The properties and impact of stars stripped in binaries

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Appendices to Chapter 5


Figure C.1: The spectral energy distribution of a co-eval stellar population with initially $10^6 M_\odot$ stars, here shown for metallicities $Z = 0.006, 0.002,$ and $0.0002$ (horizontally) and for increasing time after starburst (vertically). The figure is analogous to Fig. 5.1.

### C.1 Effect of metallicity

Main-sequence stars are more luminous and hotter at low metallicity than at high metallicity. Their emission rates of ionizing photons therefore increase with decreasing metallicity. The emission rates of ionizing photons from stripped stars are also affected by their luminosity and effective temperature. The luminosity of stripped stars increases with lower metallicity, but the effective temperature decreases (Chapter 2; Chapter 3). The reason is primarily that envelope-stripping is less efficient when the metallicity is decreased, which leads to more hydrogen left after mass transfer and therefore lower temperatures. Here, we combine the models for stripped stars at metallicities $Z = 0.006, 0.002,$ and $0.0002$, with the models from
C.1 Effect of metallicity

Figure C.2: The spectral energy distribution in the case of constant star-formation for metallicities $Z = 0.006, 0.002$, and 0.0002. The models are for $1 M_\odot \text{yr}^{-1}$ and are taken 500 Myr after star-formation started. The figures are analogous to Fig. 5.2.

We show the contribution from stripped stars to the integrated spectrum of a co-eval stellar population in Fig. C.1. The figure shows that the emission from stripped stars becomes softer when metallicity decreases, while the emission from main-sequence stars becomes harder. As shown in Fig. 5.3, the total effect of metallicity on the emission from stripped stars is small for $Q_{0,\text{pop}}$ and $Q_{1,\text{pop}}$, but large for $Q_{2,\text{pop}}$. The reason why the effect is large for $Q_{2,\text{pop}}$ is that He II-ionizing photons are created in the steep Wien-part of the spectrum and the emission rate of He II-ionizing photons is therefore very sensitive to temperature variations.

The most striking differences between our predictions and those from BPASS occur at low metallicity. Around 10 Myr after starburst and for $Z \lesssim 0.002$, BPASS accounts for chemically homogeneous evolution for the accreting stars that were spun up during mass transfer (Eldridge et al. 2017). The result is that BPASS predicts higher emission rates of H I- and He I-ionizing photons than our models for stripped stars at low metallicity.

For continuous star-formation, we show the contribution from stripped stars to the spectral energy distribution in Fig. C.2 for the cases of lower metallicity. Comparing with Fig. 5.2, we find that the contribution from stripped stars is similar for $Z \gtrsim 0.002$, while the softer spectra of stripped stars are clearly visible at metallicity $Z = 0.0002$.

The hardness of the ionizing part of the integrated spectrum affects the nebular ionization, as discussed in Sect. 5.5.3. We show the ionizing part of the spectra of co-eval stellar populations at low metallicity in Fig. C.3. The spectra of main-sequence stars are seen to become harder and those of stripped stars to become softer with lower metallicity. At $Z = 0.0002$, the hardness is similar for a population containing stripped stars and at an age of 20 Myr as for a population of only 2 Myr that contains massive main-sequence stars. However, we note that the duration for which massive stars give rise to such hard ionizing spectra is significantly shorter than the duration stripped stars emit ionizing radiation.

As a complement to Fig. 5.7, we show the hardness of the ionizing part of the spectrum for a stellar population in which stars have formed at a constant rate for 500 Myr and with
Figure C.3: The ionizing part of the spectral energy distribution for co-eval stellar populations with metallicities $Z = 0.006, 0.002,$ and $0.0002$ from top to bottom. The spectra are normalized at the ionization threshold for hydrogen, 13.6 eV. See Fig. 5.7. This panel shows the spectra for $Z = 0.006$. Including stripped stars.
C.1 Effect of metallicity

![Graph showing the effect of metallicity on various elements.]

Figure C.3: For $Z = 0.002$.
C.1 Effect of metallicity

Figure C.4: The ionizing part of the spectral energy distribution in the case of continuous star-formation, taken after 500 Myr. We compare a population containing only single stars (gray) with one containing also stripped stars (green). We show models for solar metallicity. See also Fig. 5.7.

Solar metallicity. The spectrum is only mildly affected by the presence of stripped stars. The largest differences from a population containing only single stars appear at high photon energies ($\gtrsim 40$ eV). This could lead to stronger nebular emission of O\textsc{iii}, C\textsc{iv}, and He\textsc{ii} than what is expected from single star models.

We present our predictions for properties of stellar populations with metallicities of $Z = 0.006$, 0.002, and 0.0002 in Tables C.1, C.2 and C.3. The general trends of metallicity are discussed in the sections that are mentioned in the tables.
Table C.2: Values of observable quantities for models of stellar populations including stripped stars and at $Z = 0.002$. 

Co-eval stellar population ($10^6 M_\odot$, $Z = 0.002$)

|Time [Myr]| $\log_{10} Q_{0,\text{pop}}$ [s$^{-1}$]| $\log_{10} Q_{1,\text{pop}}$ [s$^{-1}$]| $\log_{10} Q_{2,\text{pop}}$ [s$^{-1}$]| $\log_{10} \xi_{\text{ion},0}$ [erg$^{-1}$ Hz$^{-1}$]| $\log_{10} \xi_{\text{ion},1}$ [erg$^{-1}$ Hz$^{-1}$]| $\log_{10} \xi_{\text{ion},2}$ [erg$^{-1}$ Hz$^{-1}$]| $\log_{10} L_{\lambda}(1500\AA)$ [erg s$^{-1}$ Hz$^{-1}$]| $\log_{10} U$ | $\beta$
|---|---|---|---|---|---|---|---|---|---|
|2 | 52.7 (52.7) | 52.2 (52.2) | 48.9 (48.9) | 25.8 (25.8) | 25.2 (25.2) | 21.9 (21.9) | 26.9 (26.9) | -2.0 (-2.0) | -3.08 (-3.08)
|3 | 52.6 (52.6) | 51.9 (51.9) | 47.6 (47.6) | 25.5 (25.5) | 24.8 (24.8) | 20.5 (20.5) | 27.1 (27.1) | -2.0 (-2.0) | -2.74 (-2.74)
|5 | 52.0 (52.0) | 50.9 (50.9) | 45.1 (45.1) | 25.2 (25.2) | 24.1 (24.1) | 18.3 (18.3) | 26.8 (26.8) | -2.2 (-2.2) | -2.58 (-2.58)
|7 | 51.4 (51.4) | 49.5 (49.5) | 39.8 (39.8) | 24.7 (24.7) | 22.9 (22.9) | 13.1 (13.1) | 26.7 (26.7) | -2.4 (-2.4) | -2.51 (-2.51)
|11 | 51.0 (50.3) | 50.7 (47.4) | 48.6 (37.1) | 24.7 (23.9) | 24.4 (21.0) | 22.2 (10.7) | 26.4 (26.4) | -2.5 (-2.8) | -2.43 (-2.42)
|20 | 50.4 (49.1) | 50.1 (45.2) | 47.1 (-) | 24.4 (23.2) | 24.1 (19.2) | 21.1 (-) | 26.0 (26.0) | -2.7 (-3.2) | -2.34 (-2.33)
|30 | 50.1 (48.5) | 49.8 (43.8) | 46.4 (-) | 24.3 (22.7) | 24.0 (18.0) | 20.6 (-) | 25.8 (25.8) | -2.9 (-3.4) | -2.28 (-2.27)
|50 | 49.7 (47.7) | 49.3 (41.8) | 45.2 (-) | 24.1 (22.2) | 23.7 (16.3) | 19.7 (-) | 25.5 (25.5) | -3.0 (-3.7) | -2.1 (-2.09)
|100 | 49.0 (46.5) | 48.5 (40.1) | 43.0 (-) | 23.9 (21.3) | 23.3 (15.0) | 17.9 (-) | 25.1 (25.1) | -3.2 (-4.1) | -1.84 (-1.82)
|200 | 48.3 (44.9) | 47.2 (38.4) | 41.6 (-) | 23.6 (20.2) | 22.5 (13.6) | 16.9 (-) | 24.7 (24.7) | -3.5 (-4.6) | -1.54 (-1.52)
|300 | 47.6 (43.9) | 46.8 (36.4) | 41.8 (-) | 23.2 (19.5) | 22.4 (12.0) | 17.4 (-) | 24.5 (24.5) | -3.7 (-4.9) | -1.33 (-1.3)
|500 | 46.2 (42.9) | 44.6 (-) | 39.9 (-) | 22.1 (18.8) | 20.5 (-) | 15.8 (-) | 24.1 (24.1) | -4.1 (-5.3) | -0.97 (-0.93)
|800 | 45.0 (41.5) | 42.1 (-) | 36.0 (-) | 21.3 (17.9) | 18.5 (-) | 12.4 (-) | 23.6 (23.6) | -4.6 (-5.7) | 0.09 (0.19)
|1000 | 44.3 (40.8) | 41.2 (-) | 34.2 (-) | 20.9 (17.5) | 17.8 (-) | 10.8 (-) | 23.4 (23.4) | -4.8 (-5.9) | 0.97 (1.11)

Continuous star-formation ($1M_\odot$/year, $Z = 0.002$)

|Time [Myr]| $\log_{10} Q_{0,\text{pop}}$ [s$^{-1}$]| $\log_{10} Q_{1,\text{pop}}$ [s$^{-1}$]| $\log_{10} Q_{2,\text{pop}}$ [s$^{-1}$]| $\log_{10} \xi_{\text{ion},0}$ [erg$^{-1}$ Hz$^{-1}$]| $\log_{10} \xi_{\text{ion},1}$ [erg$^{-1}$ Hz$^{-1}$]| $\log_{10} \xi_{\text{ion},2}$ [erg$^{-1}$ Hz$^{-1}$]| $\log_{10} L_{\lambda}(1500\AA)$ [erg s$^{-1}$ Hz$^{-1}$]| $\log_{10} U$ | $\beta$
|---|---|---|---|---|---|---|---|---|---|
|500 | 53.3 (53.3) | 52.6 (52.6) | 49.4 (49.1) | 25.2 (25.2) | 24.6 (24.5) | 21.3 (21.0) | 28.1 (28.1) | -1.8 (-1.8) | -2.35 (-2.35)
| $g$ | $\Omega$ (Myr) | $10^{0.5}\Omega$ | $10^{1}\Omega$ | $10^{1.5}\Omega$ | $10^{2}\Omega$ | $10^{2.5}\Omega$ | $10^{3}\Omega$ | $10^{3.5}\Omega$ | $10^{4}\Omega$ | $10^{4.5}\Omega$ | $10^{5}\Omega$ | $10^{5.5}\Omega$ | $10^{6}\Omega$ | $10^{6.5}\Omega$ | $10^{7}\Omega$ |
|-----|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0.0 | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307         | 1.0307         | 1.0307         | 1.0307         | 1.0307         |
| 0.5 | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307         | 1.0307         | 1.0307         | 1.0307         | 1.0307         |
| 1.0 | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307         | 1.0307         | 1.0307         | 1.0307         | 1.0307         |
| 1.5 | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307         | 1.0307         | 1.0307         | 1.0307         | 1.0307         |
| 2.0 | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307          | 1.0307         | 1.0307         | 1.0307         | 1.0307         | 1.0307         | 1.0307         |

Table C.3: Values of observable quantities for models of stellar populations including stripped stars and at $Z = 0.0000$. 

Co-eval stellar population (10$^{-4}$ Myr).