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Impact of binaries on the HR diagram with SEVN population synthesis code

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ABSTRACT

I report the computational analysis of 4 million binaries and their impact on the Hertzsprung-Russel diagram. The study is entirely based on stellar population synthesis code Stellar Evolution for N-Body (SEVN). The evolution of the binary systems was studied from 0 Myr up to 20 Myr, with some integrations for bigger ages. The project aims at quantifiyng the effect of binary stars undergoing mass transfer on HR diagrams of populations or clusters with a different age. A focus was done on Roche-Lobe Overflow events resulting in common envelope or merging and collision.

Key words: binaries – HR diagram – SEVN – population synthesis – mass transfer – Wolf Rayet – RLO

1 INTRODUCTION

Observational surveys show that the vast majority of young massive stars orbit so close to a companion that interaction will be inevitable as the stars evolve and expand (Sana et al. (2012); Moe & Stefano (2017); Chini et al. (2012)). Binary interaction can therefore not be ignored when considering the evolution of massive stars, either individually or in stellar populations.

Binary interaction causes many exotic phenomena and produces a variety of stellar objects that are expected to be rather common. These include: stripped-envelope stars that have lost most of their hydrogen-rich envelope through Roche-Lobe Overflow (RLO); rejuvenated stars that have accreted mass from their companion through Mass Accretion mechanism (MA); long-lived stellar mergers (de Mink et al. (2014)).

The most common type of interaction, expected for about a third of all massive stars, is mass transfer when the most massive star in the binary system crosses the Hertzsprung gap (Sana et al. 2012). After interaction the hot helium core is exposed and left with only a thin layer of hydrogen on top (Claeys et al. (2011);Yoon et al. (2017)). Eventually these stars are expected to end their lives as stripped-envelope core-collapse supernovae, if they are massive enough.

Stripped stars are thought to be very hot objects, emitting the majority of their photons in the extreme ultraviolet (Götberg et al. 2017). To account for their effect on the integrated spectra of stellar populations, reliable models are needed for these stripped stars and their atmospheres.

Many efforts were made to model the radiation from populations containing single stars using spectral synthesis codes and to include the effects of binary interaction with increasing levels of sophistication over time (e.g.Bever & Vanbeveren (2003); Belkus et al. (2003)).

For what binary systems undergoing mass transfer is concerned, they happen to land in unusual places on the HR diagram. A bunch of accreting binary stars in a stellar population or a star cluster will change drammatically their position on the HR diagram, depending on their luminosities and effective temperatures. With these accreting systems we could explain the large amount of Wolf-Rayet stars (Götberg et al. 2018) that we observe in several populations, especially at high redshifts: from Binary Stellar Evolution (BSE) there are many more blue stars than what we would expect from Single Stellar Evolution (SSE). Are these blue stars the result of envelope stripping and accretion by a companion? How will their evolution, expecially the one of massive stars(Chen et al. 2015), change the correspondent HR diagram of the cluster?

The aim of this work is to use SEVN population synthesis code on a sample of 4 million stars randomly generated to learn about the changes in the HR diagram from the BSE. They undergo different events, depending on their initial masses, evolutionary steps and other features not considered here. The events which were highlighted are: RLO start; RLO and consecutive merging; RLO and common envelope; collision and merging; collision and common envelope. The reason behind the choice of concentrating on these kind of events is that they could explain the amount of observed Wolf Rayet stars.

I structured this work as follows. In Sec.2 I talk about SEVN population synthesis code and its utility for this research. In Sec.3 I report the description of the different data runs with SEVN, their outputs and their features. I also add a brief discussion about the code I wrote to unfold the data within SEVN outputs file and to retrieve the HR diagram (luminosity as a function of temperature, with a colorbar showing the number of binary systems that fall in a certain position on the plot). Here I also present the different HR diagrams that my code generated by using different metallicities as input for SEVN on the sample of 4 million binaries. I then add a list of evident changes that modify the HR diagram while evolving binary systems which undergo different events, from envelope stripping and RLO up to common envelope, or collisions. In Sec.4 I summarize my results and present the conclusions, inserting a personal interpretation of the features which I highlighted. In Sec.5 I suggest my proposals about

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the same identical analysis but using a sample of single stars whose masses are the same identical masses of the BSE run with SEVN, in orther to understand what changes considering SSE with the same initial stars. In Sec.6 I finally talk a bit about what could be done to improve this work and to start further studies.

2 SEVN

SEVN[0] , Stellar Evolution for N-Body (Spera et al. 2015), is a stellar population synthesis code entirely written in C++. It's the first population synthesis code that uses the interpolation algoritm: it follows Single Stellar Evolution (SSE) through interpolation of precomputed stellar tracks inserted in lookup tables (containing the initial conditions, meaning the stellar properties at given times, as mass, radius, luminosity).
The SSE of a star is univocally defined by two values: the zero-age MS mass Ms and its metallicity Zs. For each couple (Ms, Zs): the SSE will be always the same (for a given set of evolutionary tracks); SEVN assigns four interpolating tracks, taken from the lookup tables. The SSE evolution step-by-step is done through: estimate life percentage of the real star; evolve the interpolating tracks; evolve the fake star; evolve the real star. Note that the timesteps are different depending on the studied properties and tracks. The output will be the final fate of the systems you are studying.

SEVN2 is a stand-alone C++ software and no external dependencies/libraries are required. It is written using the C++14 standard , but compatibility is guaranteed with older GNU compilers that accepts at least the std=c++1y flag[1]. `Cmake`, to facilitate the code compilation, and C++ compiler are required. SEVN2 has been extensively tested on Linux machine, in particular on RedHat and Ubuntu systems. The compatibility with Ubuntu version > 14.04 is automatically tested in the CI/CD pipeline. If is not possible to directly install the required versions of `Cmake` and C++ compiler, an alternative solution is to use the `CONDA` package manager by installing `Anaconda`.

SEVN2 is in a Gitlab repository[2]. The repository is private, an invitation to the project is needed.[3]. There are two methods to get SEVN2 from the repository: (1) getting the source file, (2) using git clone*[4]. At this point, use the SEVN user guide written by Giuliano Iorio to learn how to compile and run the population synthesis code.

2.1 Running SEVN and output files

If the compilation and installation is successful, SEVN is ready to be run. Inside the folder `run_scripts` there are a number of scripts than can be used to run the simulations, containing the SEVN parameters that can be changed directly inside the script. Make the script executable, then run it. If you want you can use your input list instead of the default one just adding the path to the list when executing the script. The simulation output can be found inside the folder `sevn_output`. Here there are for example the files:

- `evolved_xxx.dat`, where xxx indicates the ID of the thread. These files contain a list of all the successful evolved systems with their initial properties (in input), including the used random seed for reproducibility purpose.
- `failed_xxx.dat`, containing a list of all the evolved systems that have been halted due to an error.
- `output_xxx.csv`, the proper output of the simulation, usually in `csv` format, containing the state of the evolved system at the selected times.
- `logfile_xxx.dat`, containing info on the SSE/BSE, complementary to the output files.

SEVN code exploits cpu-parallelism through *multithreading*. Each tread produces its own outputs, so the suffix `xxx` indicates the thread number (thread ID). This thread number (starting from 0) is printed without leading or trailing zeros.

[0] https://demoblack.com/catalog_codes/sevn-public-version/
[1] https://gitlab.com/sevn/SEVN
[2] https://gitlab.com/sevn/SEVN
[3] If you are interested, please contact Giuliano Iorio:giuliano.iorio@unipd.it; Michela Mapelli: michela.mapelli@unipd.it; Mario Spera: mario.spera@live.it; Guglielmo Costa: guglielmo.costa@unipd.it
[4] https://gitlab.com/sevn/SEVN.git

Table 1. List of possible events happening in BSE, that can be found in the outputfile and logfile from SEVN population synthesis code.

BSN: Supernova explosion (binary)
RLO_BEGIN: Roche Lobe Overflow begin
RLO_END: Roche Lobe Overflow end
CE: Common Envelope
COLLISION: Collision
MERGER: Merger
SWALLOWED: Swallowed star

2.2 Output files: evolved systems

Output files contain stellar and binary properties (set using the runtime options *scol* and *bcol* in the imput file) at the chosen times (set using the list or runtime option *dtout*). Each system is identified by a sequential integer ID (original position in the input file) in the first column and a unique long integer (the name) in the second one.

Outputs can contain *nan* values that represent undefined values. In particular, if a star does not exist anymore (because of a stellar merger or after a SN event leaving no remnants), the stellar properties are set to *nan*. In this case, *phase*=7 and *RemnantType*=-1. If the entire binary does not exist anymore (because it is broken or after a stellar merger), the binary parameters are set to *nan*.

2.3 Logfiles: extra information

Logfiles are partially formatted ascii file. Each row contains an header part with a fixed number of values and an info part with variable number of values. The file presents extra information about the binary and stellar evolution, complementary to the output files. Each row reports a particular event happened in a given star or binary system. In particular, there are two final columns indicating the *event* with a label in capital letter, referring to the triggering event (all the possible events are listed in Tab.1); the *time* of the simulation (in Myr) when the event is triggered.

2.4 Evolved binary: RLO

If one of the two stars in the binary system fills the Roche-Lobe (Fig.1) and a Roche-Lobe overflow begins resulting in mass transfer between the companions, the header label in the SEVN logfile will be **RLO_BEGIN**. The format of the correspondent line in the logfile is a list of indicators, explained in Tab.A1.

If the RLO previously started comes to and end both because the two stars have merged or because they both stop to fill the Roche Lobe, then the header label will be **RLO_END**. Tab.A2 contains a list of the indicators.

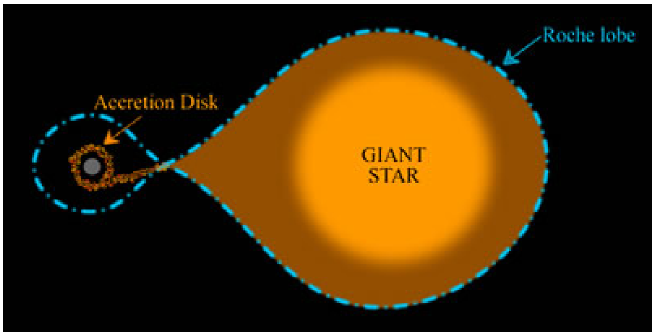

Figure 1. Roche-Lobe Overflow occurs in a binary system when a star fills its Roche Lobe. Models show that in systems such as this, any material that passes beyond the Roche Lobe of the star will flow onto the binary companion, often by way of an accretion disk.

2.5 Evolved binary: CE

If the RLO caused an unstable mass transfer or there was a stellar collision, a Common Envelope (CE) evolution is triggered (see Fig.A3). The header label is **CE**. Tab.A3 a list of the indicators.

2.6 Evolved binary: COLLISION

If the sum of the radii of the two stars in the binary system is larger than the stellar separation at the pericentre $(R_1 + R_2 \geq a(1 - e))$ and one or both stars are filling the Roche Lobe, the system ends up in a collision event. The headers label for SEVN is **COLLISION**. Indicators are listed in Tab.A4.

2.7 Evolved binary: MERGER

If the two stars in the binary system merge after a collision or an unstable RLO, SEVN writes the header label **MERGER**. A list of indicators can be found in Tab.A5.

3 METHODS

3.1 First step: 10 thousand binaries

I prepared a first run of SEVN code on a sample of 10 thousand binaries. I used an imput file containing the masses in $M_\odot$, metallicities, age in Myr, phases of the stars inside the binary systems (plus the seed, an optional parameter). I run SEVN with a bash script by imposing metallicity $Z = 0.02$. Other runtime options can be found here: https://gitlab.com/sevn/SEVN/-/wikis/SEVN-V2/run-the-code#runtime-options. Default tables for H-stars and He-stars, the core of the stellar evolution interpolated on-the-fly by SEVN, were left untouched[5]. The number of parallel threads to use was set to Nthreads=2 and the number of systems to evolve at each step to Nchunk=1000.

After retrieving the outputs (two output file, two logfiles and so on), I wrote a python code using the python package `PANDAS` (able to read output files on ascii/csv and hdf5 format). `PANDAS` read functions return a pandas dataframe. `PANDAS` dataframes can be filtered creating boolean list through boolean operations. I decided not to filter anything inside this first run step, so I concatenated the values

[5] H-stars stellar tracks, used to evolve stars with H envelopes: $< SEVN_{folder} > /tables/SEVNtracks_parsec_AGB$. He-star tracks, used to evolve pureHE stars without Hydrogen envelopes: $< SEVN_{folder} > /tables/SEVNtracks_parsec_pureHe36$

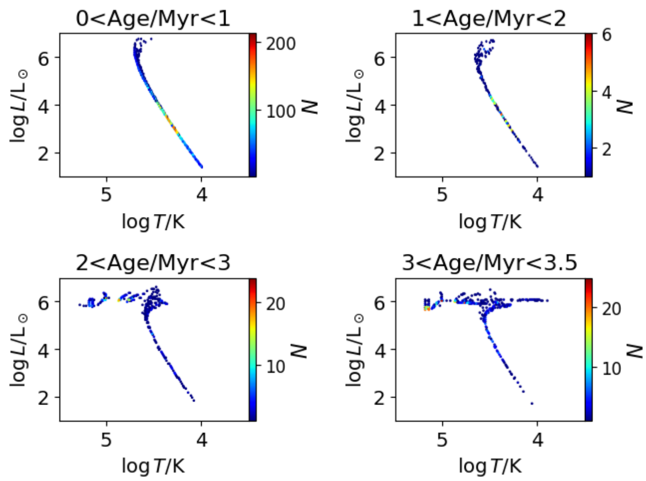

Figure 2. HR diagram of a sample of 10 thousand binary systems. Just BSE from 0 up to 4 Myr is shown.

of luminosity and temperature obtained for the binaries imposing Phase<7 for both binaries and BWorldtime between a lower and an upper limit. By choosing different time ranges in terms of limits within a *for* loop in pyhton, I was able to produce the HR diagram depicted by all the binaries in the 10 thousand systems sample. I used *plt.hexbin* but also tried with *plt.scatter*. The second one was less confusional in terms of binning, but the first one helped more in dealing with the huge dataset.

I analized both the `output_0` and `output_1`, but here I report just `output_1`.

3.2 Through the project: 4 million binaries

In order to run SEVN on a sample of 4 million binaries I used `demoblack` server[6].

3.2.1 First step: 0.02 metallicity, no filtered dataframe

I first run SEVN by imposing a metallicity $Z_2 = 0.02$, not changing tables, and setting Nthreads=20 and Nchunck=100000. The run was performed by using a bash script in which these and other information were stored. SEVN produced 20 output files that I used for the further analysis, with also failed files and logfiles.

Firstly I used the code previously written in order to see if for different time ranges the BSE was well depicted within the HR diagram. At this step, the binaries seem to concentrate along the Asymptotic Giant Branch (AGB) and towards higher temperature and lower luminosities during temporal evolution. A small number of stars is located along the MS during the first 20 Myr, and after 40/50 Myr most of the binaries are positioned above the Sub Giant Branch (SGB), at low temperatures and high luminosities. These qualitative results are showed in just one example in Fig.3 and Fig.4 (here I report just the `output_1` analysis results, since I performed it for the different outputs and saw that it is not changing too much between one thread and the other; also an average of the results could be done, maybe, taking into account some asusmptions). Within those plots I produced the

[6] Vicolo dell'Osservatorio 3, Padova - Demoblack project, PI Michela Mapelli

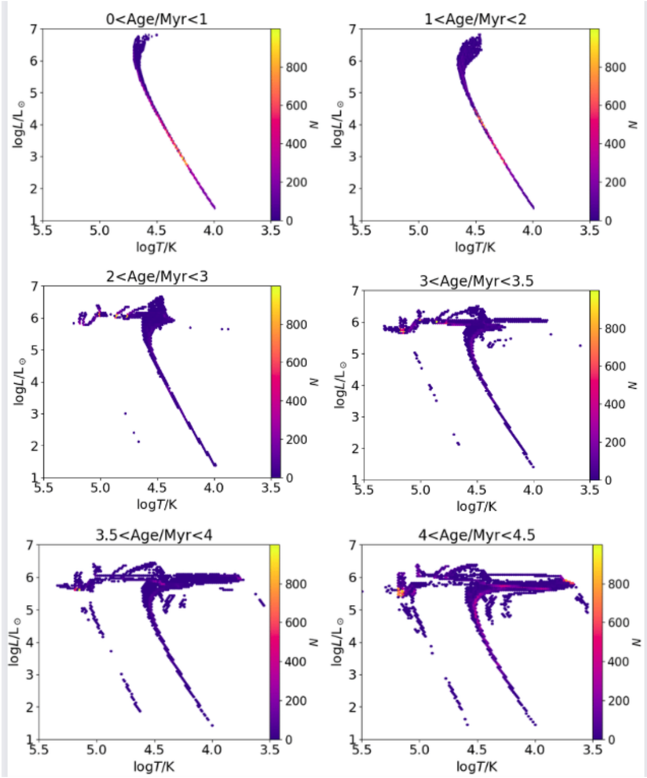

Figure 3. HR diagram of a sample of 4 million binary systems with metallicity 0.02. Just BSE from 0 up to 4.5 Myr is shown.

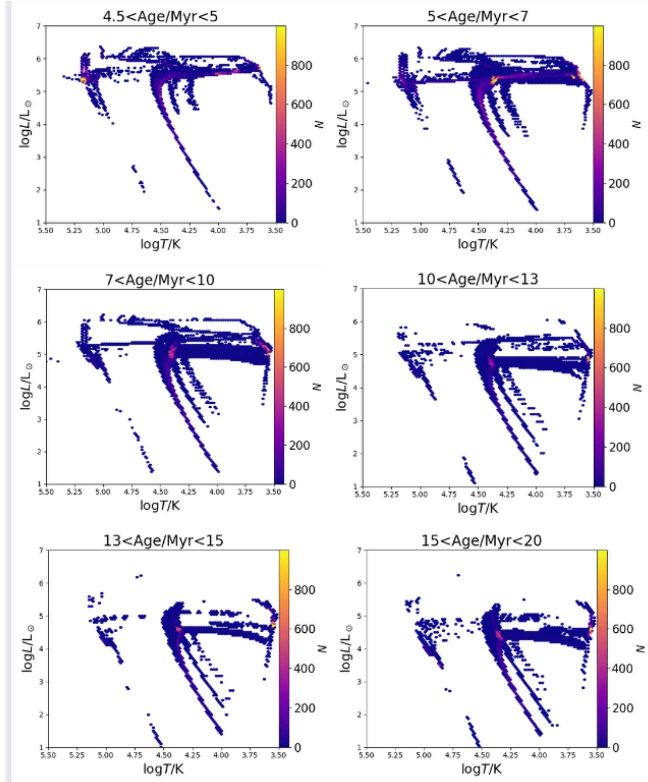

Figure 4. HR diagram of a sample of 4 million binary systems with metallicity 0.02. Just BSE from 4.5 up to 20 Myr is shown.

HR diagrams of the sample of 4 million binaries without filtering the PANDAS dataframe. More time ranges can be chosen during the analysis, however at this step from 0 up to 5 Myr the most interesting things happen (spread of the binaries towards the HB phase, crowding of the AGB, some WD remnants, and so on).

Unfortunately, some things seem not to work so well while concatenating luminosities and temperatures at time greater than 10/15 Myr. HR diagrams are very similar. However, one explanation could be the solowing down of the evolution of systems around an age between 20 and 50/70 Myr, before the fatal events that make them explode in supernovae or collapse into a big black hole.

3.2.2 *Second step: 0.01 and 0.04 metallicity*

I decided to change the metallicity parameter Z_i (abundance of Z elements) within the bash script for SEVN run. I then performed two different run of the population synthesis code by imposing:

(i) $Z_1 = 0.01$, lower than the first one, closer to solar metallicity
(ii) $Z_4 = 0.04$, higher than the second one, almost twice the solar metallicity

After retrieving the outputs within separate PANDAS dataframes, I plotted again the HR diagrams of all the binaries in the 4 million sample by changing the time ranges. See Fig.5 and Fig.6.

Time ranges have been chosen after selecting different ages, plotting their correspondent results and noticing what temporal intervals where more interesting to be studied in more details. See also here there is the problem at larger ages.

Under a qualitative point of view, the comparison between HR diagrams corresponding to $Z_1 = 0.01$ and $Z_2 = 0.02$ (Fig.5,3,4)

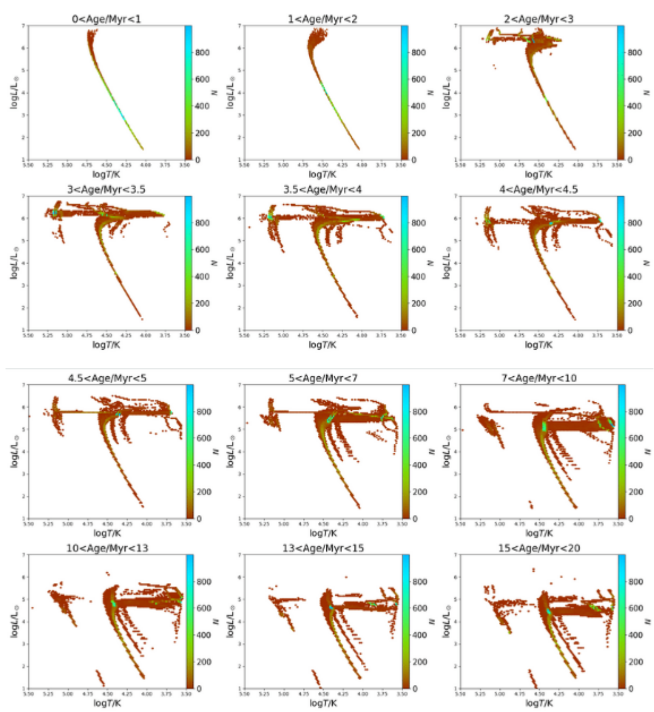

Figure 5. HR diagram of a sample of 4 million binary systems with metallicity 0.01. Just BSE from 0 up to 20 Myr is shown.

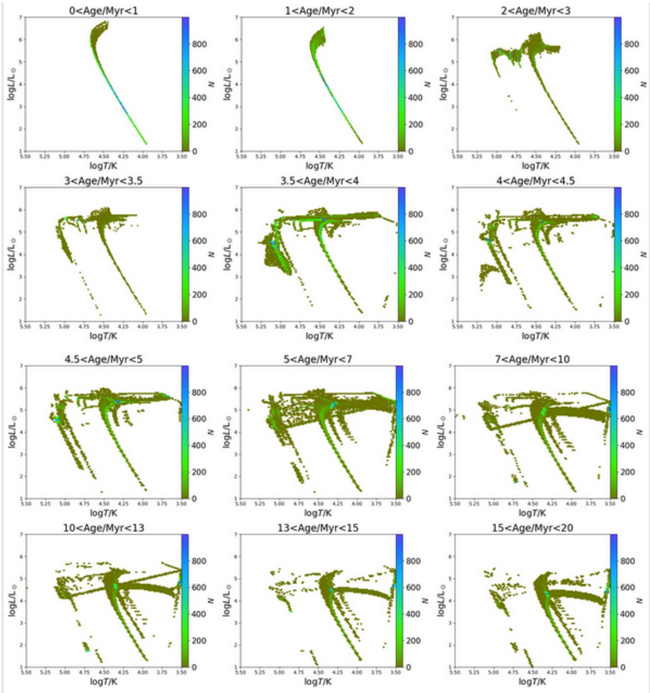

Figure 6. HR diagram of a sample of 4 million binary systems with metallicity 0.04. Just BSE from 0 up to 20 Myr is shown.

are similar up to 2 Myr, whereas above 2 Myr some things start to change. Concerning Z_1, the majority of the evolved binary systems are placed within the Horizontal Branch (HB), RGB and AGB. Some of these systems disappear above 4/4.5 Myr, probably due to some fusion/collision event (see next subsection for details). Considering Z_2, some binaries are placed along the WD sequence or in the surroundings, probably became exotic binaries or binaries with compact objects formation, and I decided not to go into details on that.

Comparing instead the HR diagrams of $Z_2 = 0.02$ and $Z_4 = 0.04$ (Fig.3,4,6), it is possible to see that for metallicity equal to $Z = 0.04$ the central left part of the HR diagram (medium luminosities, medium/high temperatures) is overcrowded. Not just the line of the WD sequence is occupied, but also a region at lower temperatures. These features seem to last up to 20 Myr. In particular, after 50 Myr the majority of the systems are disappeard from the HR diagram.

The three metallicities treated in this study have been choosen because of the aim to search for the impact of binaries encountering RLO events (with consecutive merging or collision) during their life. Actually also stellar winds should be taken into account, and SEVN is able to reconstruct the evolution of the winds within the evolving systems, however I did not consider their treatment (in fact, a series of assumptions need to be made in order to understand what kind of winds are produced, how strongly they impact on the evolution of the system and its final fate, and so on).

3.2.3 *RLO, Merging and Common Envelope*

In order to retrieve information about the number of RLO events which start and then end with a merging or a collision, I used the previous python code and `PANDAS` dataframes to select the amount of binary systems undergoing RLO event and consequently ending in merging or collision. Results are listed in Tab.2 for $Z_2 = 0.02$ and in Tab.3 and Tab.4 for Z_1 and Z_4.

Table 2. Number of binary systems undergoing RLO starting event (second column), RLO and merging (third column), RLO and Common Envelope (fourth column) in the time interval from 0 up to 20 Myr. Metallicity $Z_2 = 0.02$. Minimum luminosity in the HR diagram: $log(L)/L_{\odot}$=0.57.

Time (Myr)	RLO	RLO + merge	RLO + CE
0 to 1	2204	1793	0
1 to 2	1890	425	0
2 to 3	2654	479	0
3 to 3.5	2063	295	0
3.5 to 4	3443	331	0
4 to 4.5	3727	338	41
4.5 to 5	3112	370	84
5 to 7	11349	1420	412
7 to 10	14901	1622	1838
10 to 13	11149	1068	2736
13 to 15	5916	594	1412
15 to 20	13093	1039	4512

From the tables it is possible to see that RLO is, as also observations show us, a common event in binary systems. In particular, mass transfer is present from the very beginning of the evolution of the systems (fractions of Myr).

After RLO, directly merging usually happens. The amount of RLO+merge events increases with time. Sometimes a collision happens before merging, determined by the orbital decay of one of the two stars in the binary system, due to stellar mass loss (or gravitational radiation, or strong winds, or other mechanisms not yet understood).

Common Envelope (CE) phase after RLO appears less common in binaries, for what this sample is concerned. It seems to interest more systems when they're at least 4.5/5 Myr old. After the CE the stars gain temperature but lowers the luminosity for some time, and probably this is why there is an overcrowding in the upper left / central left region of the HR diagrams during these ages. Moreover, evolution through a CE phase with ejection of the envelope can lead to the formation of a binary system composed of a compact object with a close companion (Taam & Sandquist (2000),Ivanova et al. (2013)). Cataclysmic variables, X-ray binaries and systems of close double white dwarfs or neutron stars are examples of systems of this type: there is a compact remnant (a white dwarf, neutron star or black hole), which must have been the core of a star which was much larger than the current orbital separation.

All these considerations are valid for all three considered metallicities Z_1, Z_2, Z_4.

3.2.4 *Collision*

Some binary stars orbit each other so closely that they share the same atmosphere, giving the system a sort of peanut shape. While most contact binary stars are stable, a few become unstable and merge through collision (Tylenda et al. 2011).

Collision is contemplated by SEVN code too for BSE. I isolated binary systems undergoing collision with merging and collision with CE and reported them in Tab.A6, Tab.A7, Tab.A8.

The tables show an increasing number of collision + merging

Table 3. Number of binary systems undergoing RLO starting event (second column), RLO and merging (third column), RLO and Common Envelope (fourth column) in the time interval from 0 up to 20 Myr. Metallicity Z_1 = 0.01. Minimum luminosity in the HR diagram: $log(L)/L_{\odot}$=0.68.

Time (Myr)	RLO	RLO + merge	RLO + CE
0 to 1	1758	1385	0
1 to 2	1564	391	0
2 to 3	3246	566	8
3 to 3.5	3076	314	0
3.5 to 4	3800	378	0
4 to 4.5	3382	334	6
4.5 to 5	3109	342	8
5 to 7	10501	1248	266
7 to 10	17303	1732	1179
10 to 13	11943	1040	2400
13 to 15	6647	665	1202
15 to 20	14197	1163	3116

Table 4. Number of binary systems undergoing RLO starting event (second column), RLO and merging (third column), RLO and Common Envelope (fourth column) in the time interval from 0 up to 20 Myr. Metallicity Z_4 = 0.04. Minimum luminosity in the HR diagram: $log(L)/L_{\odot}$=0.57.

Time (Myr)	RLO	RLO + merge	RLO + CE
0 to 1	2856	2544	0
1 to 2	2796	533	0
2 to 3	3424	578	0
3 to 3.5	2516	296	0
3.5 to 4	4685	328	0
4 to 4.5	4623	333	5
4.5 to 5	4029	371	29
5 to 7	12387	1357	1408
7 to 10	14052	1403	2877
10 to 13	10926	1017	3042
13 to 15	6380	507	2699
15 to 20	13171	853	4375

events, togethere with collision and common envelope. The former is more common than the latter from the very first Myr. Usually young binary systems with the two stars much close to one another easily reach the merging and collision phase in a really short timescale, of less than 1 Myr.

The behaviour of the evolved systems is similar for all the three considered metallicity.

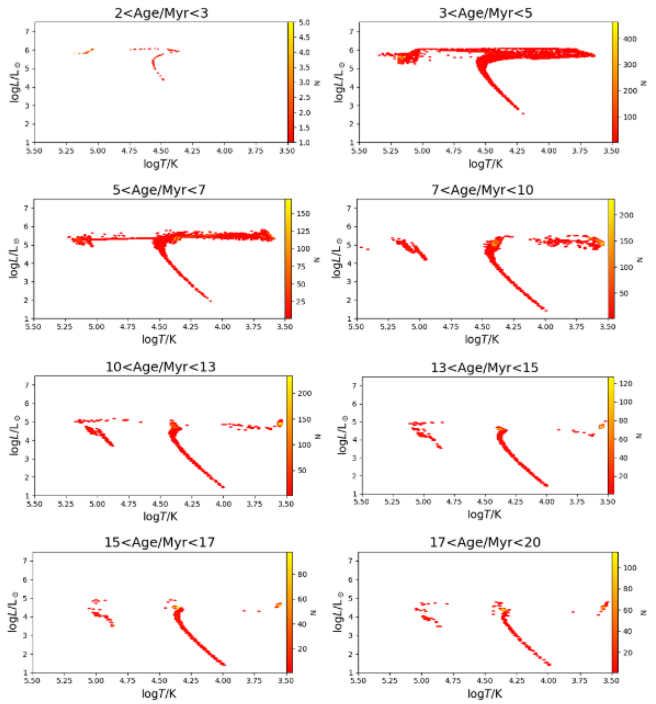

Figure 7. HR diagram of a sample of 4 million binary systems with metallicity 0.02 undergoing RLO start event.

3.2.5 *Filtered dataframes from logfiles with RegEx*

Logfiles produced by SEVN are partially formatted. To manually loading and analysing the information row by row within the files, a possibility is to use *Regular Expression* (RegEx and its python built-in module `re`. A RegEx is a sequence of characters that specifies a search pattern. Usually such patterns are used by string-searching algorithms[7]. The python module `re` uses RegEx to search for pattern in string and retrieve information from them.

At this point, by imposing some conditions on logfiles with RegEx, for example that the binary stars are both compact objects or just one of them, it is possible to make a combination of data in the output files. `PANDAS` with `merge` instruction handles all the possible joins among two dataframes (by joining together the information of data sharing the same value on a given column, e.g. an ID).

By using these tools, I implemented the previous code with a constrain given by the RegEx procedure, imposing "RLO" to be in the string defining a specific binary system. After that I repeated the same operations done before, by selecting just the binaries with at least one He white dwarf, a neutron star or a black hole in them. I produced the plots shown in Fig.7,A4,A5.

I decided to perform this step for BSE from 0 up to 20 Myr, consistently with the previous part of the analysis of SEVN outputs. I also checked for what happens after 20 Myr: the greatest part of the systems disappear, up to 50 Myr or such.

The plots show that the behaviour for the three metallicities is very similar between different temporal ages of the BSE experiencing RLO. In particular, binary systems appears after 2/3 Myr and most

[7] A tutorial for writing RegEx can be found here: http://regular-expressions.info

of them seem to concentrate in the upper left and upper right part of the HR diagram, populating the Wolf Rayet and giants regions.

RegEx can be used together with `PANDAS` functions to study what happens to other kind of systems, composed by different companions other than compact objects or underging other events, such as CE, merging, collision and so on. Here in this work I do not report the further analysis based on these suggestions, but I did some checks and an implementation could be interesting.

4 PROBLEMS AND CONCLUSIONS

Many studies are done about BSE. Their impact on the HR diagram is important to characterize, in order to be able to explain a large number of atypical and exotic phenomena.

In this work I tried to evaluate the main features of HR diagrams including binaries with different age, with a focus on the RLO starting events and the consequential merging or common envelope or collision. A lot of improvements can be done both on the codes and on the runfile options for SEVN. Some suggestions are listed in Sec.6, but others can be done.

For example, a comparison between the results on the output and logfiles with the evolved systems in the evolved files produced by SEVN could be a useful options to better characterize some interesting systems. For example, by taking a system in different part of the HR diagram and reconstructing its evolution in time by comparing the correspondent output, evolved and logfile could help in better defining the binary system's position on the HR diagram and its trajectory along the different sequences.

One problem of this work concerns the HR diagrams of binaries considering an age above 10/15 Myr. There are binaries still in the MS. However, a lot of them are concentrated in the upper part of the diagram, some of them have disappeared, so with further analysis maybe a physical explanation could be found.

5 EXTRA: SSE

In order to better characterize the evolution of the binaries in the HR diagram, I tried to use SEVN also to run the evolution of a sample of 20000 single stars, whose parameters are given by the initial 10000 binaries sample by concatenating the binaries' values. This way I was able to retrieve the HR diagrams of the same population of stars evolving as single objects and not in binary systems. I tried to implement my code to produce the HR diagrams, starting from just one time interval and then adding the others, but a better work could be done in order to highlight the main differences with respect to the binaries case.

6 FURTHER ANALYSIS

Massive stars are still object of different astrophysical studies. Also cosmological ones, since many of them - the oldest, at least - are thought to be somehow linked to Population III, Globular Clusters and other very ancient objects that could help us understanding the properties of the primordial Universe.

Since many massive stars are observed to be involved in a binary system, it could be interesting to understand how their evolution influences the environment, both in past and present times. A population synthesis code such as SEVN, with the implement of interpolation tools, could be very useful in studying how a different sample of binaries evolve in time and how much their features impact on the HR diagram. This could in fact help a lot in reconstructing the main features of both young and intermediate-age stellar populations, in recent but also older star clusters.

Moreover, many exotic objects are generated from some peculiar evolutionary events that involve binary companions. Some of these cases could be better understood if the comprehension of how their products changes the features and structure of the populations improves too.

In conclusion, by using SEVN with greater samples of binaries (and maybe also with their relative samples of single stars) the code could give interesting results and consent further implementations. Also more sophisticated codes that analyze SEVN outputs are required: with an accurate study, the final fate and the Gravitational Wave events could also be considered. Moreover, different ranges of temperatures and luminosity seem to host less or more binary systems that undergo collision or RLO or other events during their evolution in time. A deeper investigation on these features may lead to curious results and constructive discussion about the role of binaries as important characters in the history of our Universe.

DATA AVAILABILITY

The codes I used for the project, some of the plotted results, the input files and bash scripts to run SEVN and other stuff are available on a `Github` repository. Please contact me by e-mail to have access.

AKNOWLEDGMENTS

Many thanks to prof. Michela Mapelli and dott. Giuliano Iorio for the help with the project and the constructive comments which helped me to improve the codes I used. I made use of the public version of population synthesis code SEVN (version 2.14alpha) and of the useful userguide written by Giuliano Iorio to run SEVN and analyze its outputs. I also acknowledge the DFA System Administrator and collaborators for the VPN connection with the `demoblackd` server.

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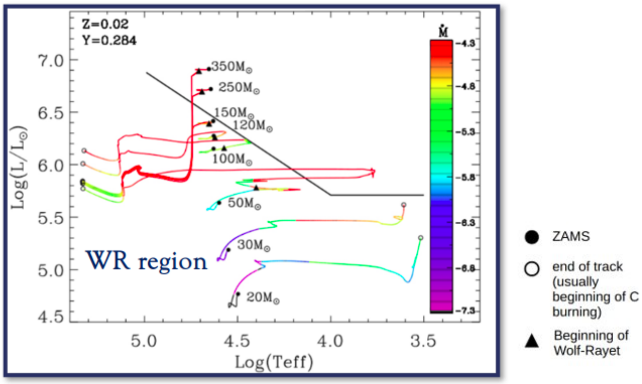

Figure A1. Plot showing the region of the HR diagram maily populated by Wolf Rayets.

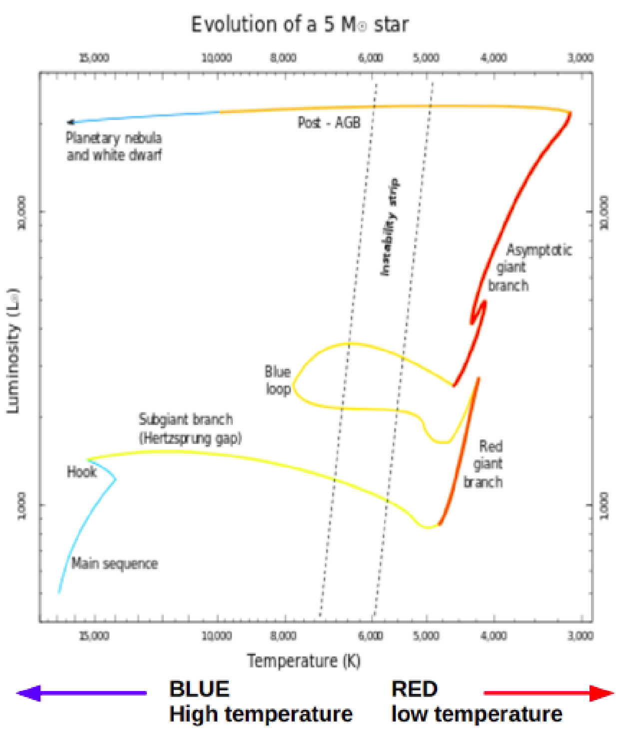

Figure A2. Plot showing the evolution in time of stars in terms of temperature and luminosity, called Hertzsprung-Russel diagram.

de Mink S. E., Sana H., Langer N., Izzard R. G., Schneider F. R. N., 2014, The Astrophysical Journal, 782, 7

APPENDIX A: SOME EXTRA MATERIAL

This paper has been typeset from a TEX/LATEX file prepared by the author.

Table A1. List of the different indicators in a single RLO_BEGIN event.

i1: id of the star filling the RLO (donor star)
d2: mass of the donor star in $M_\odot$
d3: HE core mass of the donor star in $M_\odot$
d4: CO core mass of the donor star in $M_\odot$
i5: phase of the donor star (integer phase type)
i6: remnant type of the donor (integer remnant type)
d7: radius of the donor in $R_\odot$
d8: R_L radius of the donor in $R_\odot$
i9 - d16: same as i1 - d8 but for the other star (accretor)
d17: mass ratio q ($M_{\rm donor}/M_{\rm accretor}$)
d18: critical mass ratio $q_{\rm crit}$, if $q \le q_{\rm crit}$ the mass transfer is stable, otherwise unstable
d19: Semimajor axis length in $R_\odot$
d20: Eccentricity

Table A2. List of the different indicators in a single RLO_END event.

i1: id of the star filling the RLO (donor star)
d2: mass of the donor star in $M_\odot$
d3: HE core mass of the donor star in $M_\odot$
d4: CO core mass of the donor star in $M_\odot$
i5: phase of the donor star (integer phase type)
i6: remnant type of the donor (integer remnant type)
d7: radius of the donor in $R_\odot$
d8: RL radius of the donor in $R_\odot$
i9 - d16: same as i1 - d8 but for the other star (accretor)
d17: total mass lost by the donor during the RLO in $M_\odot$
d18: total mass accreted by the acrretor during the RLO in $M_\odot$
d19: Semimajor axis length in $R_\odot$
d20: Eccentricity

Table A3. List of the different indicators in a single CE event.

i1: id of the star that starts the CE (primary)
d2: mass of the primary star in $M_\odot$ before the event
d3: HE core mass of the primary star in $M_\odot$ before the event
d4: CO core mass of the primary star in $M_\odot$ before the event
i5: phase of the primary star before the event (integer, phase type)
i6: remnant type of the primary star before the event (integer, remnant type)
i7 - i12: same as i1 - i6 but for the other star (secondary)
d13: semimajor axis length before the event in $R_\odot$
d14: semimajor axis length after the event in $R_\odot$
i15: 0-if the binary survives after the CE, 1-if the stars coalesce

Table A4. List of the different indicators in a single COLLISION event.

i1: id of the star filling the R_L (donor star)
d2: mass of the donor star before the event in $M_\odot$
d3: radius of the donor star before the event in $R_\odot$
i4: phase of the donor star (integer phase type)
i5-i8: same as i1 - i4 but for the other star
d9: Semimajor axis length before the in $R_\odot$
d10: Eccentricity before the event
d11: R_L radius in $R_\odot$ of the donor star before the event (ID=0)
d12: R_L radius in $R_\odot$ of the accretor star before the event (ID=0)

Table A5. List of the different indicators in a single MERGER event.

i1: id of the star that survives after the merger (accretor)
d2: mass of the accretor star in $M_{\odot}$ before the event
d3: HE core mass of the accretor star in $M_{\odot}$ before the event
d4: CO core mass of the accretor star in $M_{\odot}$ before the event
i5: phase of accretor star before the event (integer phase type)
i6: remnant type of accretor star before the event (integer remnant type)
i7 - i12: same as i1 - i6 but for the other star (donor)
d13: final mass of the accretor star after the merger

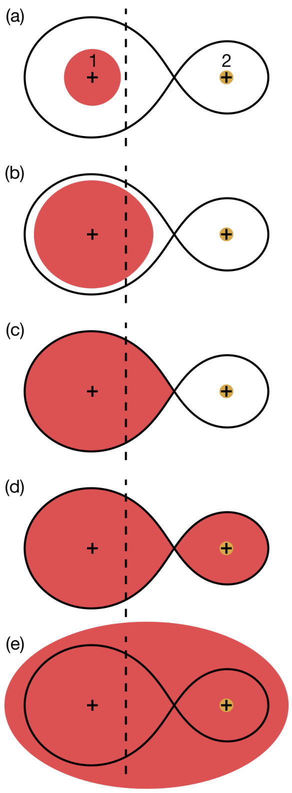

Figure A3. (a) Both stars in the binary system lie within their Roche lobes, star 1 on the left and star 2 on the right. (b) Star 1 has grown to nearly fill its Roche Lobe. (c) Star 1 has grown to overfill its Roche Lobe and transfer mass to star 2: Roche Lobe Overflow starts. (d) Transferred too fast to be accreted, matter has built up around star 2. (e) A Common Envelope, represented schematically by an ellipse, has formed (Sana et al. 2012).

Table A6. Number of binary systems undergoing collision and merging (second column) or collision and Common Envelope in the time interval from 0 up to 20 Myr. Metallicity Z_2 = 0.02. Minimum luminosity in the HR diagram: $log(L)/L_{\odot}$=0.57.

Time (Myr)	C + merge	C + CE
0 to 1	4367	0
1 to 2	28	0
2 to 3	23	0
3 to 3.5	94	162
3.5 to 4	336	656
4 to 4.5	515	565
4.5 to 5	346	734
5 to 7	2640	548
7 to 10	5207	301
10 to 13	3914	234
13 to 15	1981	112
15 to 20	4392	293

Table A7. Number of binary systems undergoing collision and merging (second column) or collision and Common Envelope in the time interval from 0 up to 20 Myr. Metallicity Z_1 = 0.01. Minimum luminosity in the HR diagram: $log(L)/L_{\odot}$=0.68.

Time (Myr)	C + merge	C + CE
0 to 1	3851	0
1 to 2	11	0
2 to 3	15	30
3 to 3.5	280	497
3.5 to 4	377	587
4 to 4.5	580	305
4.5 to 5	766	111
5 to 7	2609	433
7 to 10	4937	1120
10 to 13	3909	240
13 to 15	2291	133
15 to 20	4741	236

Table A8. Number of binary systems undergoing collision and merging (second column) or collision and Common Envelope in the time interval from 0 up to 20 Myr. Metallicity $Z_4 = 0.04$. Minimum luminosity in the HR diagram: $log(L)/L_{\odot}$=0.57.

Time (Myr)	C + merge	C + CE
0 to 1	5225	0
1 to 2	25	0
2 to 3	31	4
3 to 3.5	29	112
3.5 to 4	336	930
4 to 4.5	277	740
4.5 to 5	341	524
5 to 7	2817	1310
7 to 10	4642	371
10 to 13	3635	302
13 to 15	2140	126
15 to 20	4156	279

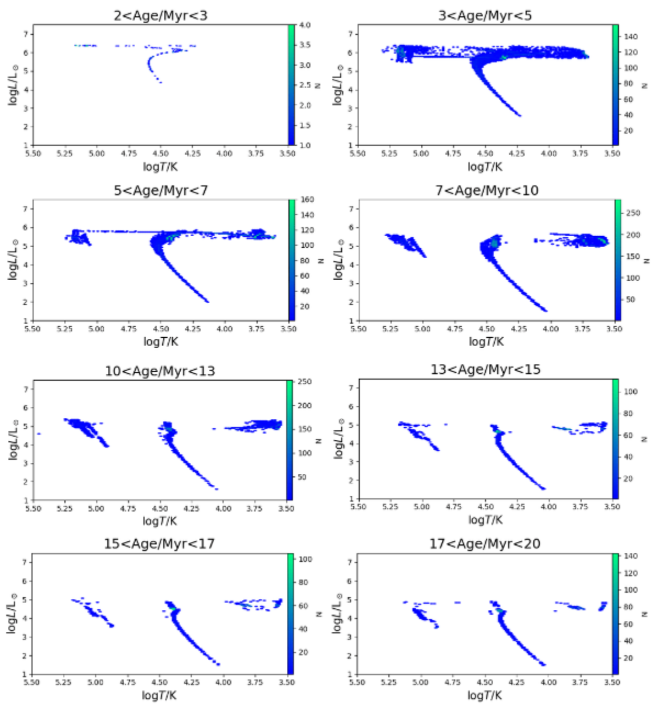

Figure A4. HR diagram of a sample of 4 million binary systems with metallicity 0.01 undergoing RLO start event.

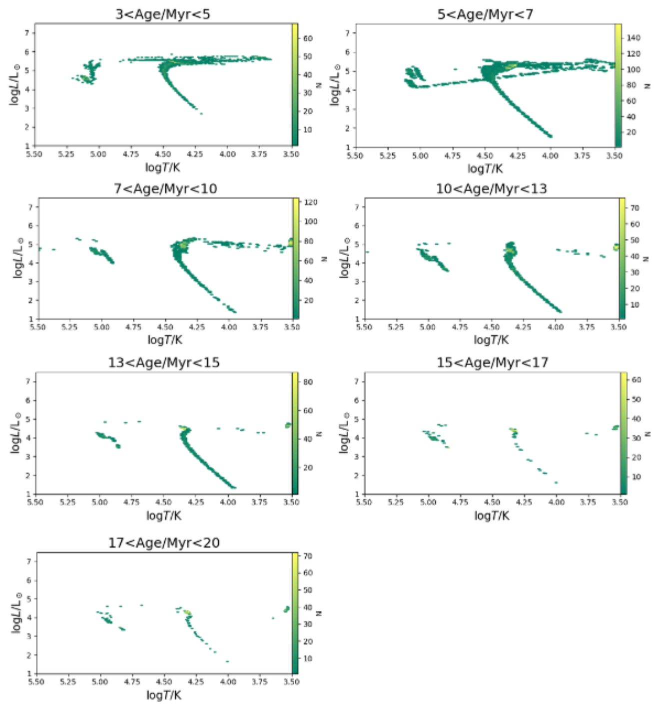

Figure A5. HR diagram of a sample of 4 million binary systems with metallicity 0.04 undergoing RLO start event.