Interacting Winds from Massive Stars
*ASP Conference Series, Vol. **VOLUME**, **PUBLICATION YEAR***
Anthony F.J. Moffat, and Nicole St-Louis, eds.

[WC]-type CSPN : Clumping and wind-driving

L. Koesterke and W.-R. Hamann

University of Potsdam, Germany

Abstract. Many Central Stars of Planetary Nebulae are very similar to massive Wolf-Rayet stars of the carbon sequence with respect to their spectra, chemical composition and wind properties. Therefore their study opens an additional way towards the understanding of the Wolf-Rayet phenomenon. While the study of Line Profile Variation will be difficult, espescially for the very compact early types, the comparision with other hydrogen-deficient Central Stars illuminates the driving mechanism of their winds. We speculate that at least two ingredients are needed. The ionization of their atmpospheres has to be stratified to enable multi-scattering processes and the amount of carbon and oxygen has to be high (more than a few percent by mass).

1. Introduction

The spectra of about a quarter of the Galactic Central Stars of Planetary Nebulae (CSPN) are dominated by broad emission lines of helium, carbon and oxygen. In the manner of Pop I Wolf-Rayet (WR) stars they are classified as [WC] stars (WR stars of the carbon sequence). Most of these Central Stars are of the subtypes [WC 2-4] and [WC 8-12] while almost no [WC 5-7] Central Stars are known. Also no [WN] type CSPN is known, except the enigmatic N66 in the Large Magellanic Cloud.

For many reasons these stars seem to be the smallscale versions at lower luminosities of about $10^{3.7}\,L_\odot$ of massive WC stars. The chemical composition as well as the wind properties (as terminal velocity and wind momentum ratio) seem to be same. Also Line Profile Variabilities (LPV) are reported for some late-type [WC] CSPN (Balick et al. 1996, Grosdidier et al. 1997, Acker et al. 1997, Grosdidier et al. 2001). Therefore the study of these CSPN gives an additional access to the WR phenomenon. Espescially the comparison of [WC] stars with other CSPN, which are either different in chemical composition and/or have different stellar temperatures, gives new insights into the driving mechanism of the strong WR winds. In this paper we give a short overview on the evolution of the [WC] CSPN (Sect. 2), report on the clumpiness of the [WC] atmospheres derived from the line wings (Sect. 3) and on the expected time scale of the LPVs in an early [WC] star (Sect. 4). Afterwards we discuss whether their winds could be driven by radiation (Sect. 5).

2. Evolution of hydrogen-deficient post-AGB stars

The stellar evolution of AGB and post-AGB stars is still not fully understood. In particular the formation of hydrogen-deficient post-AGB stars was not sufficiently explained by stellar evolution theory. As one possibility the born-again scenario was proposed by Iben (1984) and Iben & Mac Donald (1995). A post-AGB star which has already evolved to a white dwarf suffers from a very late thermal pulse and is thrown back to the AGB regime. During this pulse, the hydrogen is mixed downwards and burned and a hydrogen-deficient or hydrogen-free post-AGB star is formed, respectively. Because of numerical difficulties, this pioneering work by Iben and co-workers was not based on fully consistent but rather on semi-analytic calculations.

Recently new numerical techniques were applied which allow for a consistent treatment of mixing and burning processes (Herwig 2000, Blöcker 2000). From the first calculations three different scenarios have been derived.

LTP Late Thermal Pulse : The thermal pulse occurs while the star has already left the AGB and hydrogen burning is still going on. The star is approximately located in the regime of the Central Stars of Planetary Nebulae (CSPN). During the pulse the hydrogen at the surface remains unchanged and no convective hydrogen burning takes place. By dredge-up during the 2^{nd} AGB phase, hydrogen at the surface is decreased down to a very few percent by mass.

VLTP Very Late Thermal Pulse : This scenario is similar to the LTP but the star has already turned around the knee (in the HRD) and entered the white dwarf cooling sequence. The hydrogen burning has already ceased. During the pulse the hydrogen at the surface is efficiently mixed downwards into hot regions and a hydrogen free star is formed by convective hydrogen burning. As in the first case the star is thrown back to the AGB. This scenario is nearest to the born-again scenario proposed by Iben and co-workers and provides almost perfect hydrogen free precursors of non-DA white dwarfs.

AFTP Asymptotic giant branch Final Thermal Pulse : This is like an ordinary thermal pulse at the AGB but with a particular small envelope mass. As in the first case, the hydrogen burning ceases and the hydrogen is mixed (but not burned) with the intershell. The remaining hydrogen abundance is relatively high.

3. Clumping in [WC] atmospheres

As known from Hillier (1991) the clumpiness of WR atmospheres can be estimated from the strength of the electron-scattering line wings. Within non-LTE models for expanding atmospheres Schmutz (1997) and Hamann & Koesterke (1998) applied a very simple approximation for the clumps and investigated the density contrast D of the atmospheres of different Pop I WR stars. D (also called "clumping factor") is the density enhancement of the clumps compared to the density of a smooth atmosphere with both having the same mean density. The filling factor f_V is given by $1/D$.

Hamann & Koesterke (1998) found clumping factors of about 4 for WN stars and 16 for an early-type WC star. In accordance to their results we derive $D = 4 - 16$ from profile fits of three different models (D=1, 4, 16) to observations of the [WC 3] star Sand 3 (Fig. 1). This proves the similarity of the wind properties of Pop I and Pop II WR stars.

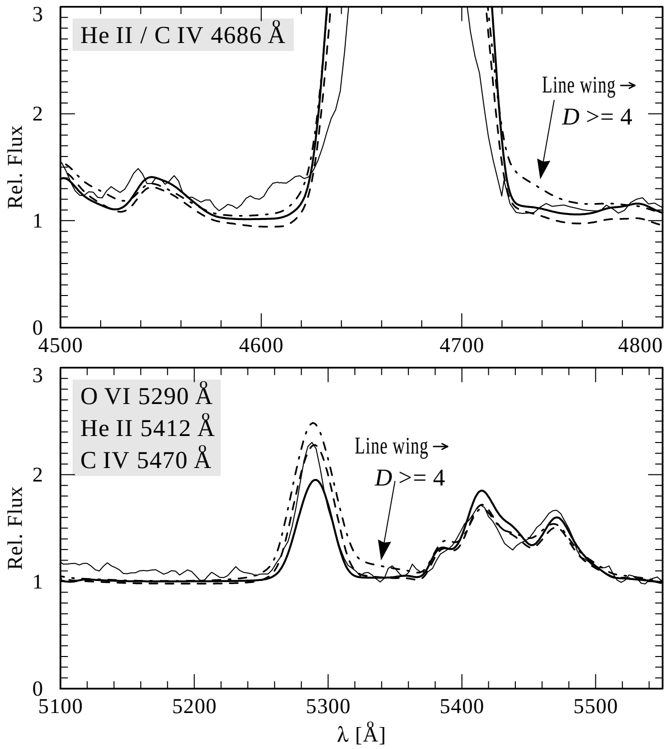

Figure 1. Observation of Sand 3 (thin, solid) compared to models with three different clumping factors (D = 1: dashed-dotted, D = 4: dashed, D = 16: solid). The model with D = 4 fits the observations best but higher clumping factors cannot be excluded.

4. Line profile variabilities

As quoted in Sect. 1, LPVs have been verified in some [WCL] CSPN. From an estimation of the flying times of wind elements through the Line Emitting Regions (LER) of different spectral lines we show that highly sophisticated observations will be needed to do the same for [WCE] CSPN. In Fig. 2 the LERs are taken from a non-LTE model of Sand 3 ([WCE]). The velocity field is calculated from the β-law with $\beta = 1$. It is an outstanding question which β is appropriate to describe the velocity field, e.g. Grosdidier et al. (2001) claim $\beta = 3 - 6$ for the [WCL] star BD +30°3639. Note that the results presented here depend on the choice of β.

The flying times of wind elements through the LERs of different ions are given in Table 1. They are in the range between 15 to 30 min, which means that observations of about 2 to 5 min would be needed to resolve the time variations of the line profiles. Even if these numbers are increased by a factor of 2 or 3 because of a different choice of β, it will be still difficult to obtain sufficient spectra. The brightest [WC] CSPN, BD +30°3639 ($m_V \approx 10.0$), was monitored by Grosdidier et al. (2001) performing 30 min observations at 1.5 m telescopes. Unfortunately all known [WCE] CSPN are much fainter ($m_V \geq 15.0$).

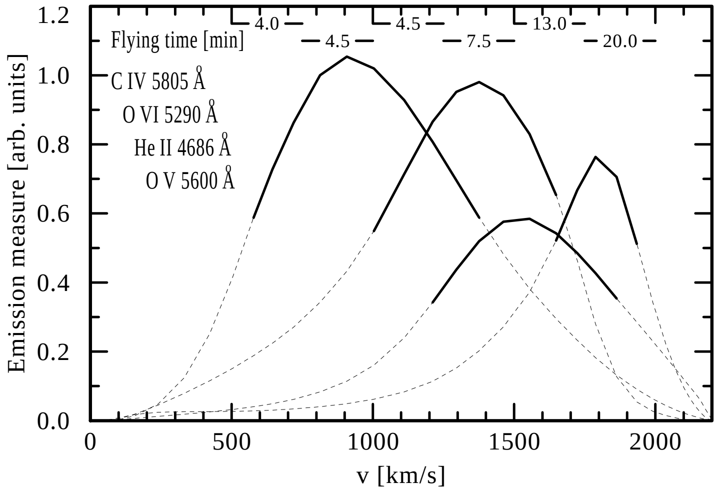

Figure 2. Line emitting regions of 4 different lines. From left to right: C IV 5805Å, O VI 5290Å, He II 4686Å, O V 5600 Å. Flying times are indicated in the upper part.

Table 1. Flying times of wind elements for different spectral lines.

Line	t [min]	Line	t [min]
He II 5412 Å	30	C IV 5470 Å	20
He II 4686 Å	30	C IV 5805 Å	15
O V 5600 Å	20	C IV 4686 Å	15
O VI 5290 Å	25		

5. Driving mechanism of the strong WR winds

The spectral analyses of these stars can provide information on the driving mechanism of the winds of hot stars. In case of the WR stars this mechanism is not fully identified but it is becoming more and more likely that these winds are accelerated by radiation. One of the hints towards this hypothesis have resulted from the comparison of wind properties of non-[WR] stars and of [WC] stars.

In particular the [WC] stars are compared to a class of hot and hydrogen-deficient Central Stars which are named PG 1159 stars. In addition three transition objects between the [WCE] and the PG 1159 stars and one hydrogen deficient sdO star are taken into consideration. While the PG 1159 stars are hotter but similar in chemical composition, the sdO star is in the temperature range of the [WC] stars but has a helium dominated atmosphere. The mass fraction of helium is about 0.98 while carbon and oxygen contribute about 0.01.

Koesterke et al. (1998) and Koesterke & Werner (1998) argued that the radiation fields of PG 1159 stars are sufficient to drive the stellar winds within the single scattering limit ($\eta = \frac{\dot{M}\, v_\infty}{L\, c}$, $\eta \approx 1$) and speculated that the much higher performance numbers ($\eta \approx 15$) of [WCE] stars might be explained by multi-scattering processes in their atmospheres. They compared the ionization structure of oxygen for a typical PG 1159 and a typical [WCE] star and found stratified ionization structures only in the [WCE] atmosphere. This favors multi-scattering processes in the wind of the [WCE] stars because, as Lucy & Abott (1993) showed, these processes are stimulated in stratified atmospheres where the leading ionization stage changes.

Koesterke (2000) compared new models including iron and found the same for this element (Fig. 3). The ionization changed twice in the [WCE] star but remained unchanged in the hotter PG 1159 star.

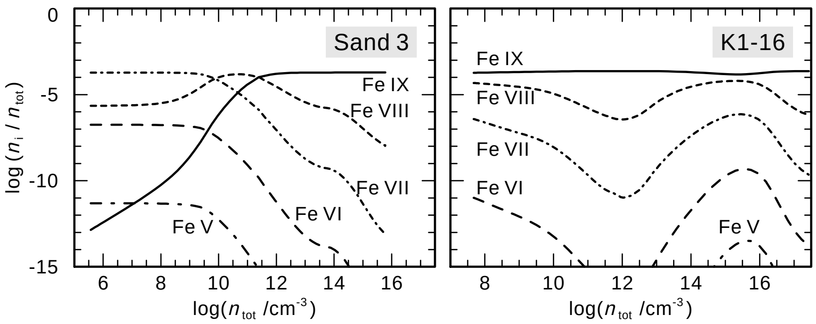

Figure 3. Ground-level non-LTE occupation numbers versus the particle density of iron for Sand 3 (left) and K 1-16 (right). The iron abundance is $2\,10^{-3}$ by mass. While the whole atmosphere of K 1-16 is dominated by Fe IX the leading iron ionization stage changes twice in the atmosphere of Sand 3. This might explain the enhanced mass-loss rates of [WCE] stars by multi-scattering processes.

The stellar evolution in terms of temperature and wind density is sketched in Fig. 4. The wind density is related to the so-called transformed radius introduced by Schmutz et al. (1989). During the [WCL] phase the stars evolve from 20 kK towards higher temperatures and reach at about 140 kK the [WCE] phase. Simultaneously the wind density increases drastically. In these phases the wind efficiency η is greater than 1. Then the mass-loss fades abruptly, possibly because their atmospheres become uniformly ionized and multi-scattering processes vanish, and the star becomes a [WC]-PG 1159 star showing absorption and emission lines in the optical. The optical emission lines vanish when the PG 1159 stage ($\eta \approx 1$) is reached and only weak P Cygni profiles persist in the UV. As before, the wind density increases towards higher temperatures.

The recently investigated sdO star points to another ingredient for strong WR winds. Its low mass-loss might be induced by its low (compared to [WR]

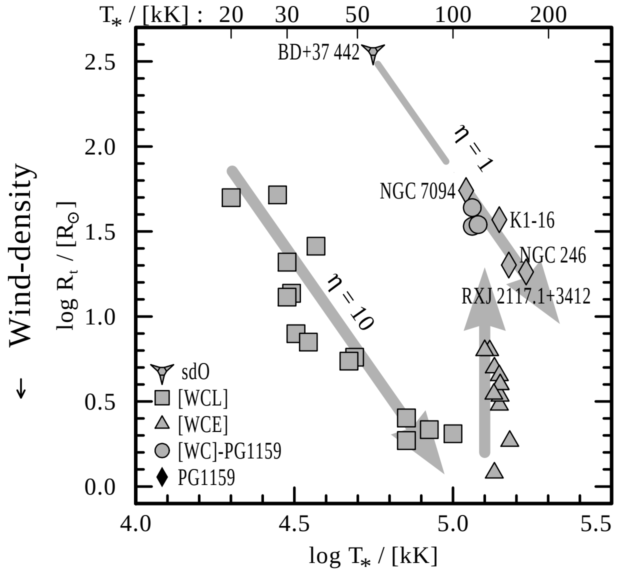

Figure 4. The post-AGB stars in the $\log(R_t)$–$\log(T_*)$–plane. A decreasing R_t can be considered as an increasing wind density. The suggested evolutionary path is indicated by the arrows. The sdO star extends the regime of the PG 1159 stars towards lower temperatures.

stars) carbon and oxygen abundane of about 1% by mass. This would favour the hypothesis that the winds are substantially driven by the lines of light metals as carbon and oxygen.

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