THE NEW SUBTYPE FOR THE SPECTRAL CLASSIFICATION OF SOME WOLF-RAYET TYPE STARS

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The modern schemes for the spectral classification of WR type stars are analyzed. The new subtype WO5 for the spectral classification of some WO stars is proposed. The importance of introduction of the subtype WO5 is substantiated. It is proposed that according to point of view of evolution, the WO5 stars are intermediate between WC and WO stars.

1. Statement of the problem

Stars are separated on defined groups with the aid of reasonable spectral classification. In the ideal case the spectral classification depends only on effective temperature and luminosity. In the classification system for the absorption spectra of 'normal' stars the effective temperature and luminosity are closely related. This is result of the fact that in the case of 'normal' stars, the absorption line spectrum and continuum spectrum forms approximately in the same region of the star.

In the case of Wolf-Rayet (WR) stars, having expanding envelope, however, the emission lines are formed in the 'stellar wind' or in the envelope of the star, which removed from the level, emitting the continuum radiation. Therefore, for the WR stars, the spectral types do not connect with the effective temperature and luminosity. The spectral subtypes of the WR stars indicate the temperature of the wind, at least qualitatively.

It has often been suggested that the ionization state of a WR spectrum is related to the ionization temperature in the wind and possibly even to an effective temperature, but this connection has not yet been established physically. It is possible that the ionization state of the wind is mainly determined by the density, and may have little or nothing relation to the effective or an ionization temperature.

2. Spectral classification of WN and WC stars.

According to the scheme proposed by Beals and Plaskett [1], the WR stars have been divided into two spectral types: the WN and WC types. WN stars which exhibit emission lines of predominantly He and N ions with little evidence for C, have been considered as C-poor objects, while WC stars, showing predominantly He and C lines and virtually no evidence for N, have been considered as N-poor. In both subtypes the visible spectra show little or no evidence for hydrogen. In 1968 Smith improved classification scheme [2] for the spectral classification of galactic Pop.I WR (WN and WC) stars. Further, essential changes of line strengths among these ions have been observed from star to star. Therefore for the spectral classification of WN stars WN4-9 (Table I) subtypes and for the spectral classification of WC stars WC4-9 (Table II) subtypes were proposed [1, 2]. These subtypes certainly represent different ionization conditions in the stellar wind of the WR stars. WN and WC stars have different chemical composition, but not all astronomers agree with this assumption [3].

Classification strongly depends on lines ratios, mainly of NIII, NIV, and NV ions for the WN subtypes, and the CIII and CIV ions (along OV) for the WC subtypes respectively. In the case of WC stars, emission lines widths are also additional criterion. Among the late WN stars, the appearance of the helium spectrum is also an criterion (Table I, Table II).

We would like to note that the spectral criteria for determination of WN subtypes depend mainly on the lines in the blue part of the spectrum, namely $\lambda\lambda$4000-4700 ÅÅ; and for determination of WC subtypes, mainly in the yellow part of the spectrum, namely $\lambda\lambda$5500-5900 ÅÅ.

It was established that the WN3, WN4 and WN5 stars could be easily separated by means of ratios of the NIII, NIV and NV ions. Early WN subtypes correlate well with the Smith subtypes. This is, mainly, because of the gradual weakening and then disappearance of, first NIII, and then NIV with transition from WN5 to WN3. The great overlap was found for the WN6, WN7 and WN8 stars. In other words there are some WN6 stars which have nitrogen line ratios similar to those of some WN7 stars, and some WN7 stars with ratios similar to WN8 stars, and conversely. WN7 and WN8 stars are similar, but they can be separated clearly on the basis of the strength and displays of the HeI spectrum.

WN subtypes are usually separated to two subgroups WNL (WN7-9) and WNE (WN2-6) versus presence of little H or absence of H in their spectra.

However in the case of WC stars there is the good agreement with the Smith subtypes.

It is known that WN stars contain CIV$\lambda\lambda$5801, 5812 in the optical region and CIVλ1550 in the UV region.

The WC subtypes contain little or no nitrogen. The only evidence for nitrogen ions in the optical region is possible weak blends of NIII ions side by side with very strong carbon features (which might even be due to other carbon ions) according to [4, 5]. In UV region NIV, and NV lines may be weakly present but blends make the identification a little uncertain [6].

The theoretical investigations suggest that the apparent composition anomalies in WN and WC subtypes are related to stellar evolution [7]. According to modern statements, WN subtypes are result of stars evolution in which CNO equilibrium products are observed on the stellar surface (in the wind). These include enhanced helium and nitrogen, and diminished carbon and oxygen (in comparision with 'normal'). WC subtypes result from the appearance of products of helium burning in which carbon and oxygen are enhanced at the expense of helium and nitrogen.

3. Spectral classification of WO stars.

In 1982 Barlow and Hummer [8] introduce the new type WO for the spectral classification of some WR stars. Table III presents spectral criteria for the definition of the WO subtypes. As we see from Table III the WO subtypes are defined by the relative strengths of OIV, OV and OVI. In [8] authors propose that the spectra of WO stars reflect an actual enhancement of the abundance of oxygen, relatively to the WC stars. Such enhancement of oxygen can be interpreted as due to α particle capture by carbon nuclei during the late stages of core helium burning in initially massive stars. The enriched material is eventually exposed on the surface by mass loss stripping. In this scenario the WO stars represent the next evolution stage after the WC phase, either at the end of core helium burning or already in the core carbon burning stage. The small number of WO stars in comparison with WC stars, is in agreement with this hypothesis.

Table 1. Spectral classification of WN stars according to [1,2].

WN subtypes	**N ions**	**Other criteria**
WN9	NIII present, NIV weak or absent	HeI, lower Balmer series P Cyg
WN8	NIII >> NIV	HeI strong P Cyg, NIIIλ4640 ≈HeIIλ4686
WN7	NIII > NIV	
WN6	NIII ≈ NIV, NV present but weak	
WN5	NIII ≈ NIV ≈ NV	
WN4.5	NIV > NV, NIII weak or absent	
WN4	NIV ≈ NV, NIII weak or absent	
WN3	NIV << NV, NIII weak or absent	
WN2	NV weak or absent	Strong HeII

Table 2. Spectral classification of WC stars according to [1,2].

W**C subtypes**	**CIII l5696/CIV l5805**	**CIII l5696/OV l5592**	**Other criteria**
WC9	CIII > CIV	OV weak or absent	CII present
WC8.5	CIII > CIV	OV weak or absent	CII not present
WC8	CIII ≈ CIV	OV weak or absent	
WC7	CIII < CIV	CIII >> OV	
WC6	CIII << CIV	CIII > OV	
WC5	CIII << CIV	CIII < OV	
WC4	CIV strong, CIII weak or absent	OV moderate	

Table 3. Spectral classification of WO stars according to [8] and our investigations.

WO subtypes	**The criteria for the classification**
WO5	CIVλ5810, OIVλ3400, OVIλλ3811, 3834 is strong, CIIIλ5696/OVλ5590 1, The intensity of OVIλλ3811, 3834 is smaller than the intensity of OIVλ3400 (OVI< OIV)
WO4	The lines of CIV are strong, the CIII lines are absent, OIVλ3400, OVIλλ3811, 3834 are strong; the intensities of the lines OVI λλ3811, 3834 and OIVλ3400 are approximately equal (OVI≈OIV)
WO3	The intensity of the lines OVIλλ3811, 3834 is greater than for the line OIV λ3400 (OVI>OIV)
WO2	The OIV lines are absent; the intensity of the line OVλ5590 is smaller than for the line CIVλ5810 (OV<CIV)
WO1	The intensity of the line OVλ5590 is greater than or is equal to Intensity of the line CIVλ5810 (OV≥CIV)

In order of excitation increase the WO subtypes runs: WO4, WO3, WO2, WO1.

The difference between WN, WC and WO subtypes can be understood purely in terms of ionization, excitation and structural differences among them. Different subtypes represent different composition. It is suggested that they result from the stellar evolution. The separation of WR stars to WN, WC, and WO types is connected with the different chemical composition and related to stellar evolution. According to modern evolutionary status, the WN and WC stars represent the early and late stages of core helium-burning phase, respectively, during the evolution of massive stars [7, 9]. On the other hand, according to [8], the WO stars represent the next evolution stage after the WC phase. Therefore, we obtain such an evolution scheme for the WR types:

$$WN \rightarrow WC \rightarrow WO$$

4.The reason for the proposition of new subtype WO5.

The new subtype WO5 is proposed because of uncertainties in the spectral classification of some WR-OVI stars. Below we discuss some of them.

HD 16523. According to [10] the spectral subtype of the WR-OVI star HD 16523 is WC5, and according to [2] the spectral subtype of this star is WC6.

Table IV presents the classification criteria for the WC5, WC6, WC8 stars according to [10] and our results for the WR-OVI stars HD 16523, HD 17638, HD 192103.

From Table IV we see that the spectral subtype of the WR-OVI star HD 16523 is uncertain as estimated from the different criteria: the ratio CIIIλ5696/CIVλ5810 and width at the half intensity for the CIII, CIVλ4650 corresponds to the subtype WC5, but the ratio CIIIλ5696/OVλ5590 corresponds to the subtype WC6.

HD 17638. According to [10], the spectral subtype of the WR-OVI star HD 17638 is WC6. From Table IV we may infer that the spectral subtype of this star is uncertain as estimated from different criteria: the intensity ratio of the line CIIIλ5696 and

OVλ5590 (CIIIλ5696 /OVλ5590), the intensity ratio of the emission lines CIIIλ5696 and CIVλ5810 corresponds to the subtype WC6, but widths of the CIII, CIVλ4650 correspond to the subtype WC5.

HD 192103. According to [10] in the spectra of the HD 192103 the emission doublet OVI$\lambda\lambda$3811, 3834 of middle intensity presents. Our results for this star correspond to the subtype WC8, which is given in [10].

We may infer that in two cases (HD 16523 and HD 17638) the spectral subtype of the WR-OVI stars, as estimated from different criteria, is uncertain. The spectra of the WR-OVI stars, HD 16523 and HD 17638 differ from the spectra of usual WC5 and WC6 stars because the emission doublet OVI$\lambda\lambda$3811, 3834 with the different intensity present in spectra of these stars. The Sanduleak stars [11] were also considered earlier as WC4 and WC5 stars [10]. However, Barlow and Hummer [8] argued that the Sanduleak stars [11]may be considered as WO stars and for the spectral classification of these stars they proposed spectral subtypes WO1-4 (Table III). The argument for this conclusion is the presence of the strong emission doublet OVI$\lambda\lambda$3811, 3834 in spectra of these stars. In the spectra of the WO stars, the carbon lines are very weak or not observable. The stars HD 16523 and HD 17638 differ from the usual WC5 and WC6 stars because in these stars the emission doublet OVI$\lambda\lambda$3811, 3834 presents. The stars HD 16523 and HD 17638 differ from usual WO (WO1-4) stars, because carbon lines have a considerable intensity in the spectra of these stars. We see that the WR-OVI stars HD 16523 and HD 17638 have a spectral characteristic intermediate between WO (WO1-4) and WC4-6 stars. In the spectra of the WR-OVI stars HD 16523 and HD 17638, the intensity of the emission doublet OVI$\lambda\lambda$3811, 3834 is smaller than that of the emission line OIVλ3400 (OVI<OIV). From Table III we see that in the spectra of WO4 stars the intensities of the emission doublet OVI$\lambda\lambda$3811, 3834 and OIVλ3400 are approximately equal (OVI $\approx$ OIV), and in the spectra of the WO3 stars already OVI>OIV. Therefore, according to the ratio of the intensities of the emission doublet OVI$\lambda\lambda$3811, 3834 and of the emission line OIVλ3400, the stars HD 16523 and HD 17638 continue WO4 stars at lower ionization potentials. According to this result we argue that for the define spectral classification of the WR-OVI stars, whose optical spectra are intermediate between WO4 and WC4-6 stars, the new spectral subtype WO5 may be proposed. Table IV lists the classification criteria for the determination of the WO5 subtype.

Table 4. The spectral classification of the WR-OVI stars.

Subtype	CIIIλ5696/OVλ5590	CIIIλ5696/CIVλ5810	The widths of the CIII, CIV λ4650(Å)
WC5	< 1	<< 1	85
WC6	> 1	<<1	45
WC8	OV weak or absent	~ 1	20
Our results			
HD 16523	1.20	<< 1	88
HD 17638	2.74	<< 1	76
HD 192103	13.25	1.13	18

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