Wolf-Rayet Phenomena in Massive Stars and Starburst Galaxies
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Photo-ionization models with Wolf-Rayet central stars

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Abstract. We summarize the goals of photo-ionization modelling of nebulae ionized by Wolf-Rayet stars and discuss the methodology. We present some examples in different astrophysical contexts: ring nebulae around massive WR stars, planetary nebulae with [WR]-type central stars, and giant H II regions with WR stars. We discuss in more detail a work in progress (Stasińska & Schaerer 1999) on the galaxy I Zw 18.

1. Introduction

Wolf-Rayet stars affect their environment in two ways. They shape it through the dynamical effect of their strong stellar winds and they heat and ionize it with their emergent far UV photons. Attempts for a unified modelling taking into account both aspects have so far been scarce in the context of WR stars (see however Arthur *et al.* 1996) but similar approaches have been developed for planetary nebulae (Mellema & Frank 1995 and references therein).

In a first approximation, one can consider the two problems separately. Photo-ionization models describe the interaction of the ionizing photons with the nebula, assuming a *given density distribution.* Since the main physical processes in photo-ionized nebulae are relatively well understood (Osterbrock 1989; Ferland *et al.* 1998 and references therein) and since photo-ionization codes are fast compared to codes treating the full radiation gasdynamics in a consistent way, photo-ionization modelling is an extremely useful tool to explore the physics of nebulae surrounding WR stars.

In this contribution, we discuss photo-ionization models related to WR stars in different astrophysical contexts.

2. What can be expected from photo-ionization models

2.1. A help for deriving the chemical composition of the nebulae

If the electronic temperature can be measured directly from temperature-sensitive line-ratios, the ionic abundances derived by classical empirical methods are generally of sufficient accuracy for practical purposes (there is however the 'temperature fluctuations'-problem as reviewed by Peimbert 1996 and Stasińska 1998). Elemental abundances obtained using simple formulae to correct for unseen ions (*e.g.*, Kingsburgh & Barlow 1994) are generally reasonably good as far as O, N, Ne and C are concerned. One might expect to improve the determinations of He, C, Ne, S and Ar abundances with tailored photo-ionization models of the objects under study. One must keep in mind, however, the uncertainties in the atomic data.

Photo-ionization models predict not only the ionization structure, but also the distribution of the electron temperature inside the nebulae. Since a direct measurement of the electron temperature is generally available only in the O^{++} zone, photo-ionization models allow to estimate the temperature in the low ionization zones, improving our knowledge of the abundances of the low-ionization species.

2.2. A tool to infer the properties of the ionizing stars

Most of the energy of hot stars is emitted through photons above 13.6 eV and is not directly accessible to observations. The surrounding nebulae convert those into line emission radiation. Provided that the nebulae are dust-free and ionization bounded, the luminosities in the hydrogen recombination lines give the total number of ionizing photons. The energy distribution of stellar photons in the Lyman continuum affects both the ionization structure and the energy budget of the surrounding nebulae (see *e.g.*, Stasińska 1996). Therefore, photo-ionization models are potential tools to infer the stellar properties in the far UV.

In the case of WR stars, in particular, for which the stellar type can be easily determined from prominent photospheric lines, photo-ionization models allow to probe the far UV energy distribution predicted by model atmospheres that reproduce the stellar lines.

However, one cannot disregard the fact that the density distribution of the nebular gas strongly affects the nebular spectrum.

3. Methodology of photo-ionization modelling

Grids of photo-ionization models are useful to pinpoint the main parameters affecting the nebular line intensities and to provide first order diagnostics (*e.g.*, Mc Call *et al.* 1985; Dopita & Evans 1986; García-Vargas *et al.* 1995; Stasińska & Leitherer 1996; Bresolin *et al.* 1999). But there is no guarantee that such models represent real nebulae correctly.

Tailored photo-ionization modelling of individual objects is necessary for a more reliable diagnostic. The first step, in such an approach, is to carefully select the crucial line ratios that will measure the quality of a model. Not only the strongest lines are to be reproduced by the model.

For example, one of the major tasks of a photo-ionization model is to reproduce the observed [OIII]4363/5007 line ratio. A failure to achieve this implies that the main heating and cooling processes are not properly taken into account. This may be an indication that the assumed ionizing radiation field is not correct. In this sense, [OIII]4363/5007 probes the ionizing radiation field. There is, however, the possibility that additional heating or cooling processes may be at work (*e.g.*, mechanical heating or conductive heating).

Another important line, in the context of WR stars, is the nebular He II 4686 line, which measures the number of stellar photons above 54.4 eV.

A photo-ionization model is constrained not only by line ratios but also by other observables like: the magnitudes of the exciting stars, the angular diameters and integrated fluxes of the nebulae, their apparent morphology and clumpiness. A model that reproduces perfectly the crucial line ratios but violates one of the above constraints is not a good model.

For each observed parameter, one must define a tolerance which takes into account not only the observational uncertainties (due to signal-to-noise, reddening or aperture effects) but also the fact that the model geometry (usually a sphere) deviates from the true geometry of the nebula. All this makes photo-ionization modelling a complex procedure, despite the fact that the basics of nebular physics are well understood.

4. Examples of photo-ionization models with Wolf-Rayet central stars

4.1. Galactic ring nebulae around massive Wolf-Rayet stars

Esteban *et al.* (1993) modeled eight Galactic ring nebulae at known distances ionized by massive WR stars of known spectral types. The spectral energy distribution of the ionizing radiation field was taken from a grid of non-LTE helium model atmospheres computed by Schmutz, with the luminosity adjusted so as to reproduce the observed visual magnitude. The nebulae were modelled as hollow spherical shells of constant density, with dimensions equal to the observed ones. For the early WR stars, good agreement was found between the stellar temperatures needed to reproduce the nebular observations and those derived from stellar line analysis. For the late WR stars, however, the flux distributions corresponding to the observed stellar features produced too much nebular ionization. The authors attributed this discrepancy to the lack of line-blanketing in the stellar atmospheres (see also Pasquali *et al.*, these Proceedings).

4.2. Planetary nebulae with [WR] central stars

Although not the subject of this meeting, planetary nebulae with WR central stars bear much resemblance with ring nebulae around massive WR stars (*cf.* Chu 1993). From a dynamical point of view, these two classes of objects are very similar, despite their different sizes and astrophysical origins. The classification of Pop. I and Pop. II WR stars follows the same schemes, the modelling of their atmospheres uses the same techniques, and the modelling of the surrounding nebulae is done with the same codes.

Peña *et al.* (1998) have analyzed a sample of five planetary nebulae with [WC2–3] type central stars. Compared to the objects studied by Esteban *et al.* (1993), the stars are much hotter. The nebular He II 4686 line is observed (and strong) in all the objects, and four nebulae have [NeV] observed as well, providing additional constraints. On the other hand, the distance to the planetary nebulae is badly known, but this is not a major problem (except that the stellar luminosity cannot be derived with such methods). For each object, models were built using as an input the stellar energy distribution from the expanding, non-LTE model atmospheres of Koesterke & Hamann (1997) that fit the observed features of the central star. In general, these atmospheres led to models that satisfactorily reproduce the observational constraints on the nebulae. It must be noted that it was necessary to relax the assumption of constant density (even with a filling factor), and adopt a composite model (which, apart from being a necessary condition to reproduce the important line ratios, was also better in describing the morphological aspect of the nebulae). However, in two objects (PB 6 and NGC 6905), the nebular modelling led to the puzzling result that the model atmospheres seem to be *lacking* ionizing photons with respect to their emission in the V band.

De Marco & Crowther (1998) modelled planetary nebulae with late [WR] central stars, but found that the particular objects they studied represented poor probes of the stellar Lyman continuum flux distribution.

4.3. Wolf-Rayet galaxies

Some giant H II regions exhibit a He II 4686 line, whose presence was considered enigmatic until it was realized that it was often associated with broad WR features. Until recently, photo-ionization modelling of such objects did not attempt to reproduce this line. With the presently available models of atmospheres of WR stars and their inclusion in spectral synthesis codes for stellar populations (Leitherer & Heckman 1995; Schaerer & Vacca 1998; Leitherer *et al.* 1999), this is now feasible. The studies of García-Vargas *et al.* 1997 on NGC 7714, González-Delgado *et al.* 1997 on NGC 1569, Luridiana *et al.* these Proceedings, on NGC 2363 and Stasińska & Schaerer (1999) on I Zw 18 explicitely consider the presence of WR stars in their photo-ionization modelling. Schaerer (1996) examines the theoretical link between the broad stellar features and the narrow He II 4686 emission line in WR galaxies. In the remaining of this contribution, we discuss the case of I Zw 18, to illustrate the difficulties of photo-ionization modelling as a probe of the far UV stellar radiation field.

5. A case study: I Zw 18

5.1. I Zw 18: a recently recognized Wolf-Rayet galaxy

I Zw 18 is a blue compact galaxy, the most metal deficient galaxy known so far, with an O/H ratio only 2% solar (Searle & Sargent 1972, Izotov & Thuan 1998). The detection of WR stars there (Legrand *et al.* 1997; Izotov *et al.* 1997), through the broad emission features at 4650Å and 5808Å, was a surprise, since stellar evolution theory predicts that very few WR stars should form in such a low-metallicity environment (*e.g.*, Meynet 1995). However, I Zw 18 had already been known as a He II galaxy (with a narrow He II 4686 emission) for some time (Garnett *et al.* 1991), indicating the contribution of something other than OB stars to its ionization.

The direct observation of WR stellar features in I Zw 18 prompted D. Schaerer to build stellar evolution tracks at the appropriate metallicity and use them in his population synthesis code (Schaerer & Vacca 1998; de Mello *et al.* 1998) with appropriate IMF parameters. He found that, for an instantaneous starburst with a Salpeter IMF and an upper mass limit of 120–150 $M_{\odot}$, such single-star evolution models could reproduce reasonably well the observed equivalent widths of the WR and nebular He II4684 features.

5.2. Why is I Zw 18 attractive for photo-ionization modelling?

Modelling is easier when the number of determining parameters is small so that one does not have to explore a huge parameter space. Under such conditions, the inferences based on modelling are more likely to be meaningful. I Zw 18 is an excellent object from this point of view, because of its low metallicity. Firstly, gas cooling is dominated by H Ly α collisional losses, and one does not have to play with parameters not constrained by the observations (such as the abundances of refractory elements), or for which the observational data is less accurate (such as the carbon abundance). Secondly, dust, if present at all inside the ionized region, is expected to have a very low abundance and should not compete with the gas in the absorption of Lyman continuum photons. Also, its possible role in the thermal balance (Shields & Kennicutt 1995) can be neglected.

5.3. The failures of previous photo-ionization models of I Zw 18

The only models of I Zw 18 published so far (Dufour *et al.* 1988; Campbell 1990; Stevenson *et al.* 1993) used, as the ionization source, the Kurucz atmospheres for a star of given temperature. As a result, of course, the He II 4686 line was never reproduced.

An interesting point is that the [O III]4363/5007 ratio was not well fitted by the models either, unless a special geometry was assumed. Dufour *et al.* (1988) invoked a composite structure of Strömgren spheres with a range of ionizing star temperatures or ionization parameters. Campbell proposed, instead, a density gradient model with a central density high enough to cause partial collisional deexcitation of [O III]5007. As a consequence, her best fit model had $O/H = 2.09 \times 10^{-5}$, *i.e.*, 70% higher than the value inferred from empirical methods.

The density distribution proposed by Campbell can actually be checked with the intensity ratio [Ar IV]4711/4740. This is difficult, because these lines are weak and [Ar IV]4711 is blended with a helium line at 4713. But with adequate equipment, such a test should be feasible. A strong argument against Campbell's model comes from the *HST* images (de Mello *et al.* 1998) which clearly indicate a depression in the Hα image in the central zone of the north-west component, where the blue stars are seen.

5.4. A new model for I Zw 18

The *HST* images of I Zw 18 together with new, high quality spectroscopic data both for the optical and the UV and the existence of appropriate stellar synthesis models, including state-of-the-art-evolutionary tracks and non-LTE expanded model atmospheres, warrant another try to model this object.

The observational constraints are provided by the spectroscopic data from Izotov & Thuan (1998) and Garnett *et al.* (1997), by the *HST* images reported by de Mello *et al.* (1998) for the size of the nebula and its total Hα emission and by the stellar fluxes in the U band reported in that paper.

The input model abundances are those derived empirically, using the same atomic data as in the photo-ionization modelling (done with the code PHOTO, in its version described by Stasińska & Leitherer 1996). While deriving the ionic abundances, the electron temperature in the O^+, N^+ zone was taken equal to 15 000 K, which is roughly what photo-ionization models give for this object. The abundances derived in such a way are: $He/H = 0.076$, $C/H = 3.03\,10^{-6}$, $N/H = 3.89\,10^{-7}$, $O/H = 1.32\,10^{-5}$, $Ne = 2.28\,10^{-6}$, $S = 3.72\,10^{-7}$, and $Ar/H = 9.18\,10^{-8}$. For Mg and Si we arbitrarily took 10^{-7}, and for Cl and Fe 10^{-8}.

The line ratios constraining the models were the following: He I 4686/Hβ, [OI]6300/Hβ, [OIII]4363/5007, [OIII]5007/[OII]3727, [SIII]6312/[SII]6716, and [SII]6716/6730. When those are fitted, with the set of adopted abundances, ratios like He I 5876/Hβ, [NII]6584/Hβ or [NeIII] 3867 are automatically close to the observed ones. Further requirements for the models were that they should be compatible with the observed nebular size, morphology, and Hα flux, and with the observed stellar continuum. For all these constraints, we defined a tolerance, as explained in Section 3. The adopted distance to the object was 10 Mpc.

The free parameters are the characteristics of the ionizing cluster (IMF, star birth history, age) and the distribution of the nebular gas. We chose the instantaneous burst model which maximizes the proportion of WR stars. The first models were run with a sequence in ages, and it was readily seen that only between 3 and 3.2 Myr is the stellar flux shortward of 54.4 eV sufficiently strong to provide significant He II 4686 emission.

Contrary to previous models, the total number of ionizing photons was determined not from the observed flux in Hβ, but from the observed flux in the *U* band, attributed to stars only. This observational constraint is extremely useful, since it concerns the stars directly. It indicates a total mass of the stars of $7\,10^4$ $M_\odot$, if one adopts the instantaneous starburst model mentioned above.

Deriving the total ionizing photon flux from Hβ, as is done when no other information is available, assumes that all the ionizing photons have been absorbed by the gas within the zone covered by the observation. This is not necessarily true, and is certainly not true for I Zw 18, since extended diffuse emission has been reported for this object (Martin 1996). The observed Hβ flux is used as a constraint to the photo-ionization model, but with a tolerance accounting for the fact that the covering factor is probably smaller than one.

Compared to previous modelling, we relaxed the assumption that the nebula must be optically thick. As in the past, we considered spherically symmetric models, but selected for further consideration only the models that reproduce the observed [OIII]/[OII] ratio (taking into account the adopted tolerance).

We started with the simplest geometry (similar to the one used in previous studies of I Zw 18): a sphere of uniform density n and filling factor ϵ. With such a geometry, and with all the constraints mentioned above, the only free parameters are n and ϵ. Exploring the available parameter space, we found that [OIII]4363/5007 is always at least one σ below the observed value. The best model gives too large a Hβ flux by a factor 3 (acceptable if the covering factor is about one third), too small [OI]/Hβ by 1–2 σ and the correct total flux in He II 4686. It also gives slightly too small an electron temperature (by one σ). On the whole, this model would be rather satisfactory, if it were not that its morphology is not compatible with the *HST* images.

The *HST* images suggest a shell geometry. We then considered a hollow sphere, like Esteban *et al.* (1993) or García-Vargas *et al.* (1997) in other contexts. For such a geometry, the [OIII]4363/5007 became much smaller (all the emission comes from zones that are distant from the star, where Ly α cooling is very efficient).

We were thus led to consider a composite model: a constant density shell filled with diffuse gas, where [OIII] would be partly emitted. Such a model gave acceptable [OIII]4363/5007. On the other hand, [OI]/Hβ was much too small and the Hβ flux still too large by a factor 3.

When looking carefully at the observed Hα spatial profile, we found however that it was not compatible with a sphere, but indicated that the ionized matter was rather distributed in a ring seen face on, with some diffuse gas in the centre. This is in line with the evidence of a covering factor smaller than one.

With such a geometry, one expects the [OIII]4363/5007 ratio to be higher because the diffuse ionizing radiation field is weaker.

The only way to explain the observed [OI]/Hβ ratio in such a context is to postulate some foreground filaments at a large distance from the ionizing star cluster.

6. Conclusions

Photo-ionization models can be used as probes of the ionizing radiation field. However, erroneous conclusions can be drawn if one does not use enough observational constraints. We have shown on the example of a work in progress on I Zw 18, that a model should aim at reproducing not only the ratios of strong lines, but also some crucial weak lines, and should be compatible with other observational data such as the stellar magnitudes and the nebular fluxes and dimensions.

In particular, the effect of nebular geometry is often insufficiently explored. The example of I Zw 18 shows that many features attributed usually to shocks (large [OI]/Hβ, large [OIII]4363/5007) are in fact naturally explained by photo-ionization if one takes into account the geometry.

In real nebulae, especially in the case of objects ionized by stars with strong stellar winds or by clusters including recent supernovae, one might expect additional heating mechanisms to be at work. The total amount of mechanical energy can be estimated from dynamical models in the case of single-star nebulae, and from adequate stellar population synthesis models (Leitherer & Heckman 1995; Leitherer *et al.* 1999) in the case of giant H II regions. The effect of this mechanical energy on the line ratios can then be studied using appropriate shock codes.

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Discussion

Lehnert: Couldn't just including shock ionization help to solve some of the problems concerning the line ratios and electron temperature?

Stasińska: My point was essentially to show that, by taking into account the geometry, photo-ionization models are actually able to do a lot more for you than you might think. Of course, the effects of shocks, in the case of I Zw 18 still need to be evaluated, but this has to be done taking into account the strong flux of stellar ionizing photons.

Dopita: In support of your viewpoint, I would like to say that shocks will not help solve the temperature problem. The shocks in photo-ionized plasmas serve only to compress the gas when the ratio of mechanical energy flux to photon energy flux is less than unity. As a consequence, shocks simply lower the ionization parameter locally, and so increase the flux in low ionization specties. The [O III] lines are largely quenched.

Schmutz: If Ly-α becomes the cooling line, then I would expect that you need to treat the radiation transport of this line. How do you solve this problem?

Stasińska: The transport of this line is treaded in an approximate manner, but this does not affect the cooling function of the electron gas.

Leitherer: Is the bubble observed in I Zw 18 related to the present starburst, and if so, can the size be used for an independent age estimate of the ionizing cluster?

Stasińska: I have not looked into that yet, but I don't think that a simple estimation of the age will be accurate anyway: I Zw 18 is not a simple Weaver-*et al.* -bubble.

Crowther: We should be very careful when using existing models for WR stars in very low-metallicity environments, because their ionizing properties are likely to be quite unlike typical examples in the local universe (since it is likely that their mass-loss properties will be much weaker).

Stasińska: Actually, what I was trying to show is that it is not so easy to probe the ionizing radiation field with the surrounding nebula, because the geometrical effects are very important.

Schmutz: Paul, don't you think that I Zw 18 is the ideal case to use the old He-only WR atmospheres?