The properties and impact of stars stripped in binaries
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Introduction
1 Introduction

Our nearest star, the Sun, is making life on Earth flourish. But this will not continue forever. By observing other stars, designing models, and comparing with their predictions, we know that, in approximately five billion years, the Sun will swell up to several hundred times its current size as it becomes a red giant (Schröder & Connon Smith 2008). The fate of the Earth is debated, but life on Earth as we know today will no longer be possible. The Sun is not special in this sense, since astronomers believe that most stars expand as they evolve and grow older.

But not every star is like the Sun. The Sun spends its life alone, but observations suggest that about half of all the stars as massive as the Sun live in couples, they are orbiting with a companion star (Duchêne & Kraus 2013; Moe & Di Stefano 2017). Binary systems are more common among massive stars. For stars more massive than about fifteen times that of the Sun, most stars have at least one and possibly more companion stars (Abt & Levy 1978; Kobulnicky & Fryer 2007; Eggleton & Tokovinin 2008; Mason et al. 2009; Chini et al. 2012; Sana et al. 2012, 2014; Kobulnicky et al. 2014).

The evolution of close binary stars can be radically different from the evolution of single stars as they may exchange a large amount of material and angular momentum, experience extreme mass-loss from the system, or even merge into one object. As a star that is orbiting around a companion star in a binary system expands, the outer layers of that star feel stronger gravitational attraction to the other star than to itself, if the companion is sufficiently close. As a result, the expanding star deforms into a drop-shape and material starts flowing to its companion. The drop-shape is referred to as a Roche-lobe (Roche 1873) and the mass-transfer as Roche-lobe overflow (RLOF, Kopal 1955; Paczyński 1966). Stars have been observed during mass-transfer (for example, the system β Lyrae, Zhao et al. 2008), and even in the process of merging (for example, the case of V1309 Sco, Tylenda et al. 2011).

At the time that mass-transfer is initiated, the star that loses mass has typically developed a compact core in its center due to the fusion of hydrogen to helium. During mass-transfer, the dilute and hydrogen-rich envelope that surrounds the core is either transferred to the companion or expelled from the system (e.g., Paczyński 1971b). The helium core is exposed, with just a small amount of the hydrogen-rich envelope left (Yoon et al. 2017; Chapter 2). Throughout this thesis, we refer to such stars as stripped stars, however, sometimes they are also referred to as helium stars.

Stars can also lose their hydrogen-rich envelopes if they have a strong stellar wind that removes material from the surface (Conti 1976, see Smith 2014 for a more recent review). The resulting exposed stellar core is, in this case, known as a Wolf-Rayet (WR) star (Wolf & Rayet 1867, see Crowther 2007 for a review).

Because stripped stars are the compact helium cores of their progenitors, they are very hot. The photons that they emit are therefore highly energetic and can ionize both hydrogen and helium (see Chapters 2 and 3). Ionizing radiation is not only hazardous for humans, it may also hinder star-formation and destroy stellar clusters (e.g., Krumholz et al. 2006; Dale et al. 2012, for a review, see McKee & Ostriker 2007). Mild doses of ionizing radiation may even be crucial for the formation of planets (e.g., Gammie 1996). Ionizing radiation greatly
affects the light emitted by stellar populations and is generally thought to be responsible for the phase change of the Universe known as the Epoch of Reionization, during which intergalactic hydrogen was ionized (see Loeb & Barkana 2001, for a review).

In this thesis, we primarily investigate the formation and properties of stripped stars. We give special focus to the ionizing photons that stripped stars emit because of the consequences they have on small and large scales in the Universe.

1.1 Modeling stripped stars

1.1.1 Sixty-five years of computing models for stripped stars

The first numerical calculations for the structure of stars that are composed purely of helium go back to the pioneering work by Crawford (1953), Oke (1961), and Cox & Giuli (1961). They constructed equilibrium models for pure helium stars powered by helium burning through the triple alpha reaction. Cox & Salpeter (1961) already discussed the structure of helium stars with a thin layer of hydrogen on top and showed that this leads to lower temperatures for the stripped star (cf. Chapter 2). The first model grid of the evolution of helium stars was created by Neil Divine as part of his PhD thesis (Divine 1965a,b). In his pioneering paper he showed the evolution of three helium stars with masses of 0.5, 1, and $6M_\odot$. Whether such helium stars actually existed remained an open question at the time. However, these early authors did express the hope that their models would serve as a step toward the eventual understanding of various types of hot stars, including Wolf-Rayet stars, the central stars of planetary nebulae, narrow-line O-type subdwarfs and possibly the stars at the extreme blue end of the horizontal branch. The mechanism by which such stars would form was also not yet known. Cox & Giuli (1961) speculated that they can form through mass loss or through contraction of a helium cloud. They do mention that they believed the second mechanism to be unlikely, an assessment with which we would agree today. Formation as a result of mass-loss is the favored modern explanation.

Only two years after the grids from Divine, Kippenhahn & Weigert (1967) presented the evolution of a $9M_\odot$ star that loses its envelope through mass-transfer to a companion star. They concluded that the star had become "almost a helium star" as it still had a small amount of the hydrogen envelope left.

Since these very earliest efforts, several studies have addressed the properties and evolution of stripped stars, including Paczyński (1967); Kippenhahn (1969); Ziolkowski (1969); Paczyński (1971a); Biermann & Kippenhahn (1971); Yungel’Son (1973); van den Heuvel (1976); De Greve & De Loore (1976); Vanbeveren et al. (1979); Iben & Tutukov (1985); Habets (1986); Dewi et al. (2002a); Dewi & Pols (2003); Tauris et al. (2013), and Tauris et al. (2015). With further increase of computing power and improved input physics, the new models are more sophisticated, accounting for large networks of nuclear reactions and treating details of specific evolutionary scenarios.
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At present, several grids of evolutionary models for stripped stars exist (see e.g., Eldridge et al. 2008; Yoon et al. 2017, and references therein). However, appropriate atmosphere models that match the surface properties of stripped stars were scarce. Stellar spectra are formed in their atmospheres, and these spectra provide the vast majority of the observational information about individual stars. So such atmosphere models are indispensable if we want to connect our evolutionary models to the details of the light from such stars. Only few individual models existed (Han et al. 2007; Groh et al. 2008; Kim et al. 2015). The available spectral model grids primarily focused on the very low-mass subdwarfs or the much more massive Wolf-Rayet stars. One of the objectives of this thesis was to fill the gap for lacking atmosphere models for intermediate masses (Chapter 3).

1.1.2 Computational techniques used in this thesis

We make use of different numerical codes; an existing evolutionary code, an existing atmosphere code, and a custom-made population synthesis code written specifically for the purpose of this thesis. We briefly describe these codes below.

Evolutionary modeling

For modeling the evolution and spectra of stripped stars, we use the 1D binary stellar evolution code MESA (Paxton et al. 2011, 2013, 2015, 2018). MESA iteratively solves the equations of stellar structure, while accounting for large networks of nuclear reactions and opacities covering a wide range of compositions (see Paxton et al. 2011). MESA can model interactions in binaries, including processes such as envelope-stripping, mass-accretion, and tidal interaction (Paxton et al. 2015). MESA describes the evolution of the interior structure of stars (e.g., temperature, pressure, and chemical composition as a function of radius or mass coordinate) and gives approximations for stellar properties, such as the effective temperature, radius, surface gravity, and bolometric luminosity. Convection is simulated by adopting the mixing-length theory (Böhm-Vitense 1958), which is implemented by approximating the degree of mixing within convective regions as a process of diffusion. Mixing beyond the boundary of the convectively unstable region is controlled by free parameters. The development of a more self-consistent approach is an active area of research (Renzini 1987; Arnett et al. 2018).

During binary interaction, the stars can be non-spherical, yet MESA approximates the evolution of the stars to 1D. Even though interacting binaries are 3D systems, we are limited to 1D calculations because 3D is at present too computationally expensive if we want to follow the long timescales on which the nuclear reactions change the stellar interiors and the surface and global properties. The 1D approximation is expected to provide realistic results, since the evolution of the star is driven by the nuclear reactions, which take place deep in the interior of the star where the potential surfaces are well-described as spheres. However,
mixing induced by aspherical morphologies could affect the evolution of interacting binary stars in a way that 1D models do not yet account for.

### Atmosphere modeling

Although evolutionary models can predict the basic surface properties of stars, they do not make detailed predictions for their spectral energy distributions. To make such predictions, one needs to model the structure of the stellar atmosphere and the way light transfers through the atmosphere layer. This yields detailed profiles of spectral lines, the distribution of the continuum light and the production rate of ionizing photons.

To model the atmospheres of stripped stars, and in particular the emerging spectra that can be observed, we use the 1D radiative transfer code CMFGEN (Hillier 1990; Hillier & Miller 1998). CMFGEN has been originally developed to model the atmospheres of hot stars and can treat strong and opaque stellar winds and regions that are out of local thermodynamic equilibrium (non-LTE). The code uses tables of atomic data and iteratively solves the radiative transfer equation over an adaptive mesh of mass coordinates distributed radially in the stellar wind. The code takes as input the velocity structure of the wind up to the maximum wind speed that is expected. Once convergence is reached, CMFGEN provides a stationary solution for a smooth outflow. The properties of the stellar wind are of key importance for the morphology of the resulting stellar spectrum. A high wind mass-loss rate, for example, gives rise to emission line formation in the stellar wind, which are characteristic to WR stars.

For our models of the spectra of stripped stars, we use the surface properties predicted by the evolutionary models of MESA as the most realistic assumption for the conditions at the base of the stellar wind. In absence of mass-loss measurements specifically for stripped stars, we use the empirical recipe of measurements for WR stars from Nugis & Lamers (2000) for stripped stars with progenitor masses above $7 M_\odot$ and the theoretical algorithm made for subdwarfs from Krtička et al. (2016) for the lower mass end. It is likely that high-mass stripped stars have lower wind mass-loss rates than what we assume, since stripped stars are not as affected by strong internal radiation pressure as WR stars (i.e., they are not close to the Eddington limit; Bestenlehner et al. 2014; Vink 2017). However, the mass-loss rate from stripped stars is still debated and largely unknown. A reason could be that the observed stripped star HD 45166 has a similar mass-loss rate to what the Nugis & Lamers (2000) recipe suggests (Groh et al. 2008), indicating that the mass-loss rate from stripped stars could follow the same relation as WR stars.

### Spectral synthesis of stripped stars

A spectral synthesis code simulates the radiative output from stellar populations based on evolutionary models and spectral models for stars. Spectral synthesis codes are particularly useful for analyzing the radiation from unresolved stellar populations, such as high-redshift galaxies, and provide estimates for the age, mass, or star-formation rate of the stellar popu-
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lation. Creating spectral synthesis codes started early (see Tinsley 1968). Modern codes are sophisticated, and, for example, include a variety of stellar types, cover a range of metallicities (see e.g., GALAXEV, Bruzual & Charlot 2003), account for effects of stellar rotation (e.g., STARBURST99, Leitherer et al. 1999, 2010, 2014), and simulate the effects of binaries (e.g., BPASS, Eldridge & Stanway 2009; Eldridge 2012; Eldridge et al. 2017). A more extensive overview is given in the introductory section of Chapter 5.

Spectral synthesis codes are based on population synthesis codes, which simulate the number of stars of different types and of different masses that are present in a stellar population. Typically, the initial number of stars of certain masses is determined by an initial mass function (IMF, see e.g., Salpeter 1955; Kroupa 2001), and the evolution of the stars is then approximated by interpolating the properties calculated in evolutionary models over mass. When the evolution of binaries is included, the code takes into account initial distributions of the binary fraction, the period distribution, the distribution of mass ratios, and in some cases also the distribution of orbital eccentricity. When and what type of interaction that is initiated is then decided by comparing the radius evolution of the two stars in each binary with the sizes of their Roche lobes. Most current binary population synthesis codes are advanced and sometimes tailored to particular research topics, but they are commonly based on the Binary Stellar Evolution (BSE) code of Hurley et al. (2000, 2002). What spectral synthesis additionally does is to assign a spectrum to each star at each point in time (see e.g., Conroy 2013, for a review).

To represent the radiation from stripped stars, we developed a spectral synthesis code specifically to meet the objectives of this thesis. It is tailored for stripped stars and we describe it in more detail in the modeling section of Chapter 5. The code is based on the evolutionary and spectral models that we created for stripped stars and that are presented in Chapter 3. It simulates the number and type of stripped stars that are present in a stellar population together with their integrated contribution to the spectral energy distribution of the full stellar population. From the spectral energy distribution we also measure the total emission rate of ionizing photons.

Since our code only estimates the radiative contribution from stripped stars and does not account for single stars and binaries that have not yet interacted, we use STARBURST99 (Leitherer et al. 1999, 2010, 2014) to represent the radiation from the remaining stars in the stellar population. STARBURST99 is a well established code that models the radiation from a population of single stars. The addition of the contribution from stripped stars is not fully accurate as we assume that some of the red giants have become stripped stars, which is not accounted for in STARBURST99. However, because red giants are very cool stars, we do not expect significant changes for wavelengths that are shorter than \( \sim 6000 \text{ Å} \) and therefore does this approximation not affect the ionizing output from the stellar population. To accurately model the radiative contribution from binary products, we would need to also account for mass-gainers and merger products for example, which is a topic of further investigation.
1.2 Formation of stripped stars

Envelope-stripping through binary interaction creates stripped stars over the full mass and metallicity range. In contrast, for single stars, stripped stars can only result from stellar winds or eruptive mass loss. This limits the formation of stripped stars to the most massive stars. In this thesis, we focus on stars stripped in binaries, that are long-lived, i.e., the stripped phase lasts for at least about 10% of the total lifetime of the progenitor star. This can only be achieved if the star is stripped prior to the completion of central helium burning. We distinguish the following three main formation channels:

**Channel 1:** Mass-transfer initiated when the donor is still a main-sequence star (Case A)

**Channel 2:** Mass-transfer initiated after the donor has completed the main-sequence, but prior to its depletion of helium in the center (Case B).

**Channel 3:** Common envelope evolution that is initiated after the donor has completed the main-sequence, but prior to its depletion of helium in the center.

We visualize these formation channels of stripped stars in Fig. 1.1, inspired by van den Heuvel’s explanatory diagrams (see e.g., van den Heuvel 1976). In the first two channels,
the accretor star either accretes the transferred material or successfully expels it from the system. The result can be that the accretor gains mass, rejuvenates, and starts spinning rapidly (e.g., Packet 1981; Braun & Langer 1995). The stripped stars resulting from channel 1 typically have somewhat lower masses than those resulting from channel 2 (e.g., Pols 1994). In the third channel, a common envelope develops after unstable mass-transfer. The accretor star and the core of the donor star spiral closer together, releasing orbital energy to the envelope during the process. With the extra energy, the common envelope can potentially be fully expelled and a stripped star is left in orbit with a close companion star (Paczynski 1976; for a review, see Ivanova et al. 2013).

It is also possible that stars lose their envelopes after helium is depleted in the center, however, the stripped star is then short-lived. This makes them less common in stellar populations and their effect on the surroundings is therefore smaller. In rare cases, envelope-stripping occurs via eruptive processes in the very last evolutionary stages of a very massive star’s life. Examples are large eruptions (Smith et al. 2004; Smith & Owocki 2006), pulsations created from pair-production that give rise to instabilities inside the star (pulsational pair instability, PPI, e.g., Woosley 2017), or internal gravity waves triggered by strong convection zones deep inside the star (e.g., Yoon & Cantiello 2010; Shiode & Quataert 2014; Fuller 2017). Such stripped stars live for even shorter. Here, we focus on the channels that produce long-lived stripped stars.

1.3 Properties of stripped stars

Stripped stars are typically small ($\lesssim 1 R_\odot$), hot ($\gtrsim 30,000$ K), hydrogen-poor, helium-rich, and span a range of luminosities ($1 \lesssim \log_{10}(L/ L_\odot) \lesssim 5$) (see Chapters 2 and 3, and references therein). The properties of stripped stars are primarily determined by their mass and they are almost independent of the formation channel. The stripped star is affected by the formation channel in just a few cases, for example at very low metallicity (cf. Chapter 2) or when mass-transfer is initiated in binaries which have long periods (Claeys et al. 2011; Yoon et al. 2017; Sravan et al. 2018).

Because many stars are in close binary systems, envelope-stripping is a common evolutionary pathway. Sana et al. (2012) estimate, based on observations of the binary fraction among massive stars, that 30 % of stars more massive than $15 M_\odot$ become stripped. This is consistent with the fraction of massive stars that have been observed to end their lives as a stripped-envelope supernovae, which also is about one third (Smith et al. 2011; Graur et al. 2017b). If we, for simplicity, assume that the companion star ends up with a similar mass as the progenitor of the stripped star, this would mean that a third of all massive stars hosts a stripped companion at some point during their evolution. If we also consider a constant star-formation rate and that stars spend about 10 % of their lifetimes as stripped, then this means that a few percent of all massive stars should currently have a stripped companion.

We now illustrate the importance of binary interactions over a broader mass range. To do this, we present an estimate of the fraction of stars that, for a given initial mass, go through
envelope-stripping or experience coalescence. We use an evolutionary model grid of single stars and take the same assumptions for the initial conditions and formation of stripped stars as in our population synthesis code, as we describe in Chapter 5. In particular, we use a mass dependent binary fraction by Moe & Di Stefano (2017). We show the result for the most massive stars in binary systems and single stars in Fig. 1.2.

The main message of Fig. 1.2 is that binary interaction is very common. In the case of \( \gtrsim 15 \, M_\odot \) stars, more than 80 \% interact, while about 20 \% of the 2 \( M_\odot \) stars interact. Envelope-stripping is the most common type of interaction for stars with masses \( \gtrsim 5 \, M_\odot \) and Case B type mass-transfer is the dominating channel. We note that the estimates depend on detailed assumptions for the stability of mass-transfer and the outcome of common envelope evolution. We take a simplified approach for the creation of Fig. 1.2 and the fraction of stripped stars created via common envelope evolution is therefore overestimated.
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One may think of a single star as normal, of binary stars as special cases, and of binary products as exotic objects, but Fig. 1.2 shows that this is not the case. Binary interaction is common, therefore, envelope-stripping is not a rare phenomenon and stripped stars are not exotic. From observations a different picture arises. Just a few stripped stars have been observationally confirmed (Gies et al. 1998; Groh et al. 2008; Peters et al. 2008, 2013; Wang et al. 2017; Chojnowski et al. 2018, see also recent candidates from Wang et al. 2018). This discrepancy is sometimes referred to as the (apparent) paradox of the missing stripped stars. To resolve this paradox, the obvious first questions are whether the models are accurate and if the observations are subject to biases and selection effects.

The paradox of the missing stripped stars

According to models, stars stripped in binaries are expected to be common. However, only a handful of them have been observed. Theoretical predictions and observations are currently in contradiction.

The predictions from the models are based on observations of the binary fractions and distributions of the initial period and mass ratio. These observations have relatively tight constraints by now and the uncertainties are expected to be small (Moe & Di Stefano 2017). The process of mass transfer has been observed, for example in the system β Lyrae (Zhao et al. 2008), and there are observed systems that must have experienced mass transfer, such as φ Persei (see Gies et al. 1998; Schootemeijer et al. 2018). However, the fraction of systems that successfully form stripped stars have not yet been probed observationally.

These considerations have led to the expectation that the resolution of this apparent paradox lies in an underestimation of the biases. Because stripped stars are so hot, they are faint in visible light, but bright in the UV and the ionizing extreme UV light. The companion stars are cooler and, therefore, bright in visible light. In Chapters 2 and 3, we discuss the possibility that a large fraction of the stripped stars are hidden by their companion stars in this way.

1.4 This thesis: outline and summary

In this thesis, entitled The properties and impact of stars stripped in binaries, we address the formation and properties of stars stripped in binaries. Our study is theoretical, but one of our primary objectives has been to provide concrete predictions that can be tested against observations. This includes observations of nearby star-forming regions where individual stellar systems can be observed and resolved (Chapters 3 and 4), but also distant stellar populations where we have to work with the integrated spectra (Chapter 5) or the effects that
1.4 This thesis: outline and summary

Individual stripped stars
Chapter 2, 3 & 4

Stripped stars in populations
Chapter 5

Cosmological impact of stripped stars
Chapter 6

Figure 1.3: A graphical summary and outline of this thesis. Image credits: ESO, Kornmesser & de Mink (artist’s impression of massive binary during mass-transfer phase), Hubble Space Telescope (image of the low-metallicity galaxy IZw18), and Kaehler, Alvarez & Abel (visualization of hydrogen reionization from simulations published in Alvarez et al. 2009).
stripped stars have through their ionizing radiation, for example, during the reionization of the Universe (Chapter 6).

Our focus is, in particular, on the ionizing emission from stripped stars. Ionizing radiation is important for a variety of astrophysical research fields. Ionizing radiation creates HII regions around individual stars that expand into the interstellar medium. The bulk of ionizing photons produced by hot stars create giant HII regions and power a diffuse field of extreme UV radiation in galaxies as a whole. Such photons can, for example, dissociate molecules and charge dust particles. The ionized gas in the HII regions shines, sometimes very brightly (see e.g., the Green Pea galaxies, Cardamone et al. 2009), in certain emission lines of ionized elements, which provides information about the local conditions as well as the ionizing sources. In a cosmological perspective, ionizing radiation caused cosmic reionization. The amount of ionizing photons that stellar populations produced is a crucial parameter for understanding the sources of ionizing radiation during this cosmic phase change.

The chapters in this thesis start with the physics of individual stars and gradually zoom out to end with a discussion of the possible implications on cosmological scales, as graphically depicted in Fig. 1.3. This thesis consists of the following chapters:

Chapter 2 We test the effect of metallicity and wind mass-loss on the structure and evolution of stripped stars. We evaluate how large their effects are on spectral properties and the emission rate of ionizing photons. Comparing the spectral energy distribution of a stripped star with possible companions, we find that stripped stars can easily be hidden by a bright companion star, which likely is the explanation to why they are rarely discovered.

Chapter 3 We extend our modeling efforts and compute large grids of binary evolutionary models and spectral models that are custom-made for stripped stars. We find that the spectra form a smooth sequence that links subdwarf type spectra with WR type spectra as the stellar mass increases. We then discuss different promising techniques to find and identify stripped stars by quantifying the most important biases. The large model grids allow to estimate which combinations of stripped stars and companions that are detectable and which biases to expect.

Chapter 4 The recently discovered WN3/O3 stars are isolated from other WR stars and show spectral features that are characteristic to stars with lower wind mass-loss than expected for WR stars. Since stripped stars are created with a delay, the WR stars originating from massive stars are expected to already have exploded and stripped stars are created without WR stars of the same star cluster being around. Stripped stars are also expected to have lower wind mass-loss than WR stars. We, therefore, discuss the possibility that the WN3/O3 stars are the long-sought products of envelope-stripping in binaries.

Chapter 5 We quantify the role of stripped stars in the ionizing emission from entire stellar populations by creating a spectral synthesis code for stripped stars that uses our spectral model grids presented in Chapter 3. We elaborate on the role of stripped stars in already
observed samples of galaxies and what their effect is on measures for ionizing emission and common star-formation rate indicators. We discuss the hardness of the ionizing spectrum and how that can affect nebular emission. We make our models available via the online interface of the spectral synthesis code STARBURST99 (Leitherer et al. 1999, 2010).

Chapter 6 We consider the effect of the ionizing radiation from stripped stars on cosmic evolution by estimating their impact on the Epoch of Reionization. We also discuss the effect of stripped stars on a few observable characteristics of the early Universe.

The final chapter of this thesis (Chapter 7) consists of a short outlook that shows a direction of research this thesis has built a base for. We show that one of the techniques presented in Chapter 3 has already helped to identify a large sample of stripped star candidates in the Large Magellanic Cloud using archival data. Are these indeed the stripped stars that have been missing and is the paradox resolved? The data is promising, but to find an answer to this question we still need careful consideration and follow-up observations. We hope that the theoretical models and methods presented in this work will continue to be of use to interpret and understand observations of these stripped stars and their implications.