A complete spectral model of a ring nebula and its associated central star

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INTRODUCTION

When we make a single study of these systems it is difficult to assign a value to the physical parameters only based on generical data, that is why we make a semiempirical methodology based in the selfconsistent modelisation of the star and the optical nebula associated. This methodology gives us the advantage to obtain coherent and more constrained physical values between all the components of the entire system than those resulting from a single study of each component. It is logic to proceed in this way because the nebula associated to the star is naturally an additional restriction to the stellar atmosphere model, as it offers information about the amount of ionizing photons. In this work we focus on the ring nebula NGC 6888. NGC 6888 is an emission nebula associated to the Wolf-Rayet star WR 136 (spectral type WN 6) and is a typical exemple of the ring nebula objects resulting from the continuous interaction between the strong stellar wind and the interstellar medium. Projected on the sky, this nebula is seen to have an almost elliptical shape with an optical axis-size of 12' x 18'. The combination of its clumpy morphology and its nitrogen enhanced abundance suggest that the gaseous ejections coming from the WR star have contributed in an important way to the formation of this ring nebula.

Figure 1. The ring nebula NGC 6888. Black lines represent the slit positions where the observations were performed. Image from Daniel López IAC taken with the Isaac Newton Telescope.

HOW TO DO A SELF-CONSISTENT MODEL FOR A NEBULA ASSOCIATED TO ONE STAR?

From spectroscopical observations first we model the stellar atmosphere using the CMFGEN code (Hillier & Miller 1998). In this case for WR 136, we have analyzed a spectrum between 900 Å and 1200 Å taken from the FUSE satellite observational program C097. To extend the wavelenght range to 1800 Å the FUSE's spectrum was combined with the individual high dispersion IUE spectra. In addition to the UV spectra, WR 136 was observed with the echelle spectrograph at the 2.1 m telescope at the National Astronomical Observatory (NAO) in San Pedro Mártir, Mexico. The so obtained spectrum ranges from 3000 Å to 7000 Å.

Once the stellar model is done, this one is used as the ionization source input for the photionization model calculated with the pyCloudy 3D formalism (Morisset 2011). The main analysis of the physical conditions of the gas in NGC 6888 was based on the echelle optical observations carried out with the 2.1 m telescope at the NAO for three different slit positions, each one with a total exposure time of two hours. After the standar reduction with the astronomical software MIDAS resulted three high resolution spectra from 3700 Å to 7300 Å. Additionally was used echelle spectroscopy performed with the Subaru Telescope (Mesa-Delgado in progress.) (Figure 1.)

Finally, if it is not possible to reproduce the ionization degree given by the lines present in the nebular spectra, the stellar model is recalculated in the way to obtain, for exemple, a hotter or colder effective temperature according with the exigence of the nebula. In this way an interational process is performed.

RESULTS

The stellar model

The input values we constrained were the mass-loss rate *Mdot*, the terminal wind velocity *Vinf*, the stellar luminosity *L*, the radius of the star R^* and the chemical composition. In the stellar winds it is expected that the recombination line luminosity is proportional to the mass-loss rate, therefore recombination lines as Hα were used to find a good value of *Mdot*. The value of the terminal velocity was constrained by fitting the blue edge of the satured C IV λ1550 Å P-Cygni profile, the obtained value fits well other P-Cygni profiles as P V λ and S IV λin the far UV spectrum of the star. When we consider a stellar atmosphere with spherical simmetry it does not make sense to assign a surface temperature to the star, therefore the temperature cannot be a global input value in the model, but it is possible to define a temperature value where τ = 2/3 and it is set in the model through the luminosity and the stellar radius at this optical depth. In this way, the *L* and R^* values were changed to fit the line profiles corresponding to consecutive ionization degrees of the same element, as the He I λ and He II λ lines. Our best model values are shown in the Table 1 and in Figure 2 is shown the model in red over the observations.

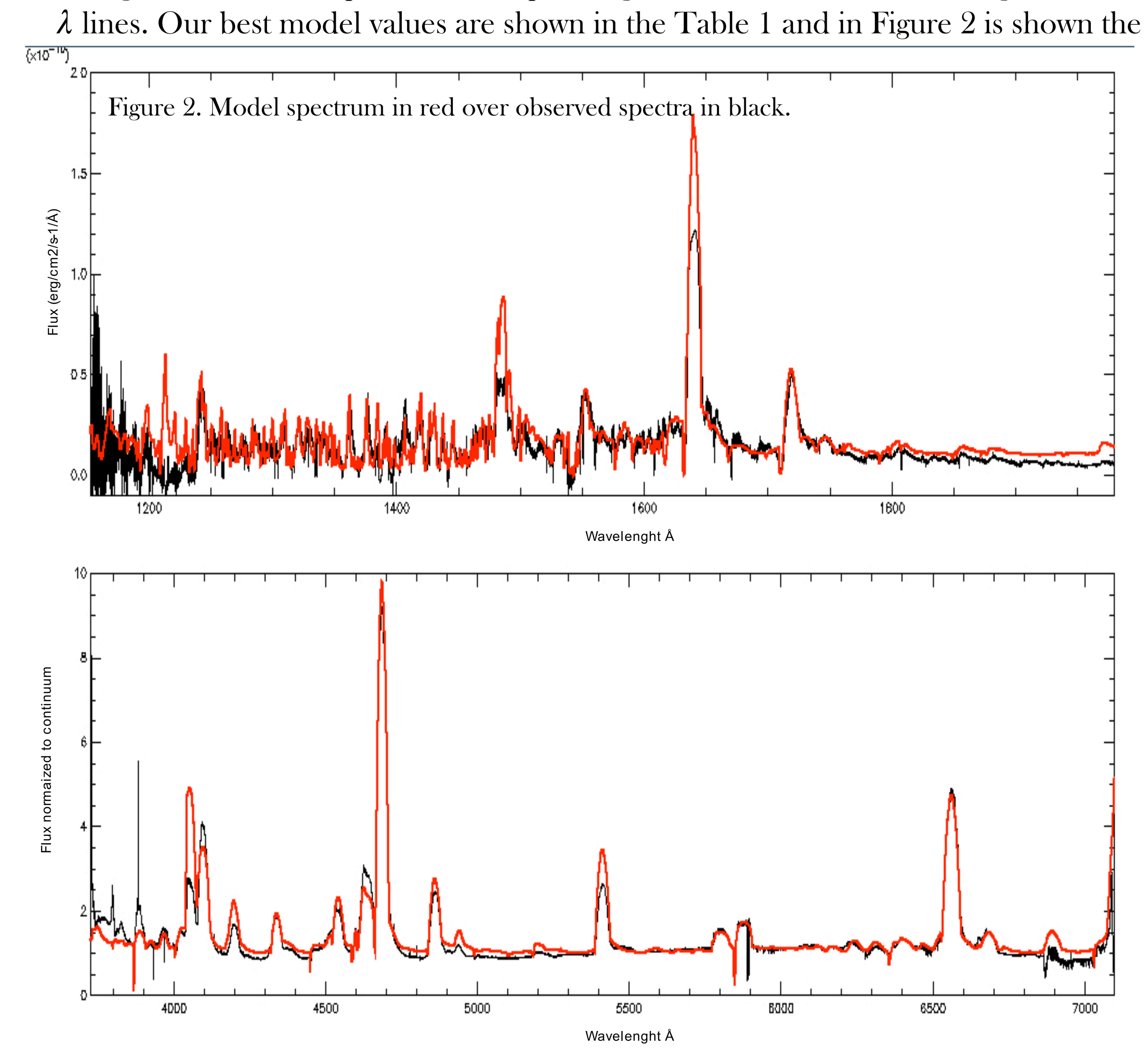

Figure 2. Model spectrum in red over observed spectra in black.

Table 1.

Stellar CMFGEN model of WR 136	
Mdot(Msun/yr)	1.18e-5
L(Lsun)	2.86e+5
Vinf (km/s)	1550
Teff[τ=2/3](K)	50150
Abundances Z/Zsun	
He	3.42
C	2.40
N	1.91
O	0.12
Si	2.08
Fe	1.26
S	1.07
P	1.28

The nebular model

To reproduce the optical spectral signatures of NGC 6888 was built a photoionization model using the pyCloudy 3D formalism, this method enable us to create a pseudo 3D model of a symmetric photoionized region through the interpolation between individual Cloudy models, this has the advantage to compare directly the observed line intensities under almost the same observational conditions, i.e. it is possible to obtain the resulting total line emissivities by integrating the contribution of each individual Cloudy model over a region constrained by a mask that represents the slit position on the nebula where the observations were performed (Fig. 3). In this photoionization model was used, as ionization source, a stellar atmosphere model of the star WR 136 calculated with the CMFGEN code described above.

We assume that NGC 6888 has an ellipsoidal shape and is made mainly of two gaseous components, one denser (450 cm-3) than the other one (1 cm-3), both with a constant density profile where the free parameters are the inner distance from the star following the respective ellipticity values and a filling factor. The required He, C, N ,O abundances to reproduce the line intensities are shown in Table 2. Additionally, taking in mind the very clumped structure of NGC 6888, was added to the model a weight value for the line emissivities, this value indicates from which component comes the major contribution to the total emission in the line of sight, once the abundances were fixed only this weight value was changed to fit the observed fluxes.

Table 2.

Line	Iobs	Imod	Q*
H1_4861A	100 ± 1.0	100	0.00
H1_4340A	50.13 ± 2.5	47.62	-1.07
H1_6563A	285.00 ± 6.0	290.86	0.93
He1_5016A	4.41 ± 0.15	4.09	-2.23
He1_5876A	25.99 ± 2.60	23.72	-0.95
C2_4267A	0.69:	0.69	0.00
O2_3726A	21.94 ± 2.10	29.96	3.37
O2_3729A	24.02 ±2.30	30.74	2.67
O3_5007A	274.34 ± 5.0	281.32	0.51
N2_6583A	130.09 ±3.0	133.47	1.18
S2_6716A	3.99 ± 0.41	5.29	2.91
S2_6731A	3.79 ± 0.35	5.48	4.19
Ar3_7136A	19.84 ± 0.60	24.87	7.40
Plasma diagnostics			
Te[O III] K	9550 ± 810	10263	
ne[O II] /cm-3	310 ± 180	316.81	
Abundances from the model 12 + log (X/H)			
He		11.20	
C		8.67	
N		7.90	
O		7.90	

*Q is a quality factor and it means how good is the fit. In general, a good line intensity fit gives a Q value between -2.0 and 2.0.

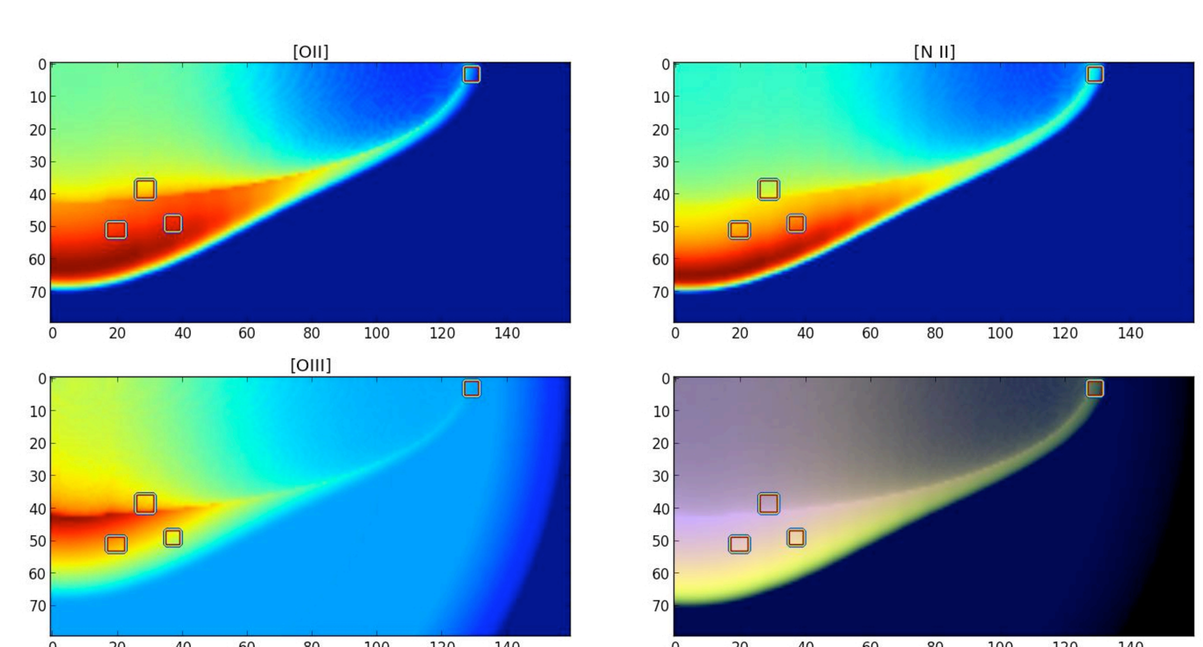

Figure 3. Intensity maps of [O II], [O III], [N II] ions RGB image plotted with pyCloudy 3D. Squares represents the corresponding slits positions where the spectroscopical observations were performed.

DISCUSION AND CONCLUSIONS

The derived values as *L*, *Mdot* and *Vinf* from the stellar model of the star WR 136 agree with the values found by other authors, i.e. Hamman et al. (1994) and Crowther & Smith (1996), but the effective temperature is lower than the precedent values and we believe this is a more realistic value; this is because a star with a *Teff* higher than 50000 K produces a higher ionized nebula than it is observed, in particular, the emission of [O III] lines obtained by the pyCloudy models are overestimated leading to decrease even more the oxygen abundance to perform a good fit. In other hand, the combination of the temperature and mass-loss effects in the wind gas considered for this model can reproduce the line profiles coming from recombination process, therefore if we really are near a good value of *Teff* so it is the same for the mass-loss rate value. It is important because this value can add a good constraition for the hydrodynamical simulations. For exemple, recently Zhekov & Park (2010) conclude that it is necessary a value 10 times lower than expected in order to reproduce the X-ray flux of the emitting hot bubble, therefore once the *Mdot* can be well constrained, we can better understand about the heating and cooling processes inside the hot bubble.

About the nebula NGC 6888, optical observations have been shown that a thin skin of gas, mainly emitting on [O III], is covering the Hα and the [N II] emission (Moore et al. 2000). Contrary to the presence of shocks as the only mechanism leading to such ionization structure, for this model we alternatively propose the presence of a gaseous component with very low density. In this way we are capable to reproduce the observed ionization structure when it is considered two gaseous components in order to obtain a higher ionization parameter beyond the Hα and [N II] emitting region of NGC 6888. We cannot immediatly rule out the importance of shock effects but given we can reproduce several emission features of the nebula only with photoionization assumptions in addition with some plasma diagnostics it leads us to suggest that maybe the photoionization heating is more important than the presence of shocks (Reyes-Pérez et al. in progress). This last idea was already established by Esteban & Vílchez (1992) combining the diagnostic diagrams of Sabbadin et al. (1977) with their observations on a zone near the one studied in the present work. The abundances derived from this model correspond with similar values in other works preceding this one (i.e Esteban & Vílchez 1992). It is remarked that in both the stellar atmosphere of WR 136 and the nebular gas there is an enhancement of nitrogen an carbon and a depletion of the oxygen content. This contibutes to the idea that the observed gas is enriched by the central star through the mass-lost driven by the stellar wind (a large discusion in Mesa-Delgado et al. in preparation).

Finally, in this work we show the advantages when modelling simultaneously the stellar and nebular spectra of a Wolf-Rayet nebula system. In this way we shown a coherent stellar and nebular model that reproduces observations of the ring nebula NGC 6888. We tested whether a stellar atmosphere model of the WR 136 star provides an optimal description of the stellar observations and is able to satisfactory reproduce the nebular observations as the ionization degree. This allowed us to determine all the physical parameters of both the star and the nebula, including the chemical abundances.

References

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