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The effects of binaries on the evolution of UV spectral features in massive starbursts⋆

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Abstract. In this paper we investigate the effects of binaries having an initial period between 1 day and 10 years on the theoretical simulation of the evolution of UV spectral features in massive starbursts. The binary evolutionary processes that dominate the evolution of the considered spectral features are the Roche lobe overflow in Case Br systems, the mass transfer rate and the merger rate. They cause UV spectral rejuvenation in starbursts that are older than 5 Myr.

Key words. stars: binaries: close – galaxies: starburst – ultraviolet: galaxies

1. Introduction

Theoretical spectral modelling of massive starbursts has been studied in detail by Leitherer et al. (1999). They focused on the effects of single stars, and binaries were ignored (see also Conti 2000 for a review). There is however overwhelming evidence that a large fraction of all massive stars has a close companion (for reviews, see Mermilliod 2001; Van Rensbergen 2001; Mason et al. 2001 and references therein) and a discussion of the effects of binaries on the content of stellar populations is necessary to make starburst studies more realistic. In order to study these effects it is essential to have a population synthesis model that includes all known aspects of single and binary evolution in combination with detailed stellar evolutionary calculations. The Brussels population number synthesis (PNS) model and our extended stellar evolutionary library have been described by Vanbeveren et al. (1998a,b,c) and by Van Bever & Vanbeveren (1998) and is summarized in Sect. 2 (see also Vanbeveren 2001). Van Bever et al. (1999) investigated the consequences of including binaries in photoionization models, in particular on the evolution of the nebular $W(H_\alpha)$ and $W(H_\beta)$ lines. The expected X-ray emission was considered by Van Bever & Vanbeveren (2000) and by Persic & Rephaeli (2002). Schaerer & Vacca (1998) presented models for WR and O star populations in young starbursts and added a discussion on possible effects of binaries. However, they adopted a binary evolutionary model that is far too simple and many binary evolutionary aspects were not considered. Van Bever & Vanbeveren (2003) investigated *in detail* the influence of binaries on the evolution of a collection of WR emission lines grouped into the so-called blue WR bump, i.e. the NIII/NV λ4640, the CIII/CIV λ4650, the HeII λ4686 and its nebular contribution, and in the so called red WR bump, i.e. the carbon multiplet CIV $\lambda\lambda$5808–5812. The present paper deals with the effects of binaries on the evolution of the UV spectral region between 1200 Å and 1850 Å and can be considered as an addendum to the study of Leitherer et al. (1999).

2. The Population Number Synthesis (PNS) model

A PNS code with a realistic fraction of interacting binaries has to account for:

- the evolution of Case A, Case Br, Case Bc and Case C binaries with mass ratio $q > 0.2$, accounting in detail for the effects of Roche lobe overflow, mass transfer, mass loss from the system, common envelope evolution;
- the evolution of binaries with small mass ratio ($q \leq 0.2$) which is governed by the spiral-in process;
- the evolution of mergers;
- the effects of the (asymmetric) supernova (SN) explosion on binary parameters.

Our PNS code was described in the papers cited in the introduction. Summarising, it relies on an extended library which contains evolutionary computations of intermediate mass and massive single stars and binary components with a moderate amount of convective core overshooting, for different initial chemical compositions ($0.002 \leq Z \leq 0.02$). The calculations of the massive stars were performed accounting for recent stellar wind mass loss rate formalisms. *The results of the starburst simulations depend critically on these massive star evolutionary computations, thus on the adopted stellar wind mass loss formalisms.*

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⋆ Figures 4 to 10 and Figs. 12 and 13 are only available in electronic form at http://www.edpsciences.org

They were rediscussed in Van Bever & Vanbeveren (2003) and to place the results of the present paper in the correct framework we advise the reader to consider the latter paper as well as those mentioned in the introduction. We have over 1000 evolutionary calculations of massive close binaries where the evolution of the mass gainer is followed up to the end of its CHeB phase. One of the crucial parameters here is the amount of matter lost by the mass loser due to Roche lobe overflow (RLOF) that is (or can be) transferred to the mass gainer, the parameter β as it was originally introduced by Vanbeveren et al. (1979).

It is likely that Case B/C binaries with initial primary mass $\geq 40\ M_{\odot}$ avoid RLOF due to a pre-RLOF large LBV-type stellar wind mass loss phase: the LBV scenario of massive binaries (Vanbeveren 1991). At the beginning of the RLOF in a Case Bc or Case C binary, the system enters a common envelope phase where most of the mass lost by the loser is lost from the system ($\beta = 0$). A parameter which can make a significant difference between population spectral synthesis with or without binaries is the value of β in Case Br binaries with initial primary mass $<40\ M_{\odot}$ and in all Case A binaries. In our PNS model we treat Case A binaries in a similar way to Case B. This means in fact that we assume that Case A binaries with initial primary mass $\geq 40\ M_{\odot}$ also avoid RLOF. This may not be true and deserves some attention when discussing the results of the spectral synthesis of starbursts.

After more than 3 decades of extensive binary evolutionary calculations by different research teams all over the world, the following overall β-formalism for Case A and Case Br binaries with primary mass $<40\ M_{\odot}$ emerges:

- binaries with mass ratio $q < 0.2$: spiral-in and $\beta = 0$;
- binaries with mass ratio $q > 0.4$: RLOF and $0 \leq \beta =$ constant $= \beta_{\max} \leq 1$;
- binaries with mass ratio $0.2 \leq q \leq 0.4$: $\beta = 5\beta_{\max}(q - 0.2)$.

Note that similar formalisms are used in most of the PNS codes used by different research teams. To calculate β ($\beta_{\max}$) one has to solve the magneto-hydrodynamic equations that describe the mass transfer and we need a model that describes in a realistic way the reaction of a star when it accretes mass under conditions which are typical for binaries. This problem is very complex and approximations are needed. An accretion model was proposed by Neo et al. (1977) but an alternative suggestion was published by Vanbeveren & De Loore (1994). In most of the cases the conclusions related to β depend in a critical way on the adopted accretion model and therefore uncertainties in the latter imply uncertainties on β. Since it can be expected that $\beta = 0$ for Case Bc/C binaries, one may speculate that $\beta_{\max}$ is a decreasing function of the period. However, it is the scope of the present paper to illustrate possible consequences of binaries on the spectral synthesis of starbursts and accounting for all uncertainties the β-model given above is sufficient.

We will present our results for different values of $\beta_{\max}$. Of course, when mass leaves the binary we have to account for the loss of orbital angular momentum. In all our PNS computations of the past we used a formalism described by Soberman et al. (1997). Matter leaves a binary through the second Lagrangian point L_2 and settles in a circumbinary ring with radius $= \eta A$ (A = distance between both components). It is straightforward then to calculate the variation of the binary period (see also Vanbeveren et al. 1998b). A "bare-minimum" for $\eta \approx 1.3 \approx$ the distance between L_2 and the centre of mass of the binary. However as argued by Soberman et al. this ring is unstable, is likely to fragment and to fall back on the binary components. The first stable ring corresponds to $\eta \approx 2.25$. We will present our calculations adopting the latter value.

An alternative formalism follows from energy considerations. Suppose that part of the mass lost by the primary during its RLOF [$= (1 - \beta)\mathrm{d}M_1$] escapes from the system. To escape, matter needs an average energy of

$$\frac{G(M_1 + M_2)}{\lambda A}(1 - \beta)\mathrm{d}M_1\,, \qquad (1)$$

with λ of order unity. For binaries with component masses $<40\ M_{\odot}$ the escape energy must be supplied by the dynamical energy E of the system. The relation $E = -\frac{GM_1M_2}{2A}$ combined with Kepler's law yields the orbital period variation. Interestingly, the two formalisms discussed above give similar results. In particular, a significant amount of mass loss from the binary is always accompanied by a large reduction of the orbital period which leads in some cases to the merging of the two components. Therefore, if PNS is computed assuming that the evolution of binaries with primary mass $<40\ M_{\odot}$ is highly non-conservative, we need to consider in detail the evolution of mergers.

Mergers are closely related to β and we will show that they may play an important role in population spectral synthesis. The binaries with initial mass ratio $q \leq 0.2$ experience a spiral-in phase. The low mass component is dragged into the atmosphere of the most massive star and merges with it. The final product will be a single star with a mass equal to the sum of the masses of both components. Note however that this single merger may have an alternative chemical composition. We consider two possibilities:

a. Due to spiral-in and merging both stars are totally mixed (Merger 1).
b. Merging is treated as real accretion whereby the low mass star is accreted onto the high mass component (Merger 2).

Merging in binaries with initial mass ratio $q > 0.2$ can happen as well but in this case it is a result of the very large orbital period reduction due to non-conservative RLOF ($\beta < 1$ and/or common envelope evolution). To have an indication of the possible effects on population spectral synthesis, once a binary satisfies the conditions to merge (Vanbeveren 2001) we mix in a homogeneous way the hydrogen-deficient CHeB mass-loser remnant with the mass-gainer which, in most cases, is still a core hydrogen burning star. To illustrate our procedure, consider a 30 $M_{\odot}$ + 20 $M_{\odot}$ binary where 50% (resp. 100%) of the mass lost by the 30 $M_{\odot}$ during RLOF leaves the binary. At the end of RLOF, the binary consists of a 12 $M_{\odot}$ hydrogen-deficient remnant (WR star) and a 28 $M_{\odot}$ (resp. 20 $M_{\odot}$) core hydrogen burning companion. When the merging conditions are fulfilled, we mix the 12 $M_{\odot}$ star with the 28 $M_{\odot}$ (resp. 20 $M_{\odot}$) companion. Of course we realise that this is only an approximation. If merging happens before the end of RLOF, we have

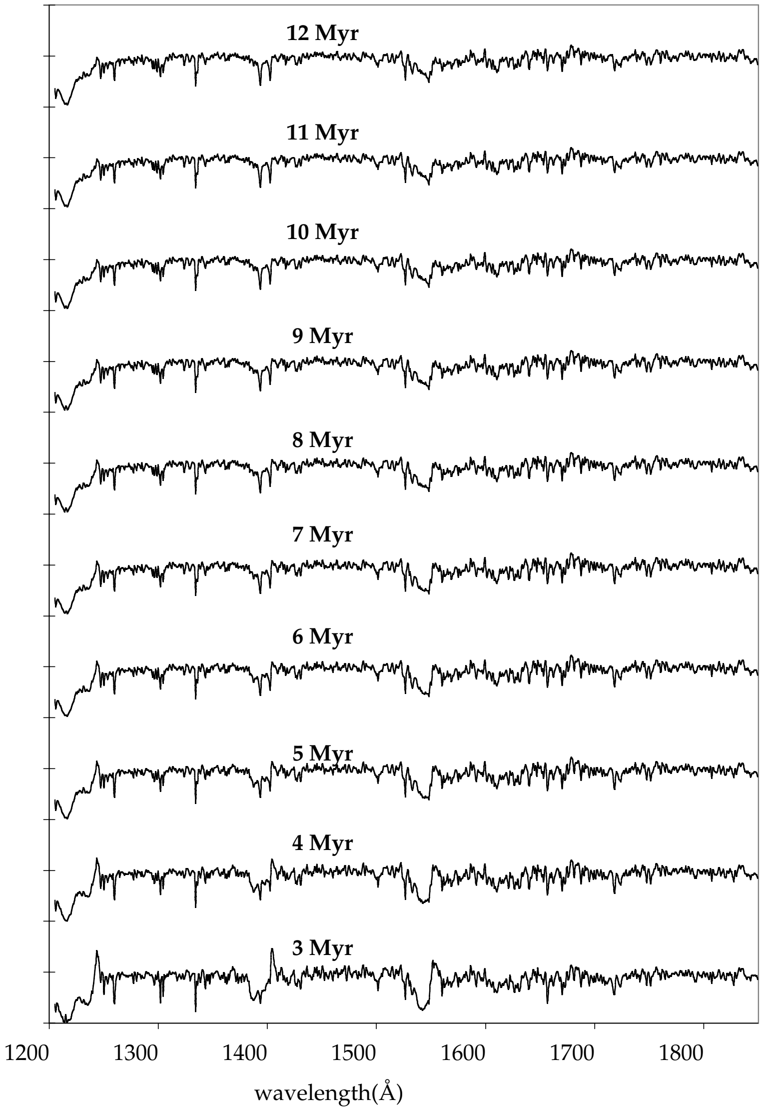

Fig. 1. The predicted UV-spectral evolution of the Standard Binary Starburst (SBS) model at various epochs after the instantaneous starburst.

to mix a star with mass >12 $M_{\odot}$, but our method can already give a first order indication of the effect. The mass gainer in a binary whose RLOF is (quasi)-conservative will be rejuvenated by mass accretion. When the RLOF is non-conservative, the merging process may become important. Since merging implies mixing, it also leads to rejuvenation. This means that whatever the value of β, one expects rejuvenation of starbursts when binaries are present. Whether accretion dominates over merging or vice versa obviously depends on β.

3. The Population Spectral Synthesis (PSS) model

PSS requires realistic spectral energy distributions (SED) and/or spectra for each star in the PNS model:

a. for the SEDs of hydrogen-deficient core helium burning (CHeB) stars resembling WR stars we use the continua of Schmutz et al. (1992);
b. for the SEDs of hydrogen-deficient core helium burning stars that do not resemble WR stars (mostly CHeB post-Roche lobe overflow binary components with mass smaller than the minimum mass of WR stars) we use a black-body energy distribution; they do not affect our results in a significant way;
c. for the SEDs of the other stars we use the homogeneous grid of atmospheres of Lejeune et al. (1997);
d. for the spectra in the [1200–1850] Å region we use the library of O stars and WR stars of Robert et al. (1993) whereas for the B stars we use the spectra published by de Mello et al. (2000). These libraries only contain spectra for solar metallicity stars. Therefore we will restrict our calculations to starbursts with Solartype chemical composition.

It is straightforward to link SEDs and spectra to non-WR stars predicted by stellar evolution: we use the $T_{\rm eff}$-spectral type calibration of Schmidt-Kaler (1982) and each SED is scaled according to the star's luminosity. The link between stellar evolutionary prediction and real WR stars deserves some attention. As inferred from the observed luminosity of WR stars and from the masses of the WR components in well known binaries, most of the WR stars have a mass larger than 5 $M_{\odot}$ (possibly even

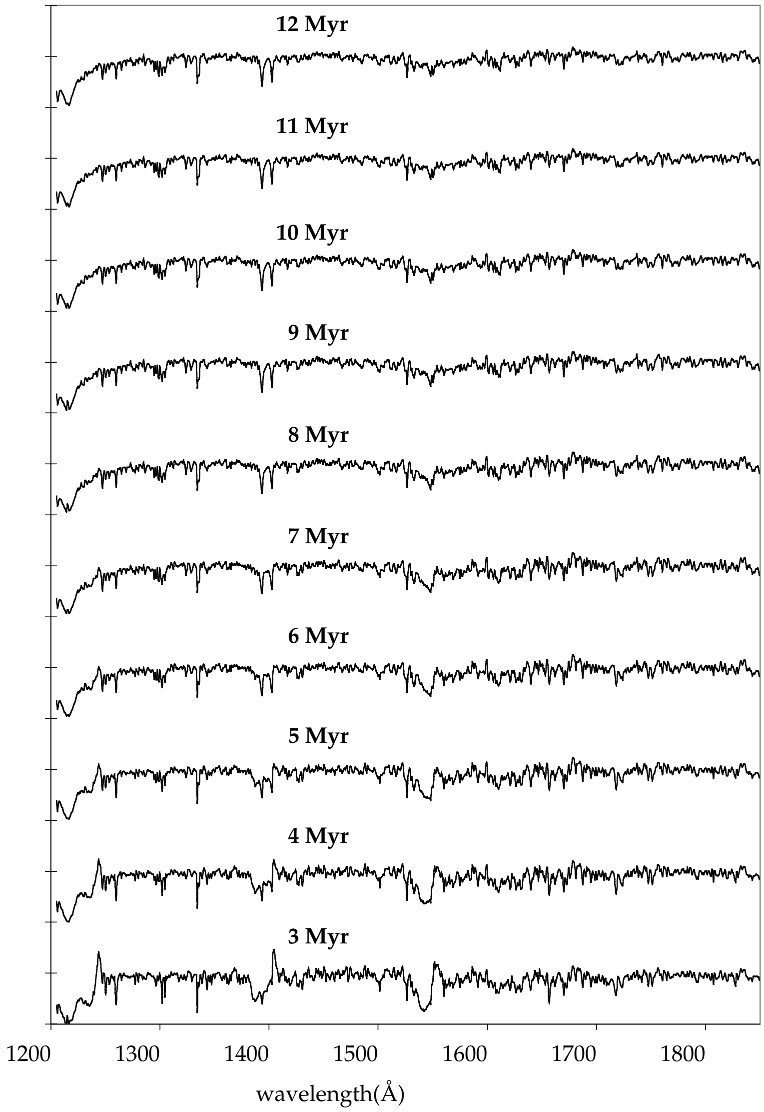

Fig. 2. The predicted UV-spectral evolution of the Standard Single Starburst (SSS) model at various epochs after the instantaneous starburst.

larger than 8 $M_{\odot}$). In our PNS and PSS we consider a hydrogen deficient CHeB star as a WR star when its mass is larger than some minimum value. We explore the consequences when different values of this minimum are considered.

The hydrostatic radii of hydrogenpoor CHeB stars are on the order of 1 $R_{\odot}$, implying evolutionary $T_{\rm eff}$ values in excess of 125 000 K. However, WR star spectra are not formed at the hydrostatic radius of the star but rather in the supersonic part of the wind. Their representative radius (at $\tau_{\rm ROSS} \approx 10$) may be 2 or 3 times larger compaired to the former. The values of these core radii depend on a number of parameters (and not in the least those affecting the velocity structure in the subsonic part of the wind, Hamann & Schmutz 1987) that are uncertain. As a consequence, linking evolutionary models (with the hydrostatic radii) and more realistic WR atmospheres is not straightforward. This problem was nicely illustrated by Hamann (1994) in his Fig. 7. We have computed the results assuming that the core radii equal the hydrostatic radii of WR stars resulting from stellar evolution, but we will also calculate the results with WR core radii that are respectively a factor 2 and 3 larger than the hydrostatic one. We remind the reader that the luminosity,

Table 1. The population parameters considered in the present calculations. Model a is the standard population (SBS with corresponding SSS). The other models are similar to model a but we change one parameter. All models have $Z = 0.02$.

Models a	*standerd*
Models b	$\phi(q)Hogeveen$
Models c	$\phi(q)Garmany$
Models d	$Merger1$
Models e	$\beta_{\rm max} = 0.5$
Models f	$\beta_{\rm max} = 0$
Models g	$< \upsilon_{\rm kick} > = 150$ km s^{-1}
Models h	$\alpha = 0.5$

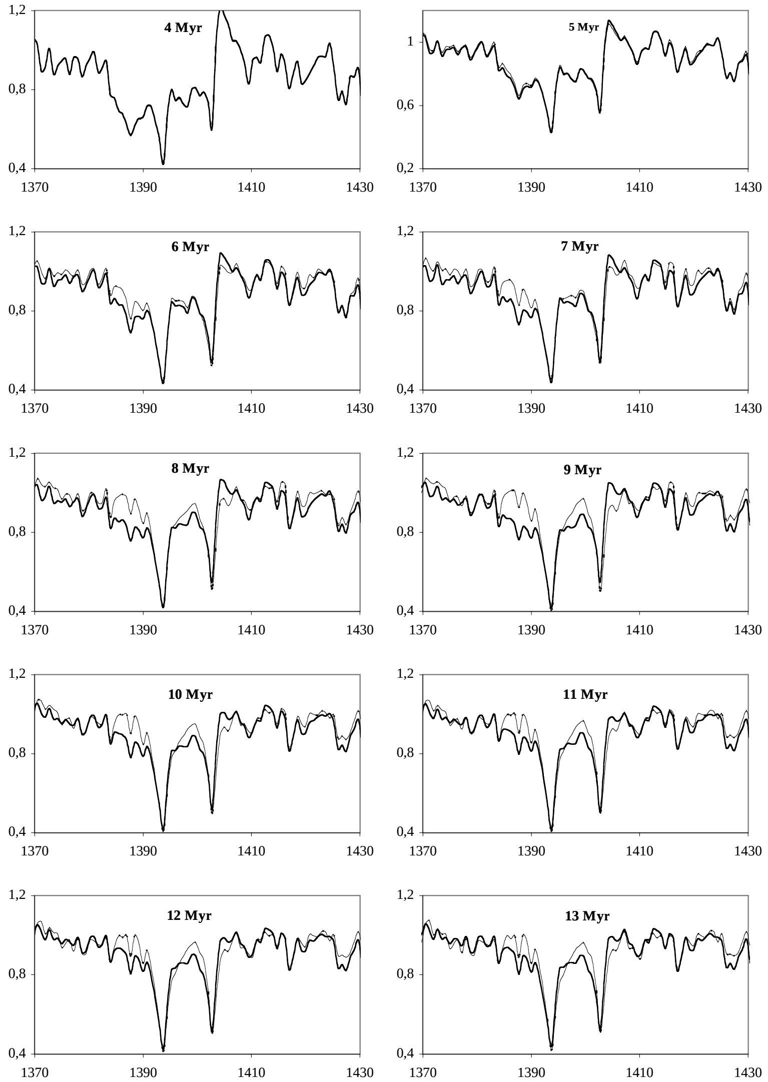

Fig. 3. The predicted evolution of the SiIV λ1400 line for the SBS model (thick line) and for the SSS model (thin line).

the lifetime and the internal structure of a hydrogen-deficient CHeB star only marginally depend on how the stars atmosphere is treated, so that artificially increasing the star's radius implies different $T_{\rm eff}$ values but does not affect its overall evolution.

4. Results

As in Van Bever & Vanbeveren (2000, 2003) we define the standard binary starburst (SBS) for Solar type chemical composition as follows.

- Case A binaries are treated as Case Br. Our simulations allow us to conclude that PNS results are rather robust to this simplification.
- The evolution of binaries that experience a common envelope and/or spiral-in phase depends on the parameter α (i.e. the amount of orbital energy which is effectively used to remove the hydrogen-rich layers of the mass loser). In the SBS model we set $\alpha = 1$. We conclude that: *the results of the present paper do not critically depend on the details of the common envelope/spiral in process*.
- Primaries of close binaries and single stars have the same Salpeter type initial mass function with $M_{\rm min} = 1\ M_\odot$ and $M_{\rm max} = 100\ M_\odot$. The mass ratio distribution is flat and the binary orbital period distribution is flat in log P (periods between 1 day and 10 years).
- The effect of the SN explosion on binary parameters is treated in full 3-D and we adopt a χ^2-distribution for the kick velocity $v_{\rm kick}$ (describing the asymmetry of the SN explosion) with an average of 450 km s^{-1}. The results of the present paper do not critically depend on the average $v_{\rm kick}$.
- The binary frequency ($=\frac{N_{\rm bin}}{N_{\rm bin}+N_{\rm single}}$) with $N_{\rm bin}$ being the number of binaries with periods between 1 day and 10 years) at birth is set to 80%.
- $\beta_{\rm max} = 1$.
- Model Merger 2 for binaries with mass ratio $q \leq 0.2$.
- A hydrogen deficient CHeB star is considered as WR when its mass is larger than 5 $M_\odot$.
- The WR atmospherical core radii (Sect. 3) equal the hydrostatic radii of hydrogen deficient CHeB stars resulting from evolution.

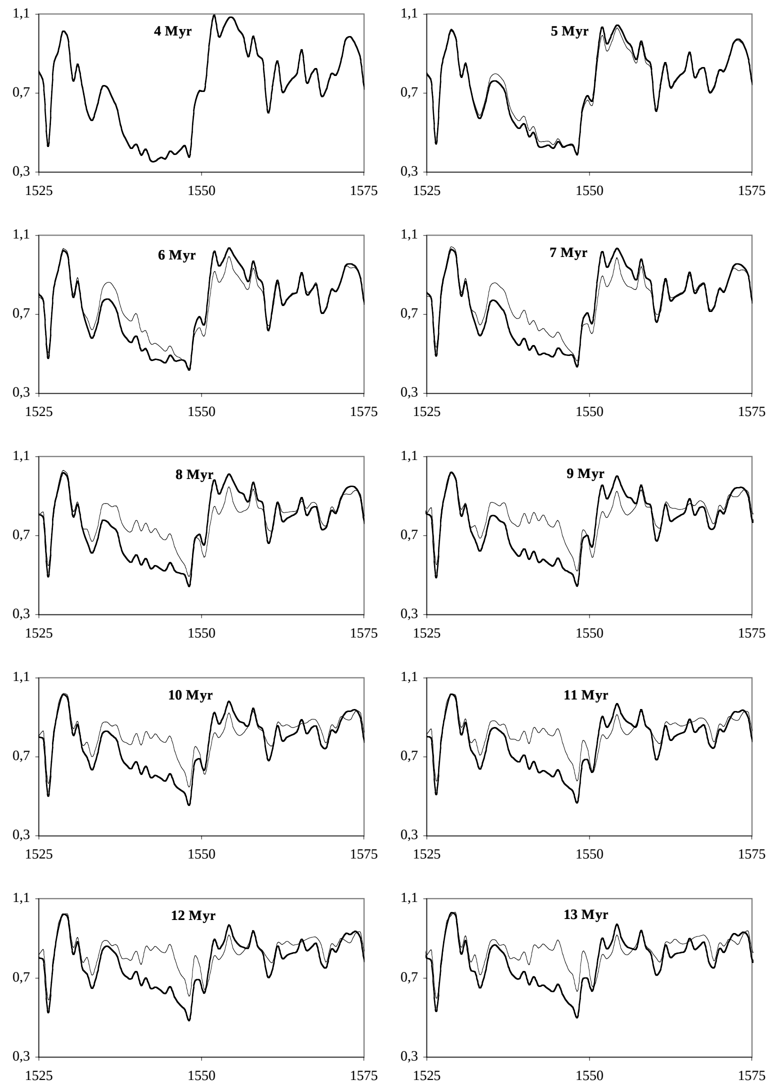

Fig. 11. The predicted evolution of the CIV λ1550 line for model h of Table 1. The thick line (resp. thin line) holds for the binary starburst model (resp. the corresponding single star starburst model).

- A Monte-Carlo method simulates the instantaneous formation of objects (an object is either a single star or a binary) with mass between 1 $M_{\odot}$ and 100 $M_{\odot}$, accounting for the distributions discussed above.
- We compare the SBS results with a standard single star starburst (SSS) model. The stellar content of the SSS model is the same as in the SBS but all primaries and secondaries in the SSS model are treated as single stars.

In order to have a *sufficient* number of *massive* stars in the simulation, one has to start with a very large number of stars with mass $\geq$1 $M_{\odot}$. However, the computing time can be reduced drastically as follows: the mass interval [1–100] $M_{\odot}$ is divided into 99 mass intervals of 1 $M_{\odot}$. A Monte-Carlo method simulates the formation of 100 or so objects in each interval and the evolution of each mass interval is computed separately. The evolutionary effects of each mass interval are then scaled according to the initial mass function and in order to obtain the spectral evolution of the complete starburst. With this procedure the spectral evolution of the whole burst is simulated in a satisfactory way by considering the detailed evolution of about 10 000 objects only.

Van Bever & Vanbeveren (1998, 2003) and Van Bever et al. (1999) discussed the effects of binaries on the evolution of the number of O and WR-type stars and of the nebular H_{β} line in starbursts. We introduced the rejuvenation of starbursts due to binary mass exchange. It is one of the goals of this paper to check whether or not this rejuvenation is visible in the UV spectral synthesis simulation as well. We first formulate the following conclusion resulting from our simulations in which we studied the effects of all single and binary parameters:

The theoretical simulation of the evolution of the [1200–1850] Å spectral region barely depends on the predicted core helium burning star population in general, and the core helium burning WR population in particular.

This means that the results of the present paper only marginally depend on uncertainties in the physics of WR stars (core radii, mass loss rates, definition of a WR star etc.) and on uncertainties in the physics of RSGs and their mass loss rate (determining the single WR star population). To study the

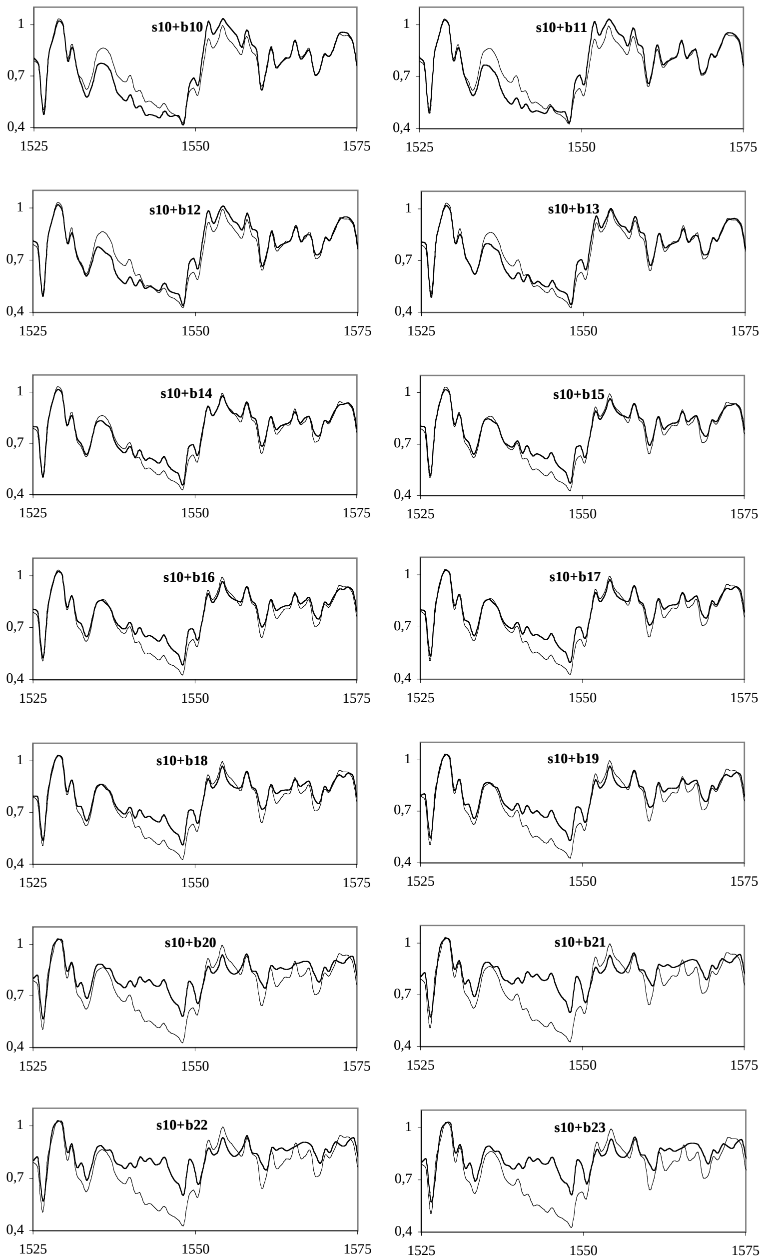

Fig. 14. Same as Fig. 12 but for a SSS model of Myr (S10), remark the similarity between the S10 model and the b18/20 models.

effects of the parameters which enter the PNS model on our results, we restrict ourselves to the models of Table 1.

Figures 1 and 2 illustrate the overall evolution of the UV of the SBS and the SSS model. Notice the difference for starbursts older than ~6 Myr which is typical for all our simulations. This difference is most pronounced in the evolution of the stellar wind features of CIV λ1550 and Si IV λ1400.

Figure 3 shows the evolution of the Si IV λ1400 line in detail for the SBS and corresponding SSS model. This line may be important for starbursts that are younger than ~3 Myr. When they are older, the interstellar component dominates and the difference between both models is marginal. We therefore restrict our further discussion to the CIV λ1550 line.

Figures 4–11 show the spectral evolution of the region centered around this line for different binary population parameters. As expected the evolution with or without binaries is similar up to 5 Myr. We note that this similarity is inherent to our adopted LBV scenario and to the treatment of the Case A binaries with primary mass >40 $M_{\odot}$. We made a test simulation in which the Case A binaries are treated with a more conservative RLOF. Rejuvenation is visible already after 3 Myr but it is fair to conclude that the overall effect is small until 5 Myr. When the starburst is older than 5 Myr, accretion stars and/or mergers appear and the differences become more important. As illustrated by the figures, the results barely depend on the treatment of the common envelope/spiral in phases (α parameters) and on how binary evolution is affected by the supernova explosion of one of the components (v_{kick}). Similar to for the WR spectral features (Van Bever & Vanbeveren 2003) the binary parameters that are most important are β_{max} in Case Br binaries, the adopted merger model and the initial binary mass ratio distribution. As a general conclusion:

When a significant number of binaries are present in starbursts, the mass transfer and the merger process are responsible for a significant UV-rejuvenation of the starburst after ~5 Myr. The effects are most visible in the CIV λ1550 line.

To illustrate this, Figures 12–14 compare the predicted CIV λ1550 line of a standard single starburst which is 6 Myr old (resp. 8 and 10 Myr old) with the corresponding standard binary starburst at different ages. As can be noticed, the SBS model of ~9 Myr (resp. 15/16 and 18/20) almost perfectly matches the SSS model.

5. Overall conclusions

Together with Van Bever & Vanbeveren (1998, 2003) and Van Bever et al. (1999) the present paper completes a study on the effects of binaries on the spectral evolution of starbursts. The results presented here allow us to conclude that core helium burning stars in general and core helium burning WR stars in particular barely affect the UV-spectral evolution. The UV-line that is most important for starburst diagnostics is the CIV λ1550 line. The mass transfer during RLOF in Case Br binaries and the merger rate in massive binaries are the most important binary processes in starbursts with $Z = 0.02$. They produce a rejuvenation of the burst after ~5 Myr which is clearly visible in the evolution of the CIV λ1550 line.

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