The properties and impact of stars stripped in binaries

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Outlook: Finding the elusive stripped stars
In this thesis, we have made theoretical predictions for the properties of stars created by envelope stripping in binaries and their spectra (Chapters 2 and 3). We then estimated the implications of the existence of stripped stars on larger scales, namely the integrated spectra of unresolved populations in distant galaxies and the contribution of stripped stars to the budget of ionizing photons throughout cosmic history in chapter (Chapters 5 and 6).

Making reliable theoretical predictions requires careful testing against observations. In particular, before extrapolating to distant stellar populations, one would wish to test the models against nearby resolved stellar populations, where the models can be tested more directly. So far, testing models for stripped stars has been challenging because only a very small number of stripped stars have been observed. At the low-mass end, plenty of subdwarfs are known to exist and at the high-mass end many Wolf-Rayet stars have been identified, but in the intermediate-mass range, on which we focus in this thesis, detections are extremely scarce. The current lack of detected stripped stars in this mass range, is what we referred to as the “paradox of the missing stripped stars”, see Chapter 1.

The most probable solution to the paradox is that observational biases have so far prevented the detection of stripped stars in large numbers. Stripped stars are likely outshined by their companions, at least in optical wavelengths, as Kippenhahn & Weigert (1967) already noted. In Chapters 2 and 3, we use our models to demonstrate these biases and we propose several search strategies.

An example of how the theoretical models can aid in the identification of stripped star candidates is presented in Chapter 4. Our simulations in Chapter 3 presented a hybrid transitional class of spectra showing a mixture of absorption and emission lines, characteristic to stripped stars with semi-transparent stellar wind outflows. In Chapter 4 we argue that the WN3/O3 stars, which comprise a newly identified class of stars that show such hybrid spectra, are likely to be candidates of missing stripped stars.

In this final chapter we consider how we can move forward in this field in the near future and ask the question: “What would it take to resolve the stripped star paradox?” Our hope is that the theoretical predictions presented in this thesis will guide observing campaigns. As an illustration we will present the early results of an ongoing study in Sect. 7.1, which has revealed several stripped stars candidates. In Sect. 7.2, we conclude with a brief reflection on the role of new and upcoming missions.

### 7.1 Searching for stripped stars using UV excess

#### 7.1.1 The power of UV colors

A promising strategy to identify stripped star candidates is by searching for unexpected UV excess in the spectra of supposed companion stars. Stripped stars are faint in the optical, but bright in the more energetic ultraviolet (UV). This means that a system consisting of a stripped star and its companion may look like the companion star alone in optical colors, but
7.1 Searching for stripped stars using UV excess

The presence of the stripped star may reveal itself in the UV colors. The spectrum would be brighter in the UV than expected from its optical colors if the star was single.

To demonstrate the power of this technique we wrote a simple Monte Carlo code that uses our model grids presented in Chapter 3 to simulate the appearance of a color magnitude diagram (CMD). We assume continuous star-formation and primarily make assumptions for the population that are similar to those described in Chapter 5. The current model still relies on somewhat crude approximations for the companion star that we plan to improve later, but the resulting color-magnitude diagram is already useful as a proof-of-concept.

The resulting color-magnitude diagrams are shown in Fig. 7.1. On the left, we show a typical CMD using the optical $B$ and $V$ filters. The diagram shows how binaries containing stripped stars reside in the same location as single stars and pre-interaction binaries. It would be practically impossible, to distinguish them from their location in the CMD. The diagram illustrates again how easily stripped stars can elude detection in the optical.

On the right in Fig. 7.1, we show the same diagram, but now we adopt an ultraviolet filter that is used by the Swift telescope (Burrows et al. 2005), $UVM2$. The diagram illustrates the powerful diagnostic that the UV colors provide, enabling to discriminate between regular

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig7_1.png}
\caption{An illustration of the power of using UV colors to identify stripped stars. These color-magnitude diagrams are created with our population synthesis models made for stripped stars. Binaries that contain a stripped star or single stripped stars are shown as blue dots, while the remaining stars in the population are shown as black dots. We show the zero-age main-sequence with a gray line and a label. \textit{Left:} The classical color-magnitude diagram created with the optical filters $B$ and $V$. \textit{Right:} A UV color-magnitude diagram in which we replaced the $B$ filter with the UV-filter $UVM2$ from the Swift satellite. The diagram shows a subset of stripped stars blue-wards of the main-sequence. We have assumed a distance of 50 kpc, models with solar metallicity, and blackbody spectra when creating the diagrams.}
\end{figure}
7 Outlook: Finding the elusive stripped stars

Main-sequence stars and stars that are hosting a stripped companion. A subset of the binaries that host stripped stars stand out as they are located blue-ward of the zero-age main sequence.

We stress that the predictions above depend on the model assumptions. In particular, they depend on the mass of the companions. This in turn depends on the birth mass of each companion, how much mass it accreted and whether it rejuvenated as a result of the accretion of mass. The diagrams we show here should only be taken as an illustration of the potential power of using UV colors.

7.1.2 Testing against observations

Motivated by the promising results shown in Sect. 7.1.1, we have undertaken the start of a systematic search for stripped stars using UV photometry. For this experiment, we use data taken from the Large Magellanic Cloud (LMC). A great advantage of using the LMC is that the distance is known accurately and we can, therefore, measure more accurate absolute magnitudes. Additionally, the stars in the LMC are less affected by extinction than the stars in the disk of our own Galaxy (see for example Appendix B). A third advantage is that a large amount of publicly available archival data exists, including photometry stretching from infrared wavelengths up to the ultraviolet.

For this experiment, we use optical and ultraviolet photometry. As an optical filter, we choose to use the $V$ filter from the OGLE survey (Udalski et al. 2008) and for the ultraviolet filter, we choose to use the $UVM2$ data from the SUMaC survey of Swift (see Siegel et al. 2014, 2015; Hagen et al. 2017), which has an average magnitude limit of 19 mag. We correct for an average foreground extinction across the LMC of $A_V = 0.26$ mag, using the extinction law of Gordon et al. (2003).

We select only sources that have well-determined photometry and that are not affected by nearby sources to avoid effects of crowding. This leads to a bias against young stellar regions. However, as described in Chapter 5, stripped stars are formed with a delay compared to a burst of star-formation and are, therefore, not expected to exist in very young regions. The final sample contains 200,000 sources, for which we have both OGLE/$V$ and Swift/$UVM2$ photometry.

The resulting color-magnitude diagram is shown in Fig. 7.2. We find about a hundred sources that show UV excess, marked in green, and that are located blue-ward of the zero-age main sequence. We mark the location of the WN3/O3 stars that were present in our sample using red diamonds. They were the topic of Chapter 4. We find that they indeed show a UV excess.

We also highlight nine of our candidate stripped stars with large green circles, because these have been observed to be eclipsing binaries in the OGLE data. This is a very exciting finding as it proves that at least these stars are binaries. Secondly, these eclipsing binaries have short orbital periods of a few days at maximum. If the systems indeed contain a stripped
7.1 Searching for stripped stars using UV excess

Figure 7.2: Ultraviolet color-magnitude diagram, highlighting the region of candidate stripped star systems with a blue background. The stars in our sample are represented by black dots and candidate stripped stars with green dots. The WN3/O3 stars that are present in our sample are marked with red diamonds. Nine of the candidate stripped stars are eclipsing binaries, marked with large green circles. Models of single stripped stars are marked in purple. With a companion star, we expect that the composite color becomes redder and there should therefore also be candidates between the location of our models and the main sequence (marked with a peach-colored line). Figure credit: M. Drout.

component, it is likely that the formation channel was via common envelope evolution since the periods are very short.

For reference, we over-plot the location expected for isolated stripped stars, based on our models presented in Chapter 3. The brightness of the models increase with mass and the highest mass stripped star shown is a 7 $M_\odot$ stripped star, with a progenitor of initially 18.2 $M_\odot$. Part of the population of stars with UV excess are located close to our models, but most of them reside in the area located between the main sequence and our models. This is the location we expect for systems that consist of a stripped star and a main-sequence
7 Outlook: Finding the elusive stripped stars

companion, as shown in Fig. 7.1. These are systems in which the companion star contributes to the composite color, without being bright enough for the source to overlap with the main sequence. There are also several stars that are brighter than what our models predict. These could be stripped stars of higher mass or systems where the companion contributes to the optical color.

To answer the question of whether we have actually found a large sample of the elusive stripped stars, further study and observational follow-up are needed. Studying the eclipsing binaries could be a first step to characterizing the candidates, understanding the radii and mass functions for the systems. Also, complementing the optical and UV photometry with more filters over the entire wavelength range could allow us to find best-fit composite spectral energy distributions and in that way better understand the constituents of the sources. Spectroscopic follow-up will, hopefully, reveal spectral lines that can be used to characterize the candidates, and ultimately, radial velocity searches will provide constraints on the binary fraction and orbital periods of the candidates.

In conclusion, we believe that the objects blue-ward of the main sequence are promising candidates of systems that may host a stripped star. The results presented in this section will be part of a series of forthcoming papers by Drout et al. (in prep.) and Götberg et al. (in prep.).

7.2 Conclusion

To conclude this thesis we note that these are exciting times for stellar and binary astrophysics. Gravitational wave detections may not provide direct constraints on binary evolutionary models, but they have certainly brought large renewed interest in the physics of binary systems and their products. The future prospect of searches for stripped stars using the UV excess technique with new facilities is not very bright. The UV instruments onboard the Hubble Space Telescope are slowly degrading and currently no new major missions dedicated to UV astronomy are planned. However, Swift is still operating and the available archives contains a wealth of data that can be mined in the search for stripped stars.

We are also optimistic about the contributions expected from the satellite Gaia (Gaia Collaboration et al. 2016, 2018). Gaia’s parallax measurements will allow for much more accurate studies of the populations of subdwarfs and Wolf-Rayet stars. For example, this may reveal over-luminous subdwarfs and under-luminous Wolf-Rayet stars (cf. Geier et al. 2017, 2018; Sander et al. 2018). Such objects would start to fill in the mass-gap of the missing stripped stars.

Direct detections of stripped stars will be crucial to calibrate and test our models for individual stripped stars, in particular their uncertain stellar wind mass-loss rates. These can then in turn be used to improve our predictions for the integrated spectra of more distant stellar populations.

We believe that accurate models of the spectra of unresolved populations will be crucial to interpret the wealth of data that will become available from new missions such as the
James Webb Space Telescope (JWST, Gardner et al. 2006). In particular, this will require careful consideration of stellar sources of ionizing radiation that are currently often not yet included in most spectral synthesis codes. These include stripped stars, but also other products of binary interaction. Also, a further crucial step would be to model the response of the surrounding gas to the ionizing radiation from stripped stars, which will give rise to nebular emission features.

Eventually, we hope this work will contribute to understanding the possible role of stripped stars on the largest scales and whether they played a role in heating and ionization of the intergalactic medium over cosmic time.