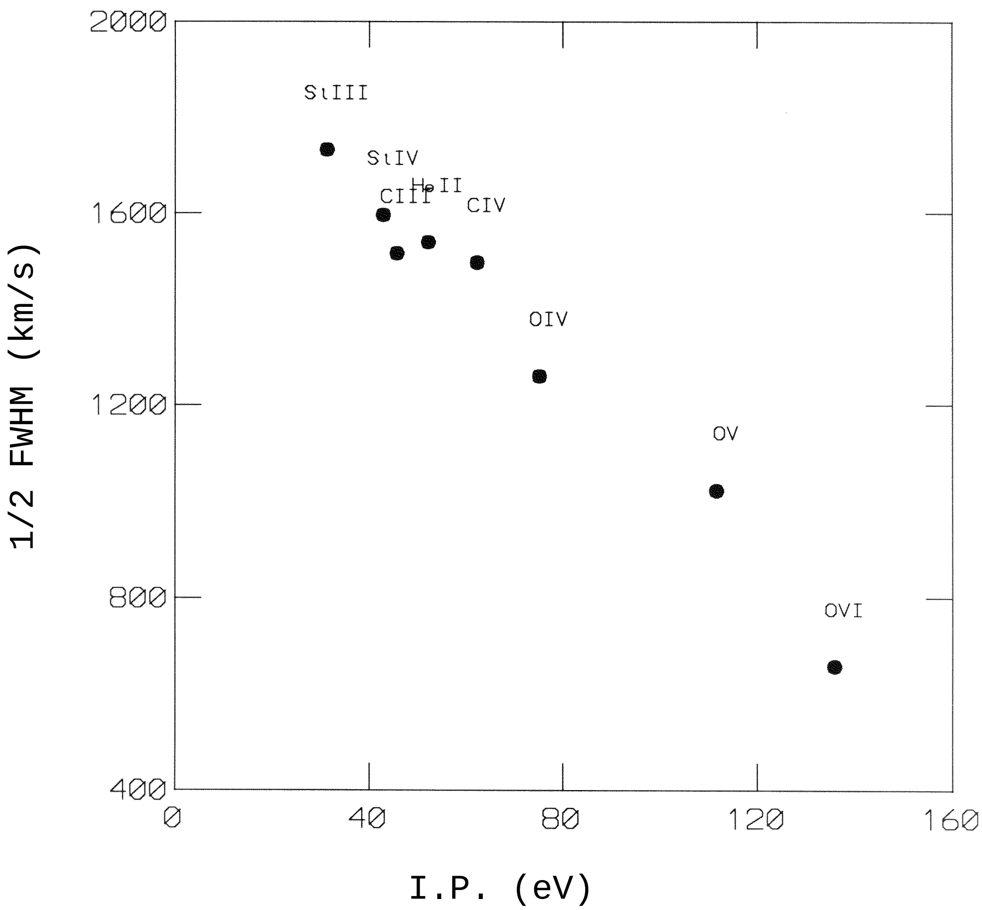

Fig. 1. The half of FWHM velocity (in km/s) *vs.* ionization potential (I.P.) for WR23. The velocities (mean where possible) are based on ultraviolet lines measurements (Niedzielski and Rochowicz 1994).

The least-squares fit to the points gives a relation of the form:

$$v = v_0 + \text{const} \times IP \quad (1)$$

where v_0 is a rough estimate of terminal wind velocity (see Rochowicz and Niedzielski 1995 for an extensive study of WR winds terminal velocities based on more reliable method).

Quantitative analysis of FWHM *vs.* IP relations for a large sample of stars is currently under way and its results will be announced during next IAU Symposium devoted to WR stars.

4. Stratification as Seen in HeII Lines

As it was shown by Niedzielski (1994) not only the average widths of different ions but also the emission lines widths of one series of HeII show stratification effects. This is demonstrated in Fig. 2 on a plot of half-width velocity *vs.* principal

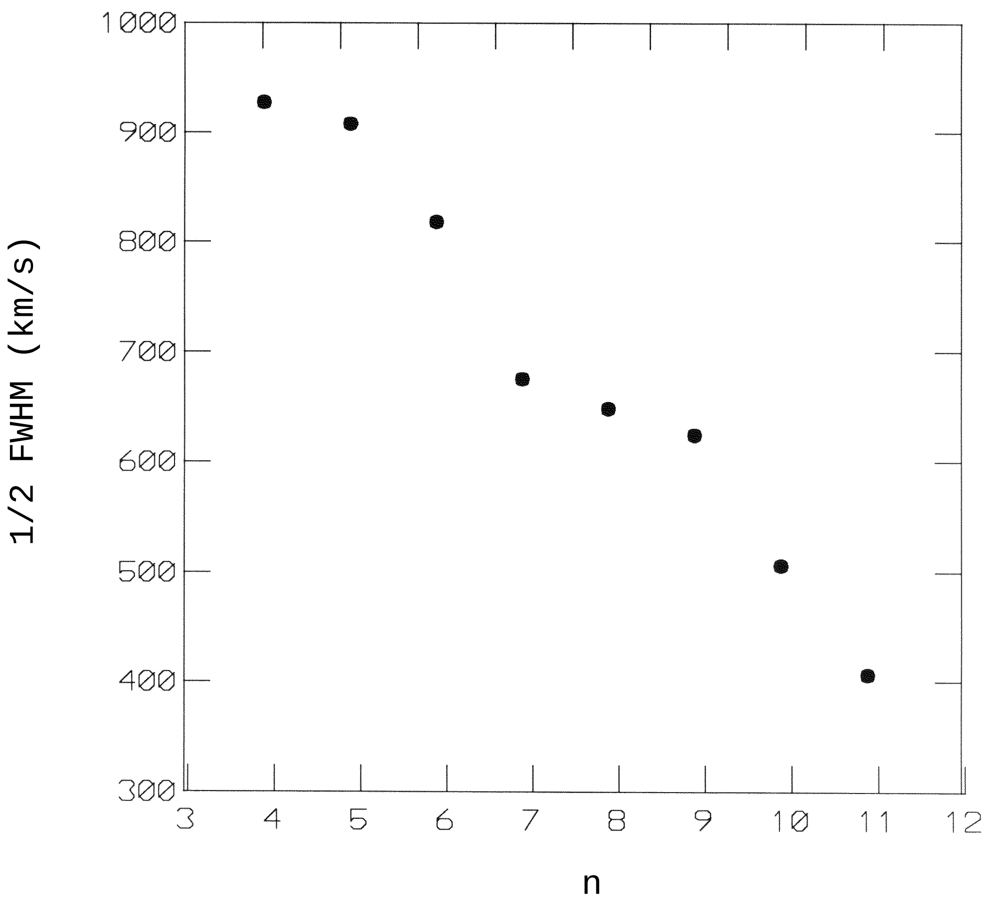

Fig. 2. The half of FWHM velocity (in km/s) *vs.* principal quantum number (n) of HeII Fowler $(n-3)$ lines for Br35. The data are given in Table 1.

quantum number n of HeII $(n-3)$ Fowler series transitions (for Br35, a WN4 star). The UV data used in this study are supplemented by the value of HeII (4–3) λ 4686 FWHM from Conti and Massey (1989). The correlation is indicating the importance of optical depth effects on the line formation region. The lines of HeII are produced in zones which must differ in velocity.

Similar correlations (or at least trends) have been found for 20 other stars from our Galaxy (5 WN and 5 WC) and LMC (11 WN including Br35). The results are summarized in Table 1. As it was noticed above, the UV data used in this study are supplemented by the values of HeII (4–3) λ 4686 FWHM from Conti and Massey (1989).

Table 1

The half of FWHM velocity of HeII Fowler $(n-3)$ lines for the sample

WR/Br Number	Spectral Type	HeII $(n-3)$ series FWHM (km/s)							
		λ2215	λ2253	λ2306	λ2385	λ2511	λ2733	λ3203	λ4686
WR 40	WN 8	–	–	–	620	680	740	850	–
WR 44	WN 4	–	–	–	570	660	770	850	960
WR 61	WN 4.5	–	–	–	460	580	770	810	900
WR 69	WC 9	–	–	–	330	630	580	–	1000
WR 92	WC 9	–	–	–	690	810	830	–	1250
WR 103	WC 9	–	–	–	710	810	760	–	1250
WR 111	WC 5	–	–	–	640	780	760	820	–
WR 134	WN 6	–	790	1240	1200	1280	–	1400	–
WR 136	WN 6	–	–	900	1050	1080	1140	1180	–
Br 1	WN 3	–	–	–	530	930	1040	1360	1220
Br 3	WN 3	–	–	510	600	800	–	1200	1020
Br 23	WN 3	–	550	540	720	800	850	910	–
Br 25	WN 3	–	–	230	420	760	990	1060	–
Br 26	WN 7	–	–	–	620	705	830	870	–
Br 29	WN 3/WCE	–	–	–	720	1010	1110	1220	–
Br 35	WN 4	410	510	620	650	680	820	910	930
Br 40	WN 3	–	–	340	530	870	910	1020	1060
Br 46	WN 3	–	–	610	500	780	870	920	–
Br 99	WN 4	–	–	500	440	680	890	1040	–
Br 100	WN 3-4	–	1030	1150	–	1270	1120	1250	–

5. Summary and Conclusions

Using archival ultraviolet spectra of WR stars we show that the emission lines originate in different regions of the envelope. It is evident that the envelope must be stratified: somehow subdivided into several zones of different physical conditions, each of them being a main source of the given ion lines.

However, these zones are further subdivided. It was predicted by Hillier (1987) that if the velocity gradient was high enough different lines of one ion should have different widths. Niedzielski (1994) proved this to be true in the case of HeII lines in the spectra of five galactic WN stars. As we have shown here this is also observed for a sample of 21 galactic and LMC stars based on the coarse analysis of low dispersion UV spectra. This may suggest that the velocity changes sometimes are quite dramatic. The stratification within the lines of one ion allows to study the variability in the WR winds by observing selected line profiles.

From the IP *vs.* FWHM velocity graphs we can study the ionization temperature and velocity gradients. As it was shown by Kuhi (1973) the velocity increases outwards and the ionization temperature decreases outwards. The model considerations of Hillier (1989) give more details concerning the structure of WR envelopes. Close to the core the velocity is low but increases rapidly, further in the envelope the velocity is higher but the velocity gradient decreases.

Ionization stratification has a crucial significance in explaining the acceleration of the WR envelopes with radiation-driven wind theory. We only announce here an ongoing study. A systematic investigation into the ionization stratification may be helpful to clarify the primary mechanism of driving WR winds.

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