The properties and impact of stars stripped in binaries

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The contribution from stars stripped in binaries to the reionization of hydrogen and helium

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Abstract

Stars stripped in binaries are sufficiently hot to produce ionizing radiation. However, despite being the most well-understood binary products, they are generally not included in models for cosmic reionization of hydrogen and helium. We use spectral synthesis made from detailed evolutionary and spectral models that were created for stripped stars together with a simple model for the reionization to estimate the impact of stripped stars during reionization of hydrogen and helium. Comparing with a model in which stripped stars are not included, we can clearly distinguish the effect of stripped stars on the reionization.

In all our models, we find that about 1/3 of the photons that reionized the intergalactic hydrogen were emitted by stripped stars. We also find that stripped stars harden the emission from stellar populations, allowing spectral indices as high as $\alpha = -1$ for $L_\nu \propto \nu^\alpha$ instead of $\alpha \lesssim -2$, which is predicted for stellar populations that only contain single stars. Stripped stars do not appear to have been efficient sources for helium reionization, but, together with massive stars, they dominated the emission of HeII-ionizing photons at redshifts larger than about 9.

The harder ionizing radiation emerging from galaxies because of the presence of stripped stars can leave an imprint in cosmic history. Intergalactic gas that surrounds stellar systems can reach high ionization states, such as CIV and SiIV, which have been observed in the spectra of background quasars. Additionally, the harder ionizing radiation from stripped stars can heat the IGM during the reionization, leading to several thousand kelvin higher temperatures than what is expected from single stars.
6.1 Introduction

Which sources are responsible for cosmic reionization is a long-standing question which the answer to shapes our scientific picture of the early Universe and is crucial for understanding why it looks like it does today (e.g., Robertson et al. 2010). The current consensus is that stellar populations produced most of the photons that ionized intergalactic hydrogen and neutral helium, while active galactic nuclei (AGN) produced the majority of the photons that fully ionized helium (Barkana & Loeb 2001; Faucher-Giguère et al. 2009; Worseck et al. 2016). However, the relative importance of the different sources of ionizing radiation has not yet been fully constrained and the ionizing radiation from stellar populations is not sufficiently understood.

Numerical and analytical models of the early Universe (e.g., Gnedin & Ostriker 1997; McQuinn et al. 2007; Finlator et al. 2018) reproduce the observed completion of hydrogen reionization around \( z \sim 6 \) (Fan et al. 2006b). However, to achieve this, the models require that a large fraction of the produced ionizing photons escape the host galaxies and reach the intergalactic medium (IGM). With an escape fraction \( (f_{\text{esc}}) \) of 20% or higher at early times the models predict that a sufficient amount of hydrogen-ionizing photons reach the IGM prior to the observed end of reionization (Bolton & Haehnelt 2007b; Ouchi et al. 2009; Haardt & Madau 2012; Robertson et al. 2013). With a lower escape fraction the reionization is significantly delayed. Alternative solutions to the missing ionizing photons at early times include, for example, a higher cosmic star-formation rate at early times because of un-detected faint galaxies (see Atek et al. 2015; Livermore et al. 2017) and un-expectedly high emission from quasars at high redshift (Madau & Haardt 2015). Here we explore the contribution of stellar sources that are rarely accounted for.

Recent advances in stellar astrophysics indicate that several types of stars that emit ionizing radiation often are neglected in models of the ionizing output from galaxies. Efforts have been made to include stellar rotation (Meynet & Maeder 2005; Levesque et al. 2012; Georgy et al. 2013; Leitherer et al. 2014) and very massive stars (VMS), with masses above 100 \( M_\odot \) (Crowther et al. 2016) in models for the spectra of stellar populations. Recent observational surveys show evidence that massive and intermediate mass stars have binary companions so close that interaction between the two stars is inevitable as the stars swell during evolution (Sana et al. 2012; Moe & Di Stefano 2017). Such binary interaction can lead to severe exchange or loss of stellar material and possibly even coalescence of the stars. The stars that are the products of binary interaction have been considered to enhance the ionizing budget from stellar populations (Van Bever et al. 1999; Stanway et al. 2016). Below, we describe several binary products that are expected to emit ionizing radiation.

Envelope-stripping is the most common type of interaction in binaries as it is the fate of a third of all massive stars (Sana et al. 2012). During either stable or unstable mass-transfer, the envelope of one star is transferred to the second star or lost, leaving the hot core exposed (Kippenhahn & Weigert 1967; Paczyński 1967; Podsiadlowski et al. 1992; Ivanova et al. 2005).
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2013). These stripped stars are so hot that they emit the majority if their radiation as ionizing (Götberg et al. 2017, hereafter Chapter 2).

Mass-transfer or coalescence can result in a star that has higher mass than initially. With more mass, the convective core grows and has access to un-processed fuel, causing it to rejuvenate. In young star clusters, these stars can appear as massive blue stragglers (Packet 1981; Braun & Langer 1995; Belkus et al. 2003; Chen & Han 2009; Schneider et al. 2014; de Mink et al. 2014). Rejuvenated mass-gainers are not expected to be sufficiently many to significantly increase the emission rate of ionizing photons from a stellar population. However, they can have high escape fraction if they are ejected from the star-forming region by the disruption of the binary via a supernova (Conroy & Kratter 2012).

Rapid rotation induced by either mass accretion, coalescence, or tidal forces in close binaries can cause the interior of the star to mix, which provides burning regions with fresh fuel (Maeder 1987). If wind mass-loss and the associated loss of angular momentum is low, as is the case at low metallicity, the star continues to rotate rapidly and may evolve chemically homogeneously (Yoon & Langer 2005; Cantiello et al. 2007; Eldridge et al. 2008).

Compact objects that experience mass accretion in binary systems are expected to radiate X-rays and dominate the output of 1 keV photons from stellar populations (e.g., Fragos et al. 2013; Madau & Fragos 2017). White dwarfs accreting material have softer emission than accreting neutron stars or black holes and could be significant contributors of $\text{He}^{II}$-ionizing radiation (Chen et al. 2015).

Envelope-stripping is probably the type of binary interaction that is most well-understood, both because models suggest that it is a common and often inevitable evolutionary phase and also because several stripped stars have been observed (Gies et al. 1998; Groh et al. 2008; Peters et al. 2008, 2013; Wang et al. 2017, 2018; Chojnowski et al. 2018). Stripped stars that are massive enough are thought to give rise to stripped-envelope supernovae, which are frequently observed (Lyman et al. 2016; Liu et al. 2016; Shivvers et al. 2017; Graur et al. 2017b), and also to constitute a necessary step towards the merger of two neutron stars (Dewi & Pols 2003; Tauris et al. 2017), which recently was detected (Abbott et al. 2017). Rejuvenated mass-gainers are predicted to be common (de Mink et al. 2013; Schneider et al. 2014) and can make a population appear to be younger (van Bever & Vanbeveren 1998), but only the most massive ones are sufficiently hot to contribute significantly with ionizing emission from stellar populations. Chemically homogeneous stars would be important sources of ionizing radiation if rotational mixing is as efficient as models assume (Yoon & Langer 2005; Szécsi et al. 2015; Kubátová et al. 2018). However, whether chemically homogeneous evolution occurs in nature is still a matter of debate (see, however, Almeida et al. 2015). The predictions for these objects are therefore uncertain. Accreting compact objects emit hard ionizing radiation that primarily contributes to $\text{He}^{II}$-ionizing photons (Madau & Fragos 2017). Our focus is on stars stripped in binaries, since these provide the most robust predictions.

Spectral synthesis codes provide models for the integrated spectral energy distributions of stellar populations by combining evolutionary models for different types of stars with libraries of spectra (for a review, see Conroy 2013). The contribution from single stars is well
modeled, as in well-established spectral synthesis codes such as STARBURST99 (Leitherer et al. 1999, 2014) and GALAXEV (Bruzual & Charlot 2003). Efforts have been made to include the effects of binaries, for example in the Yunnan simulations (Zhang et al. 2004; Chen & Han 2009; Zhang et al. 2012; Li et al. 2012; Zhang et al. 2015) and the Brussels code (van Bever & Vanbeveren 1998; Van Bever et al. 1999; Belkus et al. 2003; Vanbeveren et al. 2007). With detailed binary evolutionary models, the code BPASS (Eldridge & Stanway 2009, 2012; Eldridge et al. 2017) has recently gained popularity, also because the authors have continuously provided testable predictions using BPASS (Eldridge et al. 2013; Stanway et al. 2014, 2016). Modeling the radiative contribution from stripped stars has been a challenge since no spectral models made for stripped stars have been available. However, in Götberg et al. (2018, hereafter Chapter 3) we presented large grids of spectral and evolutionary models, which we synthesized to estimate the contribution from stripped stars to stellar populations in Götberg et al. (2019, hereafter Chapter 5). These models are publicly available on CDS\textsuperscript{1} and via the STARBURST99 online interface.

In this paper, we estimate the importance of stars stripped in binaries over cosmic history and discuss their roles during the reionization of hydrogen and helium. This is the fourth in a series of papers in which we describe and discuss the impact of the ionizing radiation emitted by stripped stars, however, it can be read independently. We use our models presented in Chapter 3 and Chapter 5 together with a simple model for cosmic reionization to understand the relative contributions from stripped stars during the evolution of the Universe.

We structure the article as follows. In Sect. 6.2, we describe how we model the sources of ionizing radiation for individual stars, for stellar populations, and over cosmic time. In Sect. 6.3, we present the ionizing emission and the influence of stripped stars on the hardness of the ionizing radiation that emerges into the IGM. In Sect. 6.4, we describe the role of stripped stars during reionization by quantifying the fraction of ionizing photons they contribute with and what their effect is on the time of reionization. Our models suggest that stripped stars impact the conditions in the IGM, which in some cases may influence observable quantities. In Sect. 6.5, we discuss their possible effect on intergalactic absorption features from metals and how they heat the IGM. In Sect. 6.6, we summarize our findings and conclusions.

6.2 Modeling cosmic reionization

In this section, we first describe the models that we use for the sources of ionizing radiation in Sect. 6.2.1. Then, we describe the semi-analytical approach we take to simulate the reionization of hydrogen and helium in Sect. 6.2.2.

\textsuperscript{1}At the time of writing the link is not yet available.
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6.2.1 Sources of ionizing radiation

We consider stripped stars, massive main-sequence and WR stars, and AGN as sources of ionizing radiation during the reionization of hydrogen and helium. Below, we describe how we model the ionizing emissivity over cosmic time for each of these sources.

Stellar populations: stars stripped in binaries and massive stars

We consider stars that are stripped in binaries via stable mass-transfer and common envelope evolution. In these cases, the result is that the compact helium core of the donor star is exposed. The stripped star is hot ($\gtrsim 30,000$ K) and long-lived if interaction occurred prior to the completion of central helium burning, which is an evolutionary phase that constitutes about 10% of the total stellar lifetime (see Chapter 2; Chapter 3). Stripped stars are formed over an extended time period after a burst of star-formation, allowing ionizing radiation to be emitted up to several hundred Myr after a starburst (Chapter 5).

We model the ionizing output from stripped stars using the detailed evolutionary and spectral models presented in Chapter 3. These models are custom-made for stars stripped in binaries. They were computed for initial donor star masses between 2 and 20 $M_\odot$ using the binary stellar evolutionary code MESA (Paxton et al. 2011, 2013, 2015, 2018) and the non-LTE radiative transfer code CMFGEN (Hillier 1990; Hillier & Miller 1998). We consider four metallicities $Z = 0.014, 0.006, 0.002$, and 0.0002, which correspond roughly to the metallicity of the Sun, the Large and Small Magellanic Clouds, and a very low metallicity environment that likely existed at high redshifts.

We compute the total radiative output from stripped stars by simulating a stellar population based on our detailed models. Details can be found in Chapter 5, but we summarize the main assumptions here. We draw initial stellar masses, $M_{\text{init}}$, assuming a Kroupa (2001) initial mass function (IMF) with lower and upper mass limits at 0.1 and 100 $M_\odot$. We determine which stars are primaries in binary systems by assuming the mass-dependent binary fraction of Moe & Di Stefano (2017). We draw companion stars to the primaries by assuming a flat mass ratio ($q = M_{\text{init,2}}/M_{\text{init,1}}$) distribution between 0.1 and 1, in agreement with observations from Kiminki & Kobulnicky (2012), Sana et al. (2012), and Moe & Di Stefano (2017). We assume initial orbital periods for the binary systems following the distribution of Sana et al. (2012) for binaries in which the primary is more massive than 15 $M_\odot$ and assume the period distribution of Öpik (1924), which is flat in log-space for lower mass systems. We assume the initial period range to span from binaries that touch at birth up to $10^{3.7}$ days (Moe & Di Stefano 2017). We determine when interaction is initiated by comparing the sizes of the Roche-lobes of the stars (Eggleton 1983), with the sizes of the stars, which we take from evolutionary models of single stars that have the same assumptions for the interior as our binary models (Chapter 3). Whether the system initiates stable mass-transfer or common envelope evolution is determined by comparing the mass ratio to a critical value, $q_{\text{crit}}$, above which stable mass-transfer follows and below which a common envelope develops ($q_{\text{crit}} = 0.65$ and...
0.4 for main-sequence and Hertzsprung gap donors, following de Mink et al. 2007 and Hurley et al. 2002, respectively). In case of stable mass-transfer, the result is a binary system containing a stripped star. For common envelope, we determine whether the envelope is successfully ejected by taking the classical $\alpha$-prescription (Webbink 1984), assuming $\alpha_{\text{CE}} = 1$ (e.g., Hurley et al. 2002) and $\lambda_{\text{CE}} = 0.5$ (see Appendix E of Izzard 2004).

We believe that our predictions for the H\textsc{i}- and He\textsc{i}-ionizing emission are relatively robust, in contrast to our predictions for the He\textsc{ii}-ionizing emission. This is because great efforts have been made to constrain the properties of young binaries, such as the binary fraction and the period distribution, which affect the number of stripped stars that are formed (e.g., Moe \& Di Stefano 2017). Also, the stripped stars are predicted, by several different binary stellar evolutionary codes, to have very similar properties independent on the evolutionary channel and which code that was used (see, however, Farrell et al. 2018). The temperature and luminosity are the main properties that determine the output of ionizing radiation. A dense stellar wind can block ionizing radiation. However, stripped stars are expected to have weak winds and their ionizing emission is therefore not expected to be hindered by the stellar wind (see e.g., Vink 2017). The emission rate of He\textsc{ii}-ionizing photons is uncertain for stripped stars. The reason is both that the outer parts of the stellar winds recombine, which blocks the ionizing emission, and that the He\textsc{ii}-ionizing photons are created in the steep Wien part of the spectrum, which is sensitive to small temperature variations (see Chapter 2, for a discussion).

To represent the ionizing output from a full stellar population, we combine our predictions for stripped stars with estimates for single stars and pre-interaction binaries. For this, we use Starburst\textsc{99} (Leitherer et al. 1999, 2010, 2014) as detailed in Chapter 5.

We note that with this approach we have not included a treatment of other binary products, such as rejuvenated companion stars. We do however expect that they do not contribute as much since they are generally cooler. We have also not accounted for the effects on the population of the fewer red giants and red supergiants that we expect, but those are also too cool to contribute with ionizing radiation. Our current approach is sufficient for the scope of this paper.

We use spectral models especially made for stripped stars in our models, which we expect will provide more accurate predictions than when down-scaled WR star models or blackbody spectra are used to represent the radiation from stripped stars as in earlier spectral synthesis models. These detailed models allow us to study the contribution from stripped stars in detail. However, we do not account for other types of binary products, some of which could contribute with additional ionizing radiation (cf. Stanway et al. 2016; Eldridge et al. 2017; Xiao et al. 2018, for further discussion).

**Yields of ionizing photons, $I_{\text{ion}}$**

A simple way to describe the ionizing radiation from stars is to integrate the emission rates of ionizing photons over time and normalize by the total mass of formed stars. This quantity describes the number of produced ionizing photons per solar mass formed stars, or, as com-
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monly re-worded, the emission rate of ionizing photons per star-formation rate or. We refer to it as the yield of ionizing photons, \( I_{\text{ion}} \) (see Madau & Dickinson 2014).

We find that stripped stars produce about \( I_{\text{ion,Hi}} = 10^{51.9} \text{ s}^{-1} (M_\odot \text{ year}^{-1})^{-1} \), while massive stars produce about \( I_{\text{ion,HeI}} = 10^{53} \text{ s}^{-1} (M_\odot \text{ year}^{-1})^{-1} \) in the case of solar metallicity. This means that stripped stars are responsible for about 5% of the total production of \( \text{H}\text{-ionizing radiation from stellar populations. Our models predict that the yield of He}\text{-ionizing photons is } I_{\text{ion,HeII}} \sim 10^{49.1} \text{ s}^{-1} (M_\odot \text{ year}^{-1})^{-1} \text{ for stripped stars, which is about an order of magnitude higher than what massive stars produce.}

Relation between redshift and metallicity

The \( \text{H}\text{-ionizing emission from massive main-sequence stars is known to increase with lower metallicity (e.g., Topping & Shull 2015). The emission from stripped stars is only mildly affected by metallicity, leading to about a factor of two higher emission rates of \( \text{H}\text{-ionizing photons at } Z = 0.002 \text{ compared to at solar metallicity (Chapter 2; Chapter 3). The yields of } \text{HeII}-\text{ionizing photons show large fluctuations with metallicity for single star populations, but remain relatively constant for stripped stars with } Z \geq 0.002 \text{ (see Appendix D.1).}

It is necessary to account for the effect of metallicity when considering the cosmic evolution of stellar populations since the average metallicity increases with the age of the Universe (e.g., Balestra et al. 2007; Gallazzi et al. 2008). We account for the change of metallicity over redshift by assuming the relation \( \log_{10}(Z/Z_\odot) = 0.153 - 0.074z^{1.34} \) of Madau & Fragos (2017, see also Kewley & Kobulnicky 2007), where we assume solar metallicity to be \( Z_\odot = 0.014 \) (Asplund et al. 2009). We then interpolate the yields of ionizing photons over metallicity using log-scales for a trend as smooth as possible. Next, we use the scaling between metallicity and redshift to obtain the appropriate yields of ionizing photons for each redshift. Our method is approximate since at each redshift a spread of metallicity have been observed (see Madau & Dickinson 2014, and references therein).

Production rates of ionizing photons, \( \dot{n}_{\text{ion}} \)

We describe the rate with which stellar populations produce ionizing photons over cosmic time (\( \dot{n}_{\text{ion}} \)) by multiplying the yields of ionizing photons (\( I_{\text{ion}} \)) with the cosmic star-formation rate, \( \psi(z) \),

\[
\dot{n}_{\text{ion}} = I_{\text{ion}} \times \psi(z)
\]

We employ the cosmic star-formation history of Madau & Dickinson (2014, their Eq. 15, also consistent with Finkelstein et al. 2015) together with the yields of ionizing photons that we presented previously. The star-formation rate of Madau & Dickinson (2014) reaches a peak around \( z \sim 2 - 3 \) and decreases for both increasing and decreasing redshifts. Star-formation in galaxies that are too faint to be observed has been suggested to provide a large fraction of the ionizing emission and impact the reionization (e.g., Bouwens et al. 2012; Wise et al. 2014). However, the importance of stripped stars relative to massive stars remains the same.
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Figure 6.1: The redshift dependent escape fractions that we assume in our standard model. The functions are given in Eqs. 6.2 and 6.3.

 independent on the star-formation history. Variations of the star-formation history is therefore not affecting our results significantly.

Equation 6.1 assumes that all ionizing photons that stellar populations produce are emitted once the stars are formed. In reality, stars emit ionizing photons during the entirety or parts of their lifetimes. However, the approximation is justified when a time interval that is much longer than the stellar lifetimes is considered. This is the case for cosmic reionization, which lasts for several hundred Myr and most of the emission of ionizing photons from stellar populations extends over about 50 Myr (see Chapter 5).

Escape fraction, \( f_{\text{esc}} \)

We model the escape fraction following the function presented by Haardt & Madau (2012). However, we modify the given function by shifting it up to reach 2% escape fraction for massive stars and 50% escape fraction for stripped stars in the local Universe. We choose the lower limit for massive stars because star-forming regions in the nearby Universe has been observed to have few percent escape fraction (e.g., Mostardi et al. 2013; Doran et al. 2013; Leitherer et al. 2016; Izotov et al. 2016a,b; Steidel et al. 2018; Tanvir et al. 2018), which simulations agree well with (Paardekooper et al. 2011; Shull et al. 2012; Paardekooper et al. 2015; Roy et al. 2015; Ma et al. 2015; Rutkowski et al. 2016). However, simulations also show that the escape fraction increases with time after star-formation has stopped, and it is likely to reach \( \sim 50\% \) after several tens of Myr because of the strong stellar winds and supernovae from massive stars (Kimm & Cen 2014; Trebitsch et al. 2017). This is the reason for our choice of the lower limit for stripped stars. Compilations over a range of redshifts indicate that the escape fraction was higher at early times (Inoue et al. 2006; Faisst 2016; Fletcher et al. 2018). Because galaxies were small in the early Universe (Bouwens et al. 2017), they had a larger relative surface area, which leads to a higher leakage of ionizing
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photons (Wise & Cen 2009; Wise et al. 2014). This motivates the increase of the function for the escape fraction with higher redshift. To avoid completely transparent galaxies, we also truncate the functions for the escape fractions so that they do not reach above 80%. The function is steep and we, therefore, also multiply the function with a factor of 0.5. The result is the following functions:

\[ f_{\text{esc,massive}}(z) = 0.02 + 0.067 \left( \frac{1 + z}{7} \right)^{3.4}, \quad f_{\text{esc,massive}} \leq 0.8 \]  

\[ f_{\text{esc,stripped}}(z) = 0.5 + 0.067 \left( \frac{1 + z}{7} \right)^{3.4}, \quad f_{\text{esc,stripped}} \leq 0.8. \]  

Haardt & Madau (2012) do not allow HeII-ionizing photons produced in galaxies to emerge into the IGM. We allow the emission of HeII-ionizing photons, using the same escape fractions with the motivation that photons may be able to escape through open holes in the interstellar medium, which means that no material can stop the radiation from reaching the IGM. We show our assumed escape fractions as a function of redshift in Fig. 6.1.

The escape fraction is an uncertain parameter that affects the resulting time of reionization and the contribution from the different sources of ionizing radiation. To explore the dependence on the escape fraction, we also consider two models with constant escape fractions. One of them assumes high escape fractions and the other assumes low escape fractions.

Active galactic nuclei

The accretion discs around supermassive black holes in the center of galaxies are so hot that they radiate both hydrogen and helium ionizing photons. Their emission is likely harder than that from stellar populations because parts of the accretion discs can reach higher temperatures than stars. The ionizing spectra of AGN can be approximated by a power-law, \( L_\nu \propto \nu^\alpha \), for which the slope varies for individual objects \((-3 \lesssim \alpha \lesssim -1)\) but can be averaged to \( \alpha = -1.7 \) (Lusso et al. 2015, see also Telfer et al. 2002). We note that the AGN spectra are unexplored observationally for the wavelength range short-wards of \(~ 350 \) Å and for photon energies smaller than \(~ 0.1 \) keV (e.g., Upton Sanderbeck et al. 2017). In this regime, the spectral slope is typically extrapolated from longer wavelengths (e.g., Haardt & Madau 2012). The number density of AGN has been observed to reach a peak at \( z \sim 2 - 3 \) and to have a steep decline for both higher and lower redshifts (e.g., Hopkins et al. 2007).

Puchwein et al. (2018) used the number density of AGN together with the assumed spectral slope and fitted the co-moving emissivity of H\(_\alpha\)-ionizing photons from AGN, \( \epsilon_{912}(z)/(1 + z)^3 \) (see also Haardt & Madau 2012). The ionizing emissivity, which has units of erg s\(^{-1}\) Hz\(^{-1}\) Mpc\(^{-3}\), relates to the production rate of ionizing photons with a constant:

\[ \dot{n}_{\text{ion, H}_\alpha} = \epsilon_{912}(z)/(1 + z)^3 \times \frac{\nu}{E} = \epsilon_{912}(z)/(1 + z)^3/h. \]  

\[ (6.4) \]
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In Eq. 6.4, \( E \) is the photon energy and \( h \) is the Planck’s constant. We use Eq. 6.4 in combination with the ionizing emissivity of Puchwein et al. (2018, see their Eq. 16) to calculate the production rate of \( \text{H}^+ \)-ionizing photons from AGN over cosmic time. For the production rate of \( \text{He}^+ \)-ionizing photons from AGN, we rescale \( \dot{n}_{\text{H}^+} \) using the average spectral shape of AGN from Lusso et al. (2015).

The escape fraction from AGN is commonly assumed to be unity because of their violent outflows and strong ionizing emission. However, recent studies suggest that it is not the case on average (Cristiani et al. 2016; Micheva et al. 2017). We follow the findings of Cristiani et al. (2016) and adopt an escape fraction of 80% for AGN, assuming that it is constant over cosmic time.

6.2.2 Cosmic reionization: a simple semi-analytic model

We estimate the contribution from stripped stars to the reionization of hydrogen and helium by calculating their impact on the evolution of the volume filling factor of ionized gas, \( x \), over cosmic time. The volume filling factor is a dimensionless parameter that describes the fraction of gas in the IGM that is ionized in terms of volume. We follow a simple approach, described for example in Madau et al. (1999); Haardt & Madau (2012), where the rate of change of the volume filling factor of ionized gas is described as the balance between the rate with which ionizing photons reach the atoms or ions in the IGM and the rate with which the ions recombine. The rate of change of the volume filling factors of ionized hydrogen and helium can be written in the form of the following differential equations:

\[
\frac{dx_{\text{H}^+}}{dt} = \frac{f_{\text{esc}} \dot{n}_{\text{H}^+} \langle n_{\text{H}} \rangle}{\langle n_{\text{H}} \rangle} - \frac{x_{\text{H}^+}}{\langle t_{\text{rec}, \text{H}^+} \rangle},
\]

\[
\frac{dx_{\text{He}^{++}}}{dt} = \frac{f_{\text{esc}} \dot{n}_{\text{He}^{++}} \langle n_{\text{He}^{++}} \rangle}{\langle n_{\text{He}^{++}} \rangle} - \frac{x_{\text{He}^{++}}}{\langle t_{\text{rec}, \text{He}^{++}} \rangle},
\]

(6.5)

where \( \langle n \rangle \) is the mean number density of a considered element in the IGM, and \( \langle t_{\text{rec}} \rangle \) is the mean recombination timescale for a given ion. The combination of the escape fraction and the production rate of ionizing photons, \( f_{\text{esc}} \dot{n}_{\text{ion}} \), describes the rate at which ionizing photons reach the IGM. We use subscripts to denote the quantities for hydrogen and helium, respectively. The escape fraction is assumed to be the same for both hydrogen and helium since it primarily is an effect of geometry within the host galaxy. However, we discuss the possibility and impact of a wavelength dependent escape fractions in Sect. 6.3. We use quantities for a co-moving cosmological volume throughout this paper, unless other is stated.

We calculate the mean recombination time of ionized hydrogen and helium following Haardt & Madau (2012):

\[
\langle t_{\text{rec}, \text{H}^+} \rangle = \left[ n_e \alpha_{B, \text{H}^+} C_{\text{IGM}} \right]^{-1},
\]

\[
\langle t_{\text{rec}, \text{He}^{++}} \rangle = \left[ n_e \alpha_{B, \text{He}^{++}} C_{\text{IGM}} \right]^{-1},
\]

(6.6)

In Eq. 6.6, the clumpy structure of the IGM is approximated by a redshift dependent clumping factor, \( C_{\text{IGM}} = 1 + 43z^{-1.71} \) (Haardt & Madau 2012). We assume that the IGM has
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a temperature of \(\sim 20,000\) K during reionization (see e.g., Miralda-Escudé & Rees 1994; D’Aloisio et al. 2018), meaning that the recombination coefficients for recombination are set to \(\alpha_{B,H\text{II}} = 1.43 \times 10^{-13}\) cm\(^3\) s\(^{-1}\) and \(\alpha_{B,He\text{III}} = 9.08 \times 10^{-13}\) cm\(^3\) s\(^{-1}\) (for Case B type recombination, following Osterbrock & Ferland 2006). The electron density, \(n_e\), accounts for the free electrons from ionization of both hydrogen and helium. We assume that the reionization of H\(_i\) and He\(_i\) were coupled as the number of He\(_i\)-ionizing photons were sufficient for He\(_i\) reionization to occur prior to H\(_i\) reionization, but the mean-free path of the photons were limited by the more abundant hydrogen (Miralda-Escudé & Rees 1994). We then assume that reionization of He\(_ii\) occurred after that of H\(_i\) and He\(_i\). Furthermore, we assume that the ionization fronts were thin compared to the size of the ionized bubbles they enclosed, which is a good approximation for all but the very first stages of reionization (for a discussion, see Madau et al. 1999). This means that there were free electrons from ionized hydrogen and singly ionized helium in the ionized bubbles during H\(_i\)-reionization, which results in an electron density of \(n_e = 1.08 \langle n_{H\text{II}} \rangle\), where the mean number density of hydrogen is \(\langle n_{H\text{II}} \rangle = 1.9 \times 10^{-7} (1 + z)^3\) cm\(^{-3}\) (Haardt & Madau 2012). We have assumed that the composition in the IGM is primordial (e.g., Wagoner et al. 1967), meaning that for every helium atom there are approximately twelve hydrogen atoms. During He\(_ii\)-reionization, the electron density was higher inside the ionized bubbles because helium was fully ionized and, therefore, \(n_e = 1.17 \langle n_{H\text{II}} \rangle\). For the calculation of the recombination times, physical units are used. The resulting recombination timescales are about 500 Myr at \(z \sim 6\) for recombination of hydrogen and about seven times lower for recombination of He\(_ii\) to He\(_ii\).

When solving Eq. 6.5, we integrate over the age of the Universe assuming a flat cosmology in the standard \(\Lambda\)CDM theory and apply \(H(z) = H_0(\Omega_M (1 + z)^3 + \Omega_\Lambda)^{1/2}\). For the cosmological parameters, we use the latest results from the Planck satellite (\(\Omega_M = 0.31\), \(\Omega_\Lambda = 0.69\), and \(H_0 = 68\) km s\(^{-1}\) Mpc\(^{-1}\), Planck Collaboration et al. 2016). The age of the Universe, \(t_{age}\), is then related to the cosmic redshift, \(z\), by the following integration:

\[
t_{age} = \int_z^\infty \frac{dz'}{H(z')(1 + z')}. \tag{6.7}
\]

In Sect. 6.2.1, we described how we estimate the production rates of ionizing photons and the escape fraction of ionizing photons for the various sources of ionizing photons that we consider. We use these together with the calculated recombination times to numerically solve Eq. 6.5 with the odeint solver in the scipy package of Python (Jones et al. 2001–) and present the solutions in Sect. 6.4. We create three models for the cosmic emissivity of ionizing photons, as summarized in Table 6.1. The standard model uses the functions for the escape fraction as described by Eqs. 6.2 and 6.3, while the other two models assume constant escape fractions, labelled “optimistic” and “pessimistic” in accordance with the values assumed for the escape fractions. We focus on the results from our standard model, but also discuss the results from the optimistic and pessimistic models.
### Table 6.1: The included sources of ionizing radiation during cosmic evolution for our two models.

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Components</th>
<th>Model</th>
<th>$f_{esc}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard</strong></td>
<td>Stripped stars (1)</td>
<td>Eq. 6.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Massive stars (2)</td>
<td>Eq. 6.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AGN (3)</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td><strong>Optimistic</strong></td>
<td>Stripped stars (1)</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Massive stars (2)</td>
<td>20%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AGN (3)</td>
<td>80%</td>
<td></td>
</tr>
<tr>
<td><strong>Pessimistic</strong></td>
<td>Stripped stars (1)</td>
<td>30%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Massive stars (2)</td>
<td>5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>AGN (3)</td>
<td>80%</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:** The models that we use to represent the ionizing emission are (1) Chapter 5 for the addition from stripped stars (now available also via the STARBURST99 online interface), (2) STARBURST99 for the contribution from massive main-sequence and WR stars (Leitherer et al. 1999, 2010), and (3) the emissivity presented in Puchwein et al. (2018). For details, see Sect. 6.2.1.

### 6.3 Ionizing emissivity over cosmic time

#### 6.3.1 Cosmic emission rates of H\textsubscript{i}- and H\textsubscript{II}-ionizing photons

Using Eqs. 6.1 and 6.4, we compute the production rates of H\textsubscript{i}- and H\textsubscript{II}-ionizing photons from stellar populations and AGN. To obtain the emission rate of ionizing photons that reach the IGM, we multiply the production rates of ionizing photons with the escape fraction for each considered source. In Fig. 6.2, we show these emission rates for the three different models described in Table 6.1 and as a function of redshift.

The figure shows that stripped stars played important roles as sources of both H\textsubscript{i}- and H\textsubscript{II}-ionizing photons, but during different epochs in time. Figure 6.2a shows the emission rate of H\textsubscript{i}-ionizing photons from stars and AGN as a function of redshift for our standard model. The model predicts that stripped stars were responsible for a few up to about 25% of the total emission rate of H\textsubscript{i}-ionizing photons prior to $z = 6$. Massive stars are predicted to have been the main provider of H\textsubscript{i}-ionizing photons at early times and AGN became important after $z = 6$. Around $z = 2 - 3$, AGN provided the majority of the H\textsubscript{i}-ionizing photons and, therefore, likely played a major role in keeping the intergalactic hydrogen from recombining. Panels b and c of Fig. 6.2 shows the cosmic emission rates of H\textsubscript{i}-ionizing photons in our optimistic and pessimistic models respectively. The panels show that in all our models, the contribution from stripped stars to the cosmic emission rate of H\textsubscript{i}-ionizing photons is relatively large. The range of metallicity gives rise to a small spread in the emission rates of
6 The contribution from stars stripped in binaries to the reionization of hydrogen and helium

Figure 6.2: The rate with which ionizing photons reach the intergalactic medium. Panel a, b, and c show the rate for H\text{\textsc{i}}-ionizing photons and panel d, e, and f for H\text{\textsc{ii}}-ionizing photons. The top row show the results for our standard model, the middle for our optimistic model, and the bottom for our pessimistic model (see Table 6.1). We show the contribution from stripped stars in dark blue, from massive stars in light blue, and from AGN in brown. The extent of the colored regions represent the spread that metallicity variations give rise to.
6.3 Ionizing emissivity over cosmic time

H\textsubscript{i}-ionizing photons, however, we note that a difference of a factor of two can have important consequences for the predictions for when reionization occurred and which sources provided the ionizing photons.

The flatter slopes of the cosmic emission rate of H\textsubscript{i}-ionizing photons compared to our other models match slightly better with the photoionization rate of the IGM, which has been observed to be remarkably flat (e.g., Becker & Bolton 2013). This could suggest that the escape fraction indeed increases with higher redshift.

Figure 6.2d-f show the emission rate of He\textsubscript{ii}-ionizing photons from the individual sources over cosmic time and for our three models. As indicated earlier, metallicity impacts the emission rate of He\textsubscript{ii}-ionizing photons from stellar populations and gives rise to a large the range of emission rates of He\textsubscript{ii}-ionizing photons for each point in time. We follow the metallicity-redshift relation of Madau & Fragos (2017), but note that the importance of stripped stars and massive stars may vary significantly. However, in all cases, AGN are responsible for most of the emitted He\textsubscript{ii}-ionizing photons as they dominate the emission for a large interval in time. However, at very high redshifts, $z \gtrsim 10$, stripped stars and massive stars can have dominated the output of He\textsubscript{ii}-ionizing photons.

6.3.2 Spectral energy distribution of the cosmic emissivity

The integrated spectrum of the radiation that emerges from galaxies into the IGM contains imprints from the sources that produced the ionizing radiation. The hardness of the ionizing radiation can, for example, be used to infer which type of source that emitted the radiation as the different sources are characterized by different spectral shapes. We show the integrated spectrum of the ionizing emissivity for four snapshots in the cosmic history in Fig. 6.3. The figure displays the emerging emissivities of stripped stars, massive stars, and AGN at redshifts $z = 1.7, 4.3, 7, and 11.7$ and in units of erg s$^{-1}$ Hz$^{-1}$ per co-moving cubic Mpc. The emissivity, $\epsilon$, is here defined as the ionizing spectrum integrated over all sources within a co-moving cubic Mpc. We model the emissivity in a similar fashion as the production rate of ionizing photons (see Eq. 6.1) by multiplying the average wavelength dependent luminosity of stellar populations, $L_\nu$, with the cosmic star-formation rate. In Fig. 6.3, we highlight the additional radiation that stripped stars contribute with as a dark green band. To create the figure, we used spectra for continuous star-formation during 1 Gyr. After such long time, the spectrum has since long reached equilibrium in the ionizing wavelengths.

With their hard, ionizing spectra, stripped stars cause the total emerging emissivity from stellar populations to harden. The effect is primarily important for $z \lesssim 7$ and it becomes larger with decreasing redshift, as seen in Fig. 6.3. At $z \sim 2$, stripped stars cause the emission to harden from a spectral index of $\sim -3$ to $\sim -1$ for photon energies smaller than about 50 eV. The effect is similar up to $z \sim 4$, and at $z = 7$, the spectral index is increased by about 0.5.

The panels of Fig. 6.3 show how the ionizing emission increased as the Universe grew older. With lower redshift, the average metallicity increased, causing the emission from massive stars to soften from spectral indices of $\alpha = -2$ to $\alpha = -3$. However, when stripped stars
The contribution from stars stripped in binaries to the reionization of hydrogen and helium

Emerging ionizing spectrum

Figure 6.3: Spectral energy distribution of the ionizing radiation that emerge into the intergalactic medium during cosmic evolution. We show the contribution from stellar populations in green shades and from AGN in gray. The contribution from stripped stars is highlighted in dark green. They cause the spectra to harden. The dashed lines show spectral slopes of $\alpha = -3$, $-2$, and $-1$, assuming $L_\nu \propto \nu^\alpha$. The panels represent four snapshots during cosmic evolution, taken at $z = 1.7$, $4.3$, $7.0$, and $11.7$. Following the relation between metallicity and redshift of Madau & Fragos (2017, see also Sect. 6.2.1), the average metallicity at these times is $Z = 0.014$, $0.006$, $0.002$, and $0.0002$. This figure adopts our standard model for the escape fractions, see Table 6.1.

are accounted for, this effect is washed out and the spectral index from stellar populations remains at $\alpha = -2$ or even higher values.

The influence of AGN is small for the hardness of the H$\alpha$- and He$\alpha$-ionizing spectrum. At these wavelengths, stellar populations dominate at all times in our model. However, the He$\alpha$-ionizing emission is dominated by AGN for most of the cosmic evolution. Only at very high redshifts, $z \gtrsim 10$, stellar populations dominate the emission of He$\alpha$-ionizing photons. It is likely that the contribution from stellar populations is larger than what our models predict at these high redshifts. The reason is that a spread of metallicities exist at each point in time, which allows for a larger contribution from stripped stars, while our models assume an average metallicity for each point in time. We also note that other sources of ionizing radiation may affect the hardness of the ionizing spectrum. Rotating massive stars could cause the H$\alpha$- and He$\alpha$-ionizing emission to be slightly harder (see e.g., D’Aloisio et al. 2018), while accreting white dwarfs and X-ray binaries could affect the hardness of the He$\alpha$-ionizing emission (Chen et al. 2015; Madau & Fragos 2017).

The escape fraction is slightly wavelength dependent, as higher energy photons have longer mean-free paths and thus easier escapes the host galaxies (Osterbrock & Ferland 2006). The result is that the spectrum that emerges into the IGM is harder than the spectrum the stars produced. However, it is not yet clear how large the effect of a wavelength dependent escape fraction is. If photons escape through large holes in the galactic gas, the emerging radiation is not hardened since no gas is hindering their propagation. We do not account for the wavelength dependence of the escape fraction, meaning that the ionizing emissivity is likely harder than what our models predict.
6.4 Reionization including stripped stars

Here, we present the results of our standard model for the cosmic evolution of the fraction of hydrogen and helium that is ionized in the IGM.

**Hydrogen reionization**

We show how the volume filling factor of ionized hydrogen, $x_{\text{H}_\text{II}}$, increases with decreasing redshift in Fig. 6.4. We find that hydrogen reionization occurs about 100 Myr earlier when stripped stars are included, which corresponds to about 10% of the total age of the Universe at the time. In our models H$I$-reionization occurs at $z \sim 5$ if stripped stars are not included, but at $z \sim 5.8$ if they are. The impact of stripped stars is small at early times, but they become important as hydrogen reionization progresses. At redshift $z = 12$, about 25% of the Universe is reionized independent on whether stripped stars are included, but when hydrogen is
completely reionized in the model including stripped stars, only 80% of the IGM is reionized if stripped stars are not included. As shown in Table 6.2, the effect of the choice of escape fraction is large for the time of reionization. However, in all models, stripped stars give rise to earlier reionization.

To evaluate the total relative importance of the different ionizing sources to the reionization of hydrogen, we integrate the individual contributions to the cosmic emission rate of H\emissionline{i}-ionizing photons from the early Universe up to the end of reionization. The resulting contribution from stripped stars to the budget of H\emissionline{i}-ionizing photons prior to the reionization is about 30% in all our models.

Figure 6.5 shows the relative contribution from the different ionizing sources to the budget of H\emissionline{i}-ionizing photons, measured from the early Universe up until the completion of reionization at $z = 5.8$ for our standard model. The figure shows that stripped stars played an important role as contributors with ionizing photons during the reionization of hydrogen. Massive stars were the most important, producing about 65% of the ionizing photons. In our models, AGN are less important as sources of H\emissionline{i}-ionizing photons and produce only about 5% of the photons that reionized the Universe. We also show the evolution of the relative contributions from the different ionizing sources to the total number of produced H\emissionline{i}-ionizing photons in Fig. 6.6a. This figure shows that the importance of stripped stars increased with the age of the Universe.

The contribution from AGN has been debated and several models consider a higher number density of AGN at earlier times, which leads to a larger contribution (e.g., Giallongo et al. 2015; Madau & Haardt 2015). However, higher emission from AGN at early times leads to earlier reionization of helium than what has been observed because of the hard spectra of AGN.

Our models concern only stripped stars with progenitors of $\leq 20 M_\odot$, which excludes the contribution from higher mass stripped stars that could provide an extra boost of ionizing emission. The models are also made for stable mass-transfer, which likely leads more of the hydrogen-envelope to remain compared to what is expected from the violent common envelope evolution (cf. Ivanova 2011; Yoon et al. 2017; Chapter 2). The difference is small at high metallicity, but is likely significant for low-metallicity environments. To accurately account for this effect, more detailed evolutionary models are required.
6.4 Reionization including stripped stars

HI-reionization

\((z = 5.8)\)

![Pie chart showing the relative contribution of ionizing photons from stripped stars, massive stars, and AGN to HI-reionization. Stripped stars contributed with a third of the HI-ionizing photons.](image)

Figure 6.5: The relative contribution of ionizing photons from stripped stars (dark blue), massive stars (light blue), and AGN (beige) to the photon budget that caused hydrogen reionization. Stripped stars contributed with a third of the HI-ionizing photons, see Sect. 6.4. This figure shows the results from our standard model, see Tables 6.1 and 6.2.

In BPASS, the inclusion of binary products results in 20% to 70% higher emission rates of hydrogen ionizing photons depending on the considered metallicity (see the yields of ionizing photons presented in Fig. D.1). This is higher than the addition we predict for stripped stars, which produce about 5% more ionizing photons than what is predicted for massive stars. The reason for the higher emission rate in BPASS compared to our models is that BPASS accounts for efficient rotational mixing and subsequent chemically homogeneous evolution of low-metallicity stars that accreted material or merged with its companion star (Eldridge et al. 2017). In consequence, BPASS predicts complete reionization for low escape fractions within the observed timescale or even gives rise to early reionization (Ma et al. 2016; Rosdahl et al. 2018). This shows that the effect of chemically homogeneous stars is significant if indeed rotational mixing is as efficient as models predict.

Helium reionization

Our models indicate that stripped stars contributed with in total only 2% of the photons that fully reionized helium. This means that the time of helium reionization is not affected and our
models reach complete helium reionization at $z \sim 3$. The main producer of the HeII-ionizing photons that caused helium reionization in our models is AGN.

We show the relative contributions to the budget of HeII-ionizing photons from the different ionizing sources that we consider in Fig. 6.6b. The figure shows that the contribution from stellar populations was dominating before $z \sim 10$ and between $z \sim 6 - 8$, stripped stars were responsible for about 10% of the HeII-ionizing photons that reached the IGM. This means that the early emission of HeII-ionizing photons could have resulted in pre-heating of the
IGM before the reionization of helium was complete. In our standard model, the reionization of helium starts around $z = 5$, when slightly more than 10% of the intergalactic helium has been fully reionized.

### 6.5 Observable consequences

Stripped stars cause the ionizing radiation that emerges into the IGM to be harder than what is expected from single star models (see Sect. 6.2.1 and Fig. 6.3). The harder emission has implications for the conditions in the IGM over cosmic history, which in some cases may affect observable quantities (for a review, see Fan et al. 2006a). Here, we discuss the impact of stripped stars on intergalactic metal absorption features and the temperature evolution of the IGM. The hard ionizing radiation produced by stripped stars likely impacts the conditions within the host galaxy and therefore the emerging spectrum (see Chapter 5).

Our models do not account for the contribution from other products of binary interaction, which can also increase the hardness of the emerging spectrum. In particular, the soft X-rays emitted by accreting compact objects could cause spectral hardening.

#### 6.5.1 Highly ionized absorbers in the IGM

Highly ionized species such as C\textsc{iv} and Si\textsc{iv} have been observed in the high-redshift IGM via absorption features in the spectra of background quasars (e.g., Ryan-Weber et al. 2006, 2009; D’Odorico et al. 2013; Doughty et al. 2018). The metals are likely expelled from galaxies via large-scale outflows, which explains that they are detected in small and dense clumps that likely indicate the location of a galaxy. The intergalactic metals are then ionized by radiation emitted by the galaxy, reaching various levels of ionization depending on the hardness and intensity of the ionizing radiation.

The observed abundance of C\textsc{iv} is in some cases unexpectedly high compared to what cosmological simulations predict (e.g., Finlator et al. 2016; Doughty et al. 2018). A reason could be that the emission from galaxies is harder than what is assumed for the galaxy spectra, but also the density of the nearest IGM may play a role (D’Odorico et al. 2013).

Stripped stars harden the ionizing radiation that emerges from galaxies and their effect on the intergalactic metals is therefore an interesting topic. The ionization thresholds of Si\textsc{iii} to Si\textsc{iv} and C\textsc{iii} to C\textsc{iv} are both within the He\textsc{i}-ionizing energy range at 33 eV and 48 eV (see e.g., Fig. 7 of Chapter 5). Stripped stars contribute significantly in to radiation within this energy range, as seen in Fig. 6.3. Our models suggest that stripped stars boost the flux at these energies by a factor of a few up to ten, depending on the metallicity of the stellar population. Detailed radiative transfer modeling is needed to accurately determine the influence from stripped stars on the ionization state of the IGM.
6.5.2 Temperature of the intergalactic medium

During reionization, the IGM was heated by excess photon energy after each ionization and simultaneously cooled through line excitations and collisional ionization from to photoelectrons (Miralda-Escudé & Rees 1994). Harder spectra of the ionizing sources leave, therefore, imprints on the IGM in terms of higher temperatures. After reionization is complete, the IGM cooled again, reaching temperatures of about $7,000 - 10,000$ K at $z \sim 5$ (Becker et al. 2011; Boera et al. 2014; Iršič et al. 2017).

With the hardening of the ionizing spectrum when stripped stars are considered, the IGM may reach 1,000 up to 5,000 K higher temperatures depending on the speed with which the ionization fronts move (cf. Fig. 2 of D’Aloisio et al. 2018, see also Upton Sanderbeck et al. 2016).

Stripped stars may therefore affect observables for the temperature of the IGM. Including stripped stars could lead to broader lines in the thermally broadened Ly$\alpha$ forest (Bolton & Haehnelt 2007a). An observed increase in the IGM temperature beyond $z \sim 5$ may, however, be interpreted as a late reionization or that the ionization fronts move at a faster speed.

The ionization fronts during reionization cool via collisionally excited Ly$\alpha$ emission and with a higher temperature the line emissivity of Ly$\alpha$ is expected to increase (Cantalupo et al. 2008). We estimate that the increased temperature that stripped stars give rise to can cause an increased Ly$\alpha$ emissivity of about a factor ten (see Fig. 1 and Eq. 6 in Cantalupo et al. 2008, also Davies et al. 2016). However, the Ly$\alpha$ emission from cooling ionization fronts during the reionization is expected to be very weak and difficult to detect (Silva et al. 2013; Pullen et al. 2014; Davies et al. 2016). Foreground Ly$\alpha$ emission is also expected to hamper the detection of the IGM signal (however, see Comaschi & Ferrara 2016). The weak signal from the reionizing IGM is predicted to be detectable with instruments equipped with higher sensitivity than current, such as the proposed space mission SPHEREx (Kovetz et al. 2017).

6.6 Summary & Conclusions

We estimate the contribution from stars stripped in binaries to the budget of photons that caused cosmic reionization of hydrogen and helium. We used detailed spectral models custom-made for stripped stars (Chapter 3). We combine the radiative contribution from stripped stars to stellar populations (Chapter 5) with a simple method to calculate the cosmic evolution of the volume filling factors of ionized hydrogen and helium. We account for the cosmic star-formation history, the recombination timescales, the intergalactic density of hydrogen and helium, and assumed clumping of the intergalactic medium. We consider three models for the escape fraction, given that it is an uncertain parameter.

Our models show that stripped stars cause the ionizing radiation that emerges into the IGM to be harder than what is expected from single stars. We also find that the additional ionizing photons that stripped stars provide constitute about a third of all the photons that led to hydrogen reionization and that they caused hydrogen reionization to occur about 100 Myr
6.6 Summary & Conclusions

earlier than when stripped stars are not accounted for.

We summarize our conclusions as follows:

1. Stripped stars cause the emerging spectra from galaxies to harden. At solar metallicity, the slope of the ionizing part of the spectrum can harden from a spectral index of $-3$ to $-1$ if stripped stars are included.

2. Our models suggest that stripped stars provided about 30% of the photons that reionized hydrogen in the Universe. The estimate is sensitive to variations of the escape fraction, while the uncertainties for binary interaction and the emission rates of $\text{H}_\text{i}$-ionizing photons from stripped stars are expected to be small.

3. The ionizing emission from stripped stars is not sufficient to significantly impact the complete reionization of helium. However, the stripped stars could have contributed to pre-heating of the IGM between $z \sim 6 - 8$.

4. The harder ionizing radiation that stripped stars introduce to the spectra of galaxies could give rise to high ionization levels of gas that surrounds the galaxies. This could explain the unexpectedly high abundance of $\text{C}\text{iv}$ that has been detected in dense regions at $z \sim 6$ (see e.g., D’Odorico et al. 2013).

5. The harder spectra that we expect from stellar populations because of the presence of stripped stars likely lead to an increased temperature of the intergalactic medium during the reionization of hydrogen. We estimate that the effect of accounting for stripped stars is an increase of 1 000 to 5 000 K. The increased temperature could lead to broader absorption lines in the $\text{Ly}\alpha$ forest and an increased emissivity of $\text{Ly}\alpha$ from cooling ionization fronts.

In anticipation of the large amount of spectra that James Webb Space Telescope (JWST, Gardner et al. 2006) will acquire, we need to develop more sophisticated spectral synthesis models that account for different types of stars in order to interpret the spectra of unresolved stellar populations. In this paper, we focused on the contribution from stars stripped in binaries to the budget of ionizing photons during the Epoch of Reionization. Other binary products that we have not accounted for here likely also contribute to the ionizing emission from stellar populations. Further detailed modeling for the spectra for these stars is needed to study their relative contributions.