CHEMICAL COMPOSITION IN THE ENVELOPES OF DIFFERENT WR SUBTYPES

T. NUGIS
W.Struve Astrophysical Observatory of Tartu
202444 Tõravere
Estonia, USSR

ABSTRACT. Valuable model–independent information about the chemical composition of WR stars can be obtained by using lines of different ions arising at transitions between highly excited energy levels. We determine the abundances of He, H, C, N, O using theoretical line intensities obtained by solving statistical equilibrium equations for level populations for different subtype WR envelope conditions.

The chemical composition of WR stars strongly differs from the mean cosmic composition. In the case of WN stars nuclear processed CNO products of H-burning are revealed in the envelopes and He-burning products in the WC envelopes.

The abundance of oxygen in WC stars differs from the predictions of recent evolutionary calculations which account for the new $^{12}C(\alpha,\gamma)\,^{16}O$ reaction rate.

1. Model–dependence

In recent years new observational evidence has been obtained which point to the complicated nature of the envelopes (winds) of WR stars (clouds, deceleration and coronal zones). This, together with the unexplained nature of their intensive mass loss, does not allow the development of physically self–consistent atmospheric models for this type of star. Therefore, it is very important to find out in every case whether the results depend on concrete models and physical parameters. For the determination of the chemical composition of WR stars it is possible to use for some most abundant elements the subordinate lines which arise from transitions between highly excited energy levels (hydrogenic transitions). Our special study shows that the ratios of theoretical intensities of these lines depend weakly on a concrete model of the envelope and physical conditions. Therefore, these lines are very suitable for abundance determinations.

Our present determinations of chemical composition are based on solutions of the statistical equilibrium equations of level populations for the ions of H, He, C, N and O. All important collisional and radiative processes of population and depopulation of levels are considered. Radiation transfer effects in line frequencies were accounted by the Sobolev escape probability method as formulated by Castor

K. A. van der Hucht and B. Hidayat (eds.),
Wolf-Rayet Stars and Interrelations with Other Massive Stars in Galaxies, 75–80.

(1970) for spherically symmetric expanding media. The partial nontransparency of WR envelopes in the continua of the lowest series of abundant ions is treated approximately as described by Nugis (1990). Usually reliable results for theoretical line intensities can be obtained by solving statistical equilibrium equations either for full transparency of the envelope in continua or by using "on-the-spot" approximation. Before the presentation of our results for the chemical compositions of WR stars, we want to prove by concrete examples that quite reliable abundances for dominant elements can be determined even in the case of quite inadequate models for the real envelopes of WR stars and even by using very simple methods of calculation of theoretical line intensities. This becomes evident when analyzing the logic of the nearly normal (solar) chemical composition for WR stars proposed by Bhatia and Underhill (1986, 1988). We repeated the calculations of level populations of some ions for their WR envelope models (HeII, HI, CIV, CIII) and obtained for the lines, used by them nearly the same theoretical intensities. They used for the abundance study strong lines arising from transitions between low energy levels (CIV λ5806, CIII λ5696, NIV λ3482 and so on). Models of Bhatia and Underhill result in strong overpopulation of low levels of the studied ions. We included in statistical equilibrium calculations a larger number of levels for C, N ions and found that for the Bhatia and Underhill models ($T_* \approx 25000$ K, $T_e \approx 100000$ K, $N_e \approx 10^{10} \text{cm}^{-3}$, $dv/dr \approx 10^{-5}$) the ratios of intensities of subordinate lines arising from transitions between low energy states and of highly excited states are in conflict with the observed data (Figs. 1, 2).

The HeII line intensity run of the Pickering series, as predicted by the calculations of Bhatia and Underhill (1986), is also in serious conflict with the observed run. In the case of every WR star the lower members of the Pickering series have intensities much smaller than the LTE prediction for an optically thin case (the mean observed coefficients $b_k\beta_{ik}$ are lower than unity (b_k is the Menzel departure coefficient and β_{ik} is the escape probability coefficient for line quanta)) (Figs. 3, 4). Bhatia and Underhill (1986) models predict $b_k\beta_{ik} > 1$ for lower members of the Pickering series. From our investigation it can be concluded that the models of Bhatia and Underhill (1986, 1988) are in serious conflict with the observed line spectra, but the line intensity ratios of subordinate lines arising at transitions between high energy levels are quite close to the ratios predicted by our WR wind models. Very wrong models can be used for obtaining reliable results, only "selected lines" must be used. For subordinate lines arising at transitions between high energy levels even very simple calculation schemes (the recombination theory) predict quite close results to those obtained by much more realistic envelope models and appropriate statistical equilibrium calculations for level populations.

2. Chemical composition

For determinations of abundance ratios of most dominant ions we used the theoretical line intensities found from the solutions of the statistical equilibrium equations for level populations for wind models of different WR subtypes. We used the mean parameters of WR stars and their winds as derived by Nugis (1989). For concrete estimates the envelope was divided into different effective subzones having different T_e values as derived from energy balance equations for free electrons. The mean

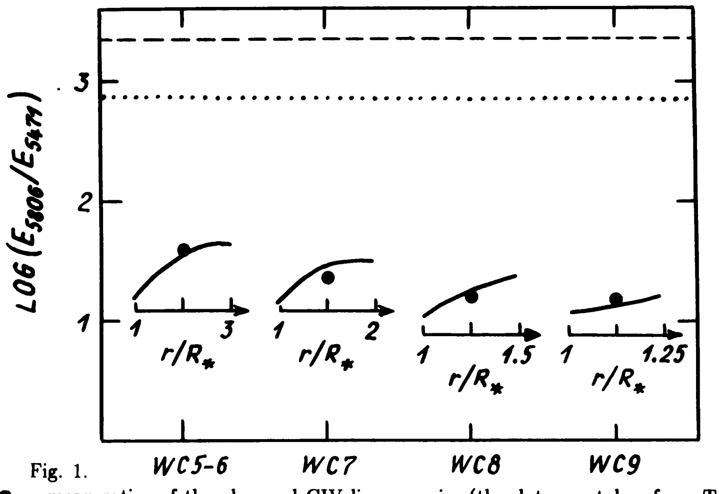

Fig. 1.

● – mean ratios of the observed CIV line energies (the data are taken from Torres, 1985).

– – – theoretical prediction of the model envelope of Bhatia and Underhill (1988) ($T_* = 25000$ K, $T_e = 100000$ K, $R_* = 10\ R_\odot$, $r = 3\ R_*$, $dv/dr = 10^{-5}$, normal C abundance).

· · · – 10^3 times higher carbon abundance with the other parameters being same as for the previous (- -) model.

—— – the predictions of our wind models at some different r values.

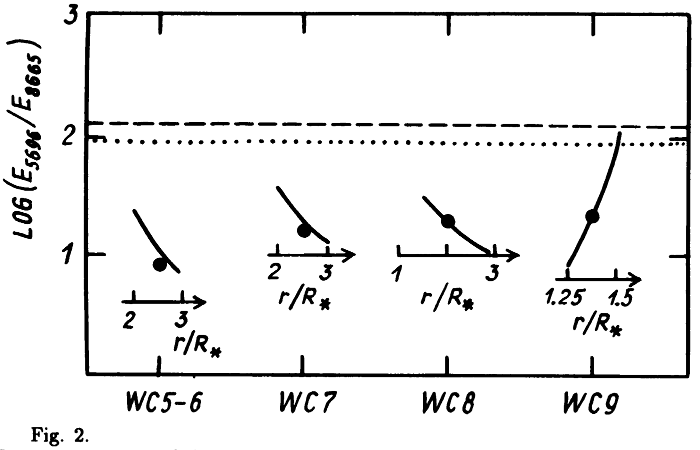

Fig. 2.

● – mean ratios of the observed CIII line energies (the data are taken from Torres, 1985 and Conti et al., 1989).

– – – theoretical prediction of the model envelope of Bhatia and Underhill (1988) ($T_* = 25000$ K, $T_e = 100000$ K, $R_* = 10\ R_\odot$, $r = 3\ R_*$, $dv/dr = 10^{-5}$, normal C abundance).

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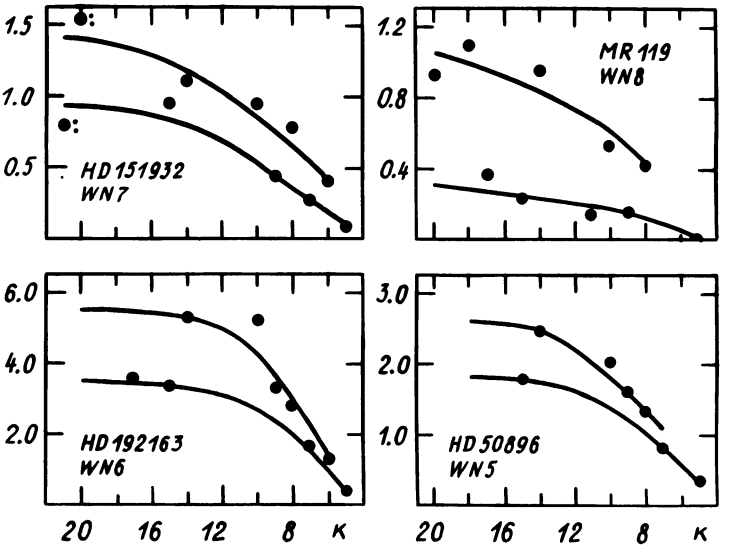

Fig. 3. Observed energies of the Pickering series lines divided by theoretical intensities corresponding to an optically thin medium having LTE populations. The difference between odd and even members of the Pickering series gives us information about the presence of hydrogen.

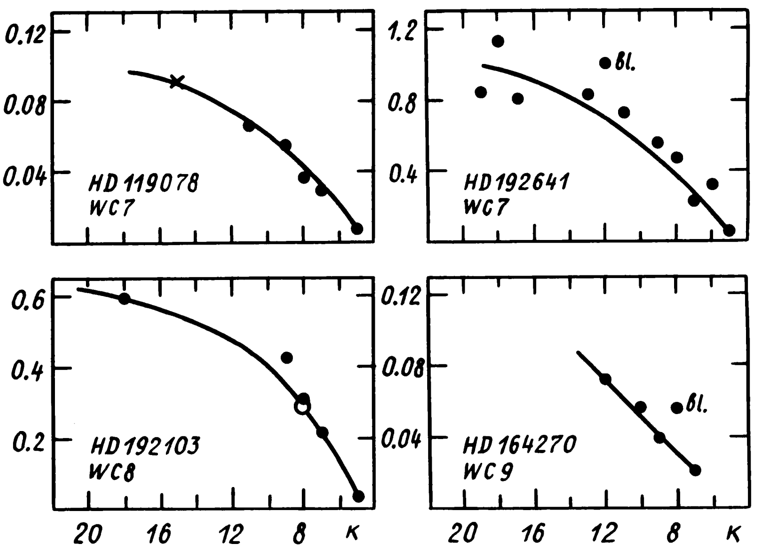

Fig. 4. Observed energies of the Pickering series lines divided by theoretical intensities corresponding to an optically thin medium having LTE populations. The difference between odd and even members of the Pickering series gives us information about the presence of hydrogen.
o — lines of HeII K-3 series;
x — lines of HeII K-5 series;
bl. — blended line.

value of the expansion velocity was adopted to be $v_{max}/2$ for early subtypes and outer regions ($r \geq 1.5R_*$) of the envelopes of later subtypes (WC8-9, WN7-8). In the inner regions of late subtype stars we adopted $v = v_{max}/3$. The velocity gradient was taken to correspond to the law $v \propto r$.

From our present calculations and also from our other recent studies we infer the presence of a coronal zone in the inner part of an envelope. This coronal zone ought to be opaque at wavelengths $\lambda < 228\AA$. The radiation temperature in that region must be higher than for $\lambda > 228\AA$ spectral region. The results of our chemical composition estimations are given in Table 1. For final determinations we used the higher members of the Pickering and Balmer series, and the lines: HeI (4471.5, 5875.6), CIV (5471), CIII (8665, 4070), CII (4267), NV (4945), NIV (2646, 6219), NIII (4379), OVI (3811, 3834), OV (2783, 5600), OIV (1343, 3063+3071, 3412), OIII (3265, 3760).

The oxygen abundance derived for 6 WC stars differs from the prediction of the latest calculations of WR evolution (Prantzos et al., 1986; Langer and El Eid, 1986; Maeder, 1987). Interestingly enough, the abundances of He, C, O for WC stars derived by us are in accord with earlier evolutionary calculations where a lower rate of reaction $^{12}C(\alpha,\gamma)\ ^{16}O$ was used. The discrepancy with evolutionary calculations was found also in the case of Ne abundance in the envelope of WC8 component of binary γ^2 Vel (Barlow et al., 1988).

TABLE 1. Chemical composition of WR stars. Mean values of the ratios of most abundant elements are presented. The numbers of the stars used for finding the mean values are given in brackets (in the case of a single estimate the HD number of that star is given).

Sp	N(He)/N(H)		N(N)/N(He)		N(C)/N(He)	N(O)/N(He)	
WN3	5–10	(9974)	0.003–0.01	(9974)			
WN4	3–10	(187282)	0.003–0.01	(187282)			
WN5	3–6	(2)	0.003–0.01	(2)	$\leq$ 0.004 (2)		
WN6	1.5–6	(2)	0.003–0.01	(2)	$\leq$ 0.001 (2)		
WN7	1.5–3	(151932)	0.003–0.01	(151932)			
WN8	0.7–1.5	(2)	0.003–0.01	(2)			
WC5–6	$\geq$ 10	(2)			0.3–0.7 (3)	0.05	(3)
WC7	$\geq$ 10	(156385)			0.2–0.4 (3)		
WC8	$\geq$ 10	(192103)			0.1–0.3 (2)	0.02	(2)
WC9	$\geq$ 10	(164270)			0.1–0.2 (9)	0.02	(164270)

We found that the carbon abundance is increasing from later WC classes to earlier classes. This tendency was found also by Smith and Hummer (1988) from IR carbon lines by using the recombination theory for predicting line intensities. Torres (1988) has not found such a trend for WC stars, but in the error limits (factor $\approx$ 2–3) all the results are in accord. In the case of WN classes some chemical evolution from later classes to earlier classes seems to be present as well.

The chemical composition of WR stars strongly differs from the mean cosmic composition. In the case of WN stars nuclear processed CNO products of H–burning are revealed in the envelopes and He–burning products in WC envelopes. The transition from WN type to WC type probably does not take place for most WN subclasses.

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DISCUSSION

Smith, Lindsey: I am glad to see you get increasing C/He from WC9 to WC4. This confirms the result by myself and Hummer.
Nugis: Yes, the results of your and Hummer's study are in accord with my estimates.

Langer: Can you exclude a vanishing hydrogen abundance in early WN stars?
Nugis: Hydrogen to helium ratio is not more than 1/3 for the studied WNE stars. For the earliest WN types, in the limits of observational errors hydrogen may be absent at all.