A Massive Star Odyssey, from Main Sequence to Supernova
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New line-blanketed model atmospheres and their impact on synthesis models

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Abstract. A new grid of ionizing fluxes for O-type and Wolf-Rayet stars is presented for use with evolutionary synthesis codes and analyses of single star H II regions. A total of 230 expanding, non-LTE, line-blanketed model atmospheres have been calculated for five metallicities (0.05, 0.2, 0.4, 1 and 2 $Z_\odot$). We have used the WM-basic code of Pauldrach *et al.* (2001) for O-type stars and the CMFGEN code of Hillier & Miller (1998) for WR stars. The stellar wind parameters are scaled with metallicity for both O-type and WR stars. The ionizing fluxes of the new models, incorporated into the evolutionary synthesis code STARBURST99 (Leitherer *et al.* 1999), are compared with the predictions of the original STARBURST99 and Schaerer & Vacca (1998) for an instantaneous burst. We find large changes in the output ionizing fluxes as a function of age, especially below the He^+ edge. In contrast to previous studies, nebular He II λ4686 will be at, or just below, the detection limit in low metallicity starbursts during the WR phase. The new models have lower fluxes in the He I continuum for $Z \geq 0.4\,Z_\odot$ and ages ≤ 7 Myr because of the increased line-blanketing. The accuracy of the new model atmosphere grid is tested by constructing photo-ionization models for an H II region where the ionizing flux is provided by an instantaneous burst. The new models occupy the same region in nebular diagnostic diagrams as the observational data of Bresolin *et al.* (1999), particularly during the WR phase. The new model grid and updated STARBURST99 code can be downloaded from `http://www.star.ucl.ac.uk/starburst`.

1. Introduction

The properties of young, unresolved stellar populations are often derived from optical nebular emission line observations by using the theoretical ionizing fluxes predicted by an evolutionary synthesis code as input into a photo-ionization code (*e.g.*, Stasińska, Schaerer, & Leitherer 2001). The reliability of this technique largely depends on the accuracy of the model atmospheres and evolutionary tracks employed in the evolutionary synthesis code. Over the years, evolutionary synthesis codes have developed from using simple, plane-parallel, LTE model atmospheres to represent massive stars to expanding, non-LTE O-type and Wolf-Rayet (WR) models. For example, Leitherer *et al.* (1999) use the non-LTE, expanding, pure helium models of Schmutz, Leitherer, & Gruenwald (1992; SLG92) to represent stars with strong mass loss, and LTE blanketed models from the library of Lejeune, Cuisinier, & Buser (1997) for all other stars in their synthesis code STARBURST99. Schaerer & Vacca (1998; SV98) employ the

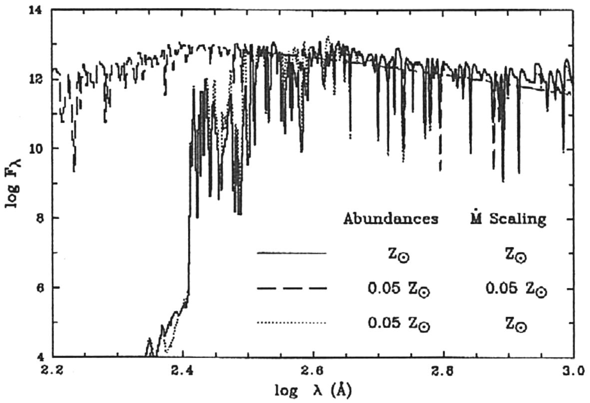

Figure 1. The flux distribution of a $T_* = 100\,000$ K WC model for three different assumptions about the abundances and mass loss scaling: (*a*) abundances and mass loss rate scaled to solar (solid); (*b*) abundances and mass loss rate scaled to 0.05 $Z_\odot$ (dashed); and (*c*) 0.05 $Z_\odot$ abundances but mass loss rate scaled to solar (dotted). Only model (*b*) with wind parameters scaled to 0.05 $Z_\odot$ has a significant flux below the He^+ edge at 228 Å because of the reduced wind density.

same WR atmospheres but use the COSTAR non-LTE, expanding, line-blanketed model atmospheres of Schaerer & de Koter (1997) to represent O-type stars on and near the main sequence.

Numerous studies have empirically tested the accuracy of O-type and WR model atmospheres by analysing H II regions ionized by single massive stars (*e.g.*, Esteban *et al.* 1993; Crowther *et al.* 1999; Kennicutt *et al.* 2000; Oey *et al.* 2000). Overall, they conclude that the ionizing fluxes are generally too hard, particularly the pure helium WR atmospheres of SLG92, because of the lack of line blanketing. With recent advances in computing and the development of large codes to calculate non-LTE, line-blanketed, expanding model atmospheres, it is now possible to compute a grid of realistic ionizing fluxes for O-type and WR stars. We have done this by using the WM-basic code of Pauldrach *et al.* (2001) for O-type stars and the CMFGEN code of Hillier & Miller (1998) for WR stars. We have calculated 46 models for each of five metallicities (0.05, 0.2, 0.4, 1 and 2 $Z_\odot$) for use with the STARBURST99 evolutionary synthesis code and analyses of single star H II regions.

2. The model atmosphere grid

For the O-type star grid, we calculated supergiant and dwarf models for eleven effective temperatures from 25 000 - 50 000 K, covering O3 to B1.5 spectral types. We used gravities and radii from Vacca, Garmany & Shull (1996) and our own revised M_V - spectral type calibration. Wind parameters at $Z_\odot$ were determined using the terminal velocity v_∞ *vs.* spectral type calibrations of Prinja, Barlow & Howarth (1990) and Lamers, Snow & Lindholm (1995), and the wind momentum-luminosity relationship of Kudritzki & Puls (2000) for the mass loss

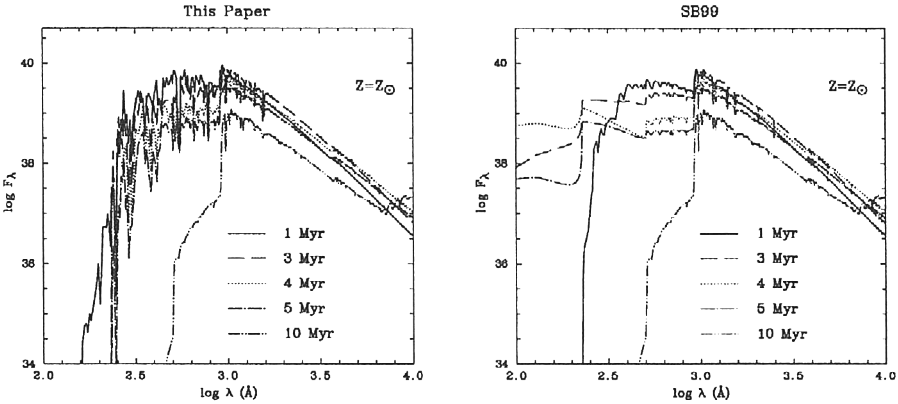

Figure 2. Spectral energy distributions of the new models (*left*) compared with STARBURST99 (*right*) at time intervals of 1, 3, 4, 5 and 10 Myr for an instantaneous burst at Z$_\odot$.

rate $\dot{M}$. We followed Leitherer, Robert & Drissen (1992) in scaling both $\dot{M}$ and v_∞ with metallicity by using power law exponents of 0.8 and 0.13 respectively.

The WR grid is based on what we consider to be the most realistic parameters derived for these stars from recent analyses. In total, we have calculated twelve models at each metallicity for both WN (30 000 - 120 000 K) and WC (40 000 - 140 000 K) stars. We adopted representative luminosities of 3×10^5 L$_\odot$ (WN) and 2×10^5 L$_\odot$ (WC). We fixed the chemical composition at C/He = 0.2 and C/O = 4, by number for the WC grid and varied the He mass fraction Y from 0.76 (WNL) to 0.98 (WNE). For mass loss rates at Z$_\odot$, we used the mass loss-luminosity-chemical composition relationships of Nugis & Lamers (2000) which are corrected for inhomogeneities in the WR winds. For the terminal velocities, we used the data given by Prinja *et al.* (1990).

We have chosen to scale the wind parameters with metallicity using the same scaling laws we adopted for the O-type star grid. Recent work suggests that the strengths of WR winds depend on metallicity (see Crowther, these Proceedings). We find that the wind density controls the transparency of the wind below the He$^+$ edge, as can be seen from Figure 1. Only the model with wind parameters scaled to 0.05 Z$_\odot$ has a significant flux below 228 Å because of the reduced wind density. The predicted number of He$^+$ ionizing photons is thus very sensitive to the adopted wind density and scaling law.

The Nugis & Lamers (2000) mass-loss-luminosity calibration reproduces the average mass-loss rates for strong-lined Galactic WR stars rather well. The weak-lined WR stars, however, fall up to ~0.5 dex below this calibration. In addition, a few stars exist with even weaker winds (*e.g.*, Sand 4 (WR 102, WO2, Esteban *et al.* 1992), BAT99-2 (WN3b, Garnett & Chu 1994)) which emit strongly below λ228 Å, since nebular He II is observed in their surrounding nebulae. These peculiar stars are not accounted for in our calculations. Fortunately, such WR stars are relatively few in number, so it is probable that neglecting their contribution is acceptable for the large massive star population in a starburst.

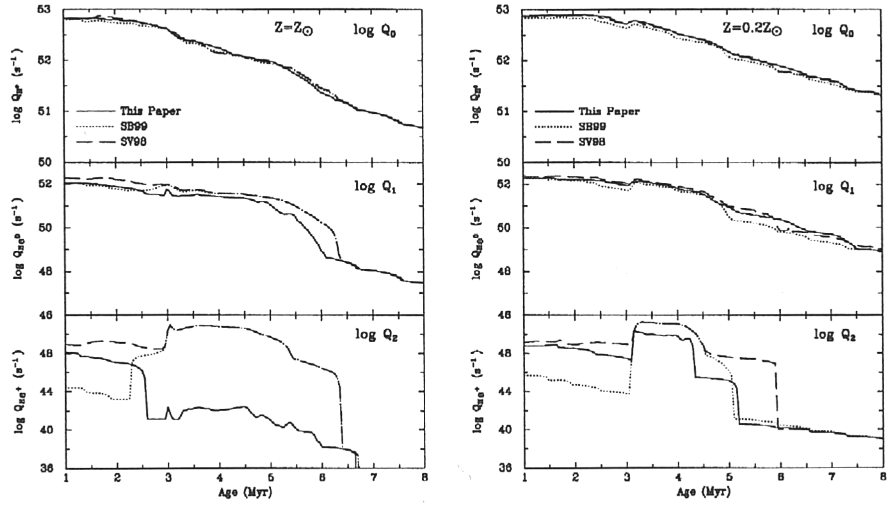

Figure 3. The evolution of the photon luminosity in the ionizing continua of hydrogen ($\log Q_0$), He I ($\log Q_1$) and He II ($\log Q_2$) at 0.2 $Z_\odot$ and $Z_\odot$ for an instantaneous burst.

3. Evolutionary synthesis comparisons

We have integrated the new O-type and WR star grids into the synthesis code STARBURST99 of Leitherer *et al.* (1999) which uses the evolutionary tracks of Meynet *et al.* (1994). The O-type star grid simply replaces the Lejeune *et al.* (1997) library of LTE models for $T_{\rm eff} > 25\,000$ K. Since the WR grid is based on realistic parameters, the WR temperatures T_* are lower than the hydrostatic core temperatures of Meynet *et al.* (1994). The interfacing of WR atmospheres to evolutionary models is problematic because of the optically thick nature of the WR winds. The method we have adopted is based on taking a weighted mean of the uncorrected hydrostatic temperature $T_{\rm hyd}$ and the corrected (by extrapolation) hydrostatic temperature $T_{2/3}$. This method produces temperature distributions for WN and WC stars which span the observed range occupied by Galactic and LMC WR stars. We compare the ionizing flux distributions obtained with the new models integrated in STARBURST99 (SB99) with the standard version of SB99 (Lejeune *et al.* LTE grid and the WR grid of SLG92), and a modified version of SB99 which replaces the O-type star LTE models with the COSTAR models of Schaerer & de Koter (1997). This modified version (denoted by SV98) is representative, but not identical to, the synthesis models of SV98. We consider an instantaneous burst with a total mass of 10^6 $M_\odot$, a single Salpeter power law slope of 2.35 and lower and upper mass cut-offs of 1 and 100 $M_\odot$. The enhanced mass loss tracks of Meynet *et al.* (1994) are used for all the comparisons.

In Figure 2, we show the spectral energy distributions obtained with the new model grids compared with SB99 at time intervals of 1, 3, 4, 5 and 10 Myr for $Z_\odot$. The most dramatic differences are seen below the He^+ edge at 228 Å during the WR phase at 3 - 5 Myr. The new line-blanketed models have negligible flux below 228 Å at $Z_\odot$ in contrast to the very hard ionizing fluxes of

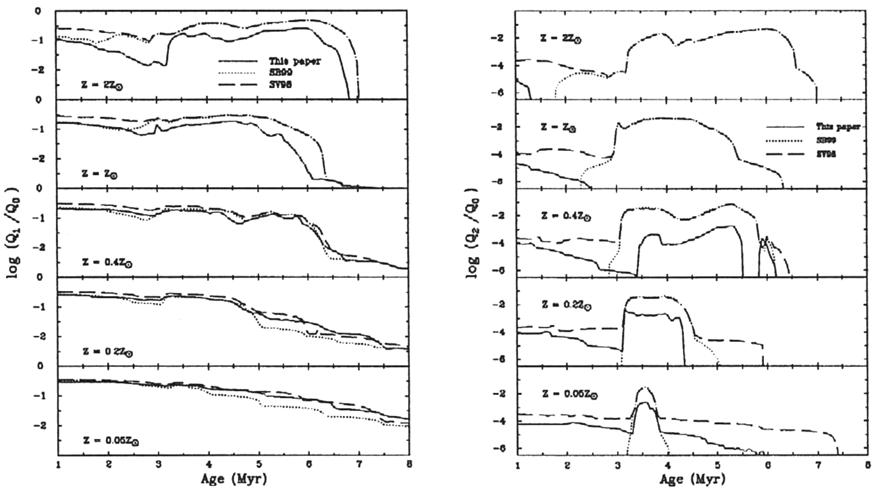

Figure 4. The evolution of the hardness of the ionizing spectra shown by the ratios of $\log(Q_1/Q_0)$ (*left*)) and $\log(Q_2/Q_0)$ (*right*) at all five metallicities for an instantaneous burst.

the SLG92 atmospheres. The detailed differences between the new models and previous work, and their dependence on metallicity, are best seen by examining the ionizing fluxes and their ratios. In Figure 3, we show the evolution of the photon luminosity from 1 - 8 Myr in the ionizing continua of H I ($\log Q_0$), He I ($\log Q_1$) and He II ($\log Q_2$) for 0.2 $Z_\odot$ and $Z_\odot$. The evolution of the hardness of the ionizing spectra $\log(Q_1/Q_0)$ and $\log(Q_2/Q_0)$ for all five metallicities is shown in Figure 4.

The new models have lower ionizing fluxes below 504 Å at ages of less than ~7 Myr for metallicities $\geq 0.4\,Z_\odot$. This is because WR stars contribute an important fraction of the He I ionizing flux and our new WR models are line-blanketed compared to the SLG92 grid. At 5 Myr, the ratio Q_1/Q_0 is softer by a factor of ~2 at 2 $Z_\odot$ compared to SB99 and SV98 because of the effect of the WR line-blanketed atmospheres, whereas at $Z = 0.05\,Z_\odot$, the models agree with SV98 because at this low metallicity, the main contributors to Q_1 are O-type supergiants because of the low WR/O number ratio at this metallicity.

The most pronounced revisions are seen in Q_2 during the WR phase at 3 - 6 Myr in Figure 3 for $Z_\odot$. The number of He II ionizing photons emitted is now negligible compared to SV98 and SB99 because of the WR wind density effect and the conspicuous bump in the SV98 and SB99 models disappears. At metallicities below solar, Q_2/Q_0 (Figure 4) is softer in the WR phase compared to SV98 and SB99 by, for example, a factor of ~25 at 0.4 $Z_\odot$. Assuming case B recombination and an ionization-bounded nebula, $\log Q_2/Q_0 \geq -2.33$ for nebular He II λ4686 to be 1% of the strength of Hβ. From Figure 4, the highest value of $\log Q_2/Q_0 = -2.4$, corresponding to $I(\text{He II}/I(\text{H}\beta) = 0.08$, occurs at the beginning of the WR phase at 0.2 $Z_\odot$. Thus any nebular He II will be marginally observable.

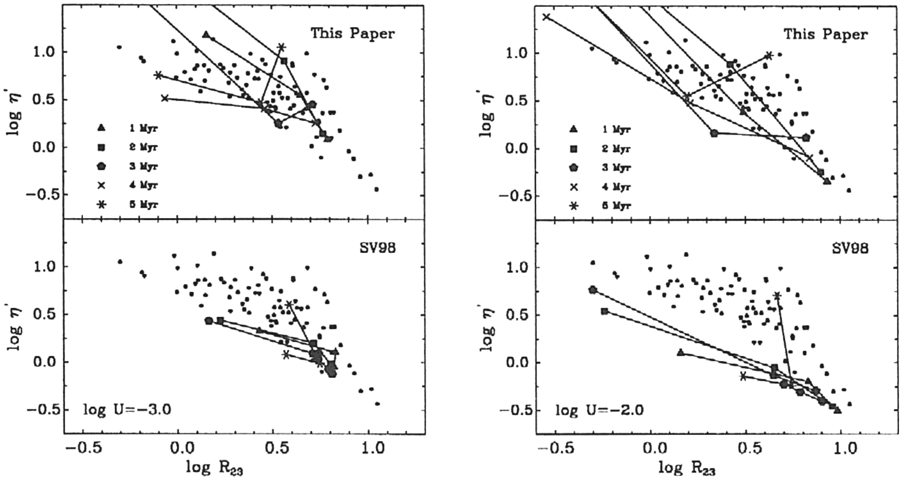

Figure 5. The predicted strength of the softness parameter η' plotted against the abundance indicator R_{23} for 2, 1 and 0.2 $Z_\odot$ for cluster models with $\log U = -3$ and -2 using (a) the new models and (b) the COSTAR and SLG92 models of SV98. The observed data points for the extragalactic H II region sample of Bresolin *et al.* (1999) are shown for comparison.

4. Impact on nebular diagnostics

We now assess the impact of the new line-blanketed O-type and WR star grid on the ionization of H II regions by computing diagnostic line ratios using CLOUDY (Ferland 2002) and the spectral energy distributions from our updated version of STARBURST99 as the ionizing flux input. We have calculated simple dust-free, plane-parallel, ionization-bounded photo-ionization models with a constant gas density $n = 50$ cm^{-3} and a filling factor of unity. In Figure 5, we plot the 'radiation softness' parameter η' defined by Vílchez & Pagel (1988) as

$$\eta' = \frac{[\mathrm{O\,II}]\,\lambda\lambda 3726,3729/[\mathrm{O\,III}]\,\lambda\lambda 4959,5007}{[\mathrm{S\,II}]\,\lambda\lambda 6717,6731/[\mathrm{S\,III}]\,\lambda\lambda 9069,9532}$$

against the abundance parameter $R_{23} = ([\mathrm{O\,II}]\lambda 3727 + [\mathrm{O\,III}]\lambda\lambda 4959{,}5007)/\mathrm{H}\beta$. The η' parameter provides an excellent test of the correctness of our new models since it is a sensitive measure of the softness of the radiation field. We show the predicted values of η' for metallicities of 2, 1 and 0.2 $Z_\odot$ and ages of 1 - 5 Myr for an instantaneous burst model of mass 10^6 $M_\odot$. Since η' is sensitive to the ionization parameter, we show two cases with $\log U = -3$ and -2. We compare the predictions of the new grid with the COSTAR and SLG92 WR models of SV98 and the observational data of Bresolin *et al.* (1999) for extragalactic H II regions. It can be seen that the SV98 models are too hard, particularly for the $\log U = -2.0$ case, whereas the new models provide a better fit to the data points. We conclude that, for the parameter range explored, the ionizing fluxes of the new models are in much better agreement with the observed emission line ratios of H II regions than previous model grids.

The new model grids for O and WR stars, the updated STARBURST99 code, and the full version of this paper (MNRAS in press) can be obtained from `http://www.star.ucl.ac.uk/starburst`.

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Discussion

LEITHERER: It is unfortunate that the interfacing of the tracks and atmospheres cannot be done in a self-consistent way. Therefore, users of the new models should be made aware that this is still a free parameter requiring calibration.

SMITH: Yes, thank you for that comment, Claus.

MASSEY: To me, it doesn't seem like there's much observational justification any more for the 'enhanced' mass-loss tracks. Certainly, the normal mass-loss tracks of the Padova group, or the older Geneva tracks Schaerer *et al.* (1993) and Schaller *et al.* (1992) do a better job of reproducing the number statistics of WR stars, as I showed in my talk. Have you looked at what this would do to your STARBURST code if you actually used models based upon the observed mass-loss rates, rather than the enhanced ones?

SMITH: The enhanced mass loss rate tracks of Meynet *et al.* (1994) have become the default evolutionary tracks to use for evolutionary synthesis, because the standard mass loss tracks produce too few WR stars, overall.

GIES: Have you compared your new model spectral fluxes with the observed EUV fluxes of the B-type supergiant ϵ CMa, one of the few cases where it is possible to measure the short wavelength flux?

SMITH: No, we haven't done this yet.

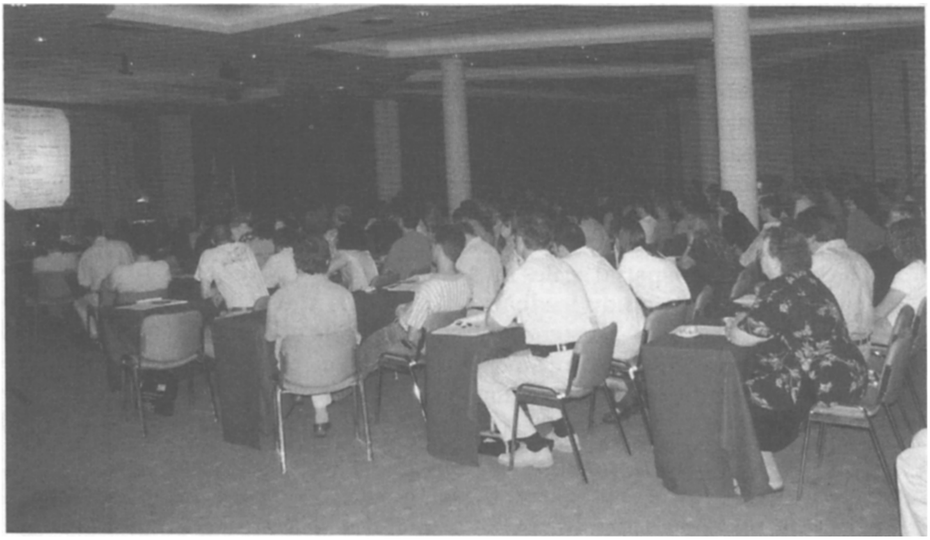
CROWTHER: On average our predictions indicate that WR stars produce negligible He II ionizing photons. Of course, individual WR stars with unusually high temperatures and weak winds do show strong nebular He II 4686 as predicted by the latest atmospheric models (*e.g.*, BAT99-2, DR 1).

MARCHENKO: Could you comment on the hydrogen content in the early-type WN stars? There is a rather peculiar subclass, WN3, which shows clear presence of substantial amounts of hydrogen.

SMITH: We have defined the parameters of the WR grid to represent average values for WR stars. Since the vast majority of WNE stars show no evidence for hydrogen, we have assigned a zero hydrogen content to this class of WN stars.

NAJARRO: Linda, since the mass loss rate plays a crucial rôle on the energy distribution and the Q-values and you are using a fixed mass loss rate per spectral type, I was wondering if you have made any error estimates caused by using other mass loss rate values.

SMITH: No, the emergent flux below 228 Å depends on the wind density and hence on the mass loss rate adopted and the scaling law used to scale the wind parameters with metallicity. Since the precise scaling is not well determined, the predicted flux below 288 Å should be regarded as rather uncertain.



The massive star population, attentive as always