

A consistent spectral model of WR 136 and its associated bubble NGC 6888

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We analyse whether a stellar atmosphere model computed with the code CMFGEN provides an optimal description of the stellar observations of WR 136 and simultaneously reproduces the nebular observations of NGC 6888, such as the ionization degree, which is modelled with the pyCloudy code. All the observational material available (far and near UV and optical spectra) were used to constrain such models. We found that the stellar temperature T_* , at $\tau = 20$, can be in a range between 70 000 and 110 000 K, but when using the nebula as an additional restriction, we found that the stellar models with $T_* \sim 70$ 000 K represent the best solution for both, the star and the nebula.

1 Introduction

NGC 6888 is an emission nebula associated with the Wolf-Rayet star WR 136 with spectral type WN6(h), and both have been already studied in several wavelength ranges from X-rays to radio emission, but all the previous works focus only on the modelling of the star or the nebula but not both simultaneously. This is why we focus in a semiempirical method based in the self-consistent modelling of the star and its associated nebula. It is logical to proceed in this way because the nebula associated to the star is naturally an additional restriction to the stellar atmosphere model, because the nebula can tell us about the ionizing ultraviolet photons coming from the star and then reprocessed and re-emitted with low energy through recombination and collisional processes.

2 Observational restrictions

The main analysis in this work is based on the optical observations of the star WR 136, the nebula using the REOSC echelle spectrograph (Levine & Chakrabarty 1994) attached to the 2.1-m telescope at the Observatorio Astronómico Nacional (OAN) in San Pedro Mártir, B. C. México. In addition to the optical spectra of WR 136, we retrieved several reduced IUE spectra and from the *FUSE* satellite observational program C097.

3 Stellar atmosphere models of WR 136

To model the observed stellar spectra of WR 136, in the UV and optical ranges, we used the CMFGEN code (Hillier & Miller 1998).

For the stellar models computed in this study, the input values used to constrain the model atmosphere for WR 136 were the mass-loss rate \dot{M} , the terminal wind velocity V_∞ , the stellar luminosity L , the

hydrostatic radius of the star R_* (at optical depth τ equal to 20) and the chemical composition.

As the modelled spectral features do not respond linearly to the input parameters, we calculated a grid of models in order to find the more appropriated models which reproduce most of the observed spectral signatures. From this grid, we obtained *star1* which fits very well most of the stellar spectral characteristics. This model is presented in Table 1. In addition we also show in this table models from the literature, as Hamann et al. (2006) (hereafter HGL06) and Crowther & Smith (1996) ones.

The main difference between *star1* and the model reported by HGL06 is the stellar radius R_* which in our case has a low value of $1.5 R_\odot$ (compared to the value of $3.34 R_\odot$ by HGL06) leading to a higher stellar temperature T_* of 110 kK. Additionally the chemical composition, represented by the values of X and Y, is different. These differences indicate that it could exist more than one solution for a stellar model of a WR star as both, *star1* and HGL06 model, reproduce similarly well the stellar spectrum (see Fig. 68 by HGL06). This apparent degeneracy has already been remarked in a study of WR stars modelling by Hillier (1991).

To investigate this degeneracy we searched for other CMFGEN models that could fit the stellar observations. In a simple manner we used interpolated values between the model *star1* and the HGL06 model for the radius, the clumping factor (f_V) and the hydrogen and helium fractions by mass, X and Y. The result is model *star2* which has an effective temperature of 90 000 K (its characteristics are presented too in Table 1). Model *star2* reproduces the stellar spectrum similarly well as *star1*. It is presented in Fig. 1, in green.

We computed two additional models. The first is *star3* which basically uses HGL06 model parameters but it was calculated with the CMFGEN code. Model *star3* reproduces very well the results of HGL06 model, which shows that CMFGEN and the Potsdam WR model atmosphere code are equivalent. The last one is model *star4* which is almost the same as *star3* but calculated with the β value equal to 2, leading

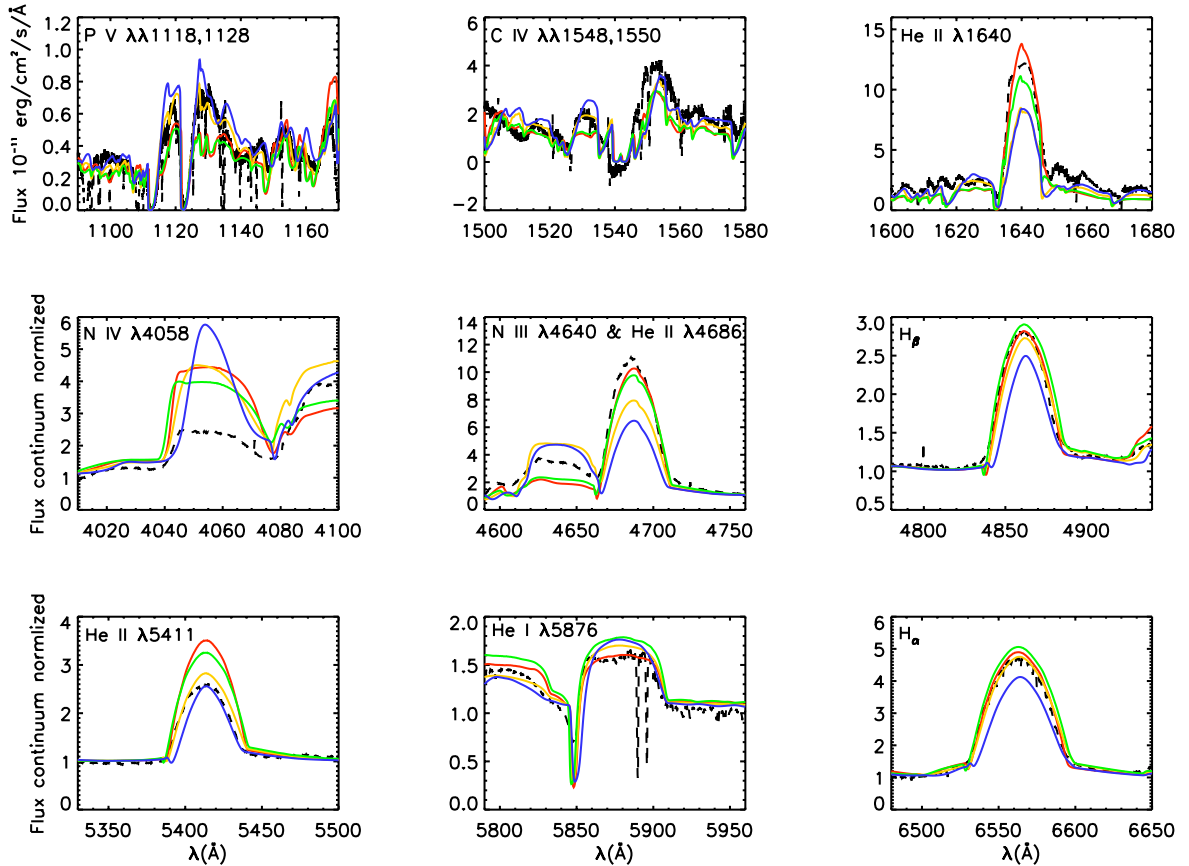


Fig. 1: Selected lines from the observed spectra to constrain the models. In each plot the dashed black line is the observed spectrum; red, green, yellow and blue lines are respectively the *star1*, *star2*, *star3* and *star4* models obtained through the CMFGEN code but reddened. The optical spectrum is shown as flux-normalized.

to a lower $T_{2/3}$ value because the wind region becomes more extended. Models *star3* and *star4* reproduce fairly well the observed stellar continuum and many spectral features (lines yellow and blue in Fig.1). The differences among all these models appear mainly in the He lines, where the He II/He I line ratio is well reproduced when considering an effective temperature of 110 000 K but it is underestimated when the effective temperature is reduced, i.e., at a lower stellar temperature the stellar He I lines are stronger and the stellar He II lines become weaker than observed.

All the stellar model characteristics are presented in Table 1.

4 NGC 6888 as an additional restriction

The key difference between the stellar models comes from the far UV region of the spectra, whose UV photons are absorbed by the nebula (between 1.0

and ~ 7.0 Ryd). This difference is clear when we compare the models with a blackbody with the same temperature than the modelled spectra, 70 000 or even 46 000 K, we would see an excess of UV photons which would lead to a much more ionized nebula, contrary to the high absorption of the UV photons emitted by the star, due to the presence of the stellar wind (Reyes-Pérez et al. 2015).

Owing to there are not stellar observations in the far UV to discriminate which stellar model is reproducing the real spectral energy distribution of the star WR 136, it is necessary to add an external restriction. In this case, such additional restriction is the associated nebula NGC 6888 that is highly sensitive to this UV ionizing radiation. To reproduce the optical spectra of NGC 6888 we computed a photoionization model using the pyCloudy package (Morisset 2013) based on the 1D photoionization code Cloudy (Ferland et al. 1998). As we aim to build a consistent model of the system we used as ionizing sources the stellar atmosphere models of the star WR 136, as calculated with the CMFGEN code and described in §3.

Tab. 1: Stellar model parameters

Model	R_* [R_\odot]	$\log L$ [L_\odot]	$\log \dot{M}$ [$M_\odot \text{yr}^{-1}$]	V_∞ [km s^{-1}]	T_* [kK]	$T_{2/3}$ [kK]	β	f_V	X	Y
This work <i>star1</i>	1.50	5.45	-4.63	1550	110	55	2	0.1	0.016	0.95
This work <i>star2</i>	2.10	5.40	-4.95	1550	90	48.30	1	0.175	0.068	0.91
This work <i>star3</i>	3.38	5.40	-4.95	1550	70	45.91	1	0.25	0.12	0.86
This work <i>star4</i>	3.38	5.40	-4.95	1550	70	42.26	2	0.25	0.12	0.86
HGL06	3.34	5.40	-4.95	1600	70.8	...	1	0.25	0.12	0.86
Crowther & Smith (1996)	5.00	5.30	-3.91	1750	55.7	28				

The results of the photoionization model show that, under the assumptions made for this model (Reyes-Pérez et al. 2015) and using *star1* as ionizing source, the observed line fluxes are not well reproduced. In particular the lines from highly ionized elements (O^{++} , Ar^{++}) are extremely overpredicted. The fact that the ionization of the nebula is strongly overpredicted could be due to a too high stellar effective temperature, because the only way to reproduce the observed low line intensity of high ionized elements is to consider a star with a temperature lower than the value derived for model *star1*, i.e., we must deal with their energy of ionization photons.

The predicted emission lines improve very much and fit well the observations when we use the model *star3* which has $T_* = 70\,000$ K, indicating that the star WR 136 emits the UV ionizing photons corresponding to a star with this low effective temperature. The details about the photoionization model and its results can be found in Reyes-Pérez et al. (2015)

5 Conclusions

We computed several atmosphere models using the code CMFGEN to reproduce the stellar observations of WR 136. The characteristics of the star such as L , \dot{M} and V_∞ agree with the values found by other authors, i.e., HGL06 and Crowther & Smith (1996).

We find that models with very different effective temperature, T_* from 70 000 K to 110 000 K, can reproduce fairly well the stellar continuum and several emission lines. Therefore there is a degeneracy in atmosphere models, than apparently is due to our misunderstanding of the structure of the wind velocity field.

To decide which stellar model produces the correct UV amount of ionizing photons coming from WR 136, we computed a photoionization model for

the associated ring nebula NGC 6888, using the SED produced by the stellar models. This led us to conclude that WR 136 follows better the spectral behaviour of a star with a T_* of 70 kK.

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Andreas Sander: The position of WR 136 in the analyses of Hamann et al. (2006) is already close to the degeneracy region. Of course the hidden inner part of the velocity field is something that is important and might cause additional degeneracy between atmosphere models, but it seems that already a large fraction of the spectrum is formed in the wind of WR 136. Therefore I would not trust the particular value of T_* so much.

Franciso (Paco) Najarro: Are your assumed oxygen and silicon abundances (both well above 10^{-3} by mass) a bit too high for that spectral type?

Jonnathan Reyes-Pérez: I think it is not the case. The oxygen and silicon are similar to those published by van der Hucht et al. (1986) for WN stars, and recently Skinner et al. (2010) have constrained the silicon abundance using X-ray observation performed for WR 136.