The Relation Between Progenitor and Remnant Masses in Double Neutron Star Systems

Masterarbeit zur Erlangung des akademischen Grades

"Master of Science (M.Sc.)"

im Studiengang Astrophysik

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Vorgelegt der

Mathematisch-Naturwissenschalftlichen Fakultät
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Rheinische Friedrich-Wilhelms-Universität Bonn
Deutschland

October, 2019

I hereby declare that this thesis was formulated by myself and that no sources or tools other than those cited were used.

_____   _____
            Date   Signature

To my Loved Ones

τί δὴ τοῦτό ἐστι Πυθαγόρας ἐρωτώμενος,
῾τὸ θεάσασθαι᾿ εἶπε ῾τὸν οὐρανόν᾿

When Pythagoras was asked about the purpose
for which humans were created, he said,
"To look upon the heavens"

ACKNOWLEDGMENTS

During my effort for the completion of this Master Thesis many people had stand by me and contributed in one way or another.

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Chapter 1

INTRODUCTION

The cycle of life and death of stars baffled astronomers for many years. The study of stellar structure and evolution continues -up to this date- to be of paramount importance, since it is crucial to our understanding of various branches of astronomy, e.g. the structure of galaxies, and chemical history of the Universe.

The aim of this thesis is to investigate and get an insight in one of the most debated topics in Stellar Astrophysics; the connection between the progenitor and remnant masses, especially in the case of double neutron star (DNS) binary systems. The existence of those systems was recently confirmed by the detection of gravitational waves emitted during a merging event, accompanied by the detection of a kilonova -the "afterglow" of such an event- as described in the seminal paper of the LIGO/VIRGO collaborations (Abbott et al. 2017).

In this chapter, a synopsis that extends from the formation to the death of Helium stars will be attempted. A detailed coverage of the principles of stellar evolution is beyond the scope of this thesis and a fundamental knowledge is assumed. Moreover, for the interested reader, there are classical textbooks (Kippenhahn et al. 2012; Clayton 1968; Prialnik 2000; Eggleton 2006) covering almost every aspect in the field of stellar astrophysics. Nevertheless, for the sake of completeness, a small introduction to several fundamental notions, tailored to our needs, will also be carried out in the next few pages.

1.1   Helium stars

From the large primordial molecular clouds, protostars are being constantly formed via a process called *gravoturbulent cloud fragmentation*. When the accretion of the surrounding material from the protostellar core ceases, the protostar is said to be in the *pre-main sequence* (PMS) phase of its evolution, and continues to contract under the force of gravity until the central temperature becomes sufficiently high for nuclear fusion reactions on Hydrogen to occur. At this point, the star enters the *main sequence* (MS) evolutionary phase as a zero-age main sequence (ZAMS) star where it will spend most of its life.

During the MS stage, the star converts Hydrogen to Helium either via the pp-chain reactions, or via the CNO cycles, depending on its initial mass and chemical composition. Slowly but steadily, the Hydrogen in the core is being consumed by the aforementioned nuclear networks, and Helium builds up forming a Helium core. This process continues until the Hydrogen in the stellar core is depleted, resulting to an inert Hydrogen envelope engulfing the newly formed He-core; subsequently, the star exits the MS phase and the nuclear reactions in its interior that provided the necessary pressure support against gravity, effectively stop. Since the star is not in an equilibrium state anymore, it starts to contract until Hydrogen is ignited in a shell around the inert Helium core. At this point, the star enters the so-called

red-giant branch (RGB) and the Hydrogen-rich envelope, on top of the H-burning shell, inflates rapidly whilst the He-core continues to contract due to the *mirror principle* (see Kippenhahn et al. 2012, p. 369).

As we will explain in a moment, the Hydrogen envelope can be lost when the star is in the RGB phase, with more than one ways, exposing the He-core of the star. This naked, Hydrogen deficient, He-core is what we refer to as a *Helium star*. We can classify He-stars into two groups: low-mass *hot subdwarfs* (sd) that can be further subdivided into several categories (e.g. sdB, sdO) based on their spectra, and more massive *Wolf-Rayet* (WR) stars that can also be subdivided into several classes (e.g. WN, WC). For a more detailed discussion we refer the reader to the work of Han et al. (2002); Han et al. (2003); Heber (2009); Chiosi & Maeder (1986); Langer (2012).

1.1.1   Formation of Helium stars

Helium stars can be formed either in isolation or as part of a binary system. In both scenarios, the physical mechanism that is responsible for the stripping of the Hydrogen envelope is of the utmost importance.

In the former case of a single He-star, the necessary mass loss is being achieved due to strong, radiation-driven, stellar winds. However, the specifics of such a process have not been fully resolved yet, and an enhanced mass loss scheme, e.g. caused by rotational mixing, magnetic fields, or even strong He-flashes should be considered for the progenitor of the He-star (Sweigart 1997; Heber 2009).

In the case where the He-star progenitor is part of a binary system, the required strong mass loss can be achieved via different channels, depending on how wide the binary system is. These channels include the stable Roche-lobe overflow (RLO) and the Common Envelope (CE) ejection. We will discuss these mass loss mechanisms below. It should be mentioned that sdB stars can also originate from the merging of two Helium white dwarfs (He-WD) in a close binary, resulting to an object with enough mass to ignite Helium (Han et al. 2002).

1.1.2   Evolution of single Helium stars

Once the He-star progenitor has been stripped from its Hydrogen envelope during its RGB phase, the compression of the core continues until it reaches the necessary conditions for Helium to ignite at its centre. The ignition of core Helium burning signifies the transition to the Helium main sequence (He-MS) as a He-ZAMS star (see Fig 1.1). The last two concepts are defined in a similar way to the (Hydrogen) main sequence and ZAMS respectively.

During the He-MS stage, the star burns its ^{4}He supplies via the triple-alpha process producing Carbon (^{12}C) and the stable Oxygen isotope ^{16}O, as a byproduct. When the Helium in the core is depleted, the contraction/expansion process we described above is repeated; the idle metal core that has been formed, consists mainly by Carbon, Oxygen, Neon, and Magnesium and it is surrounded by a He-rich envelope. This whole structure will contract until Helium is ignited in a shell at the bottom of the envelope, followed by the ignition of Carbon in the centre (given that the star is massive enough). The fate of the He-star at this point depends on its mass; if it has not retain enough mass for Carbon ignition, it will gradually cool off and end its life as a Carbon/Oxygen white dwarf (CO WD). On the other hand, if it is massive enough to ignite Carbon, either on or off centre, its fate could be an Oxygen/Neon/Magnesium white dwarf (ONeMg WD), a hybrid white dwarf (CONeMg WD), or even collapse as a supernova.

To demonstrate the aforementioned stages, the evolutionary track of a $3.0 M_\odot$ He-star (with and without mass loss) is illustrated in the $T_c - \rho_c$ plane (Fig 1.1) (see also Habets 1986a,b; Nomoto 1987). The letters denote the beginning and end of several phases up to the off-centre neon ignition. The A-B phase shows the contraction that follows after the RGB stage of the progenitor. The moment of core He-ignition is denoted by the black circle at point B, and signifies the entrance to the He-MS phase (B-C). At point C, Helium has been exhausted and the core contracts whilst He-shell burning follows. During the D-E phase, the Carbon is ignited in the core making a loop in the diagram around $\rho_c = 10^6$
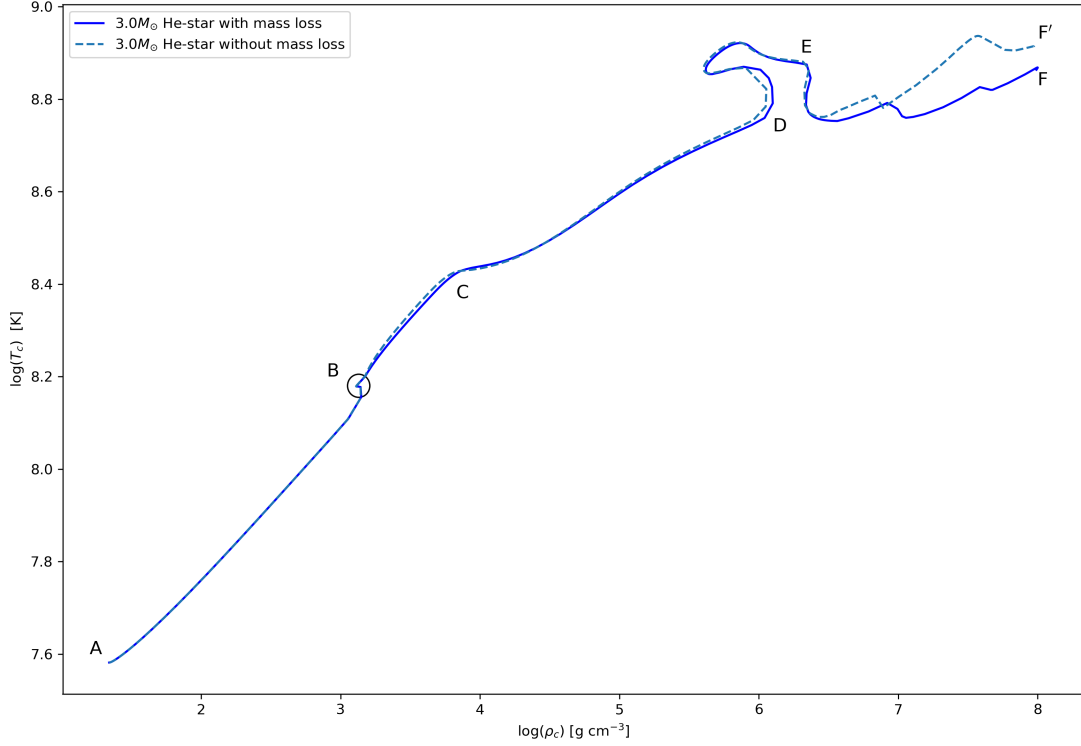
Figure 1.1: The evolution of a $3.0 M_\odot$ He-star, with and without mass loss. The point where the star enters the He-MS as a He-ZAMS can be seen as a small hook inside the black circle. An analytic explanation of the letters along the evolutionary tracks, is provided in the text.

g cm^{-3}. Finally, the E-F/F$'$ shows the Carbon-shell burning along the contraction of the O-Ne-Mg core; at the endpoint (F/F$'$), Neon is ignited off-centre.

For a more complete and comprehensive overview of the evolution of single He-stars, we provide, in the form of a Kippenhahn diagram, the net energy production rate with respect to the internal structure of the $3.0 M_\odot$ star (with mass loss) we used in the example above (Fig 1.2). In this diagram, the x-axis expresses the remaining time of the calculations whilst the y-axis shows the inner structure of the star in terms of mass coordinates. The color scale is associated with the energy production.

By taking a careful look at Fig 1.2, we observe that during the He-burning in the convective core, the star experiences an approximately $\sim 0.3 M_\odot$ mass loss via stellar winds. As a result of this core burning process, a C-core of $\sim 1.2 M_\odot$ is formed that continues to grow up to $\sim 1.42 M_\odot$ due to He-shell burning. Similarly, an Oxygen core is formed of about $\sim 1.34 M_\odot$ as a result of the more advanced burning stages.

Mixing mechanisms

Although protostars begin their life with, a more or less, uniform elemental composition which is the same as the composition of the cloud they originated from, the ongoing nuclear reactions transform and creates new elements that are not necessarily distributed uniformly throughout the stellar interior. This is because there are several ways for a star to stir and mix its material. These mixing mechanisms are usually caused by various instabilities and can contribute on different levels based on specific conditions. In this section we will briefly explain four major mixing processes leaving the effects of rotation for a
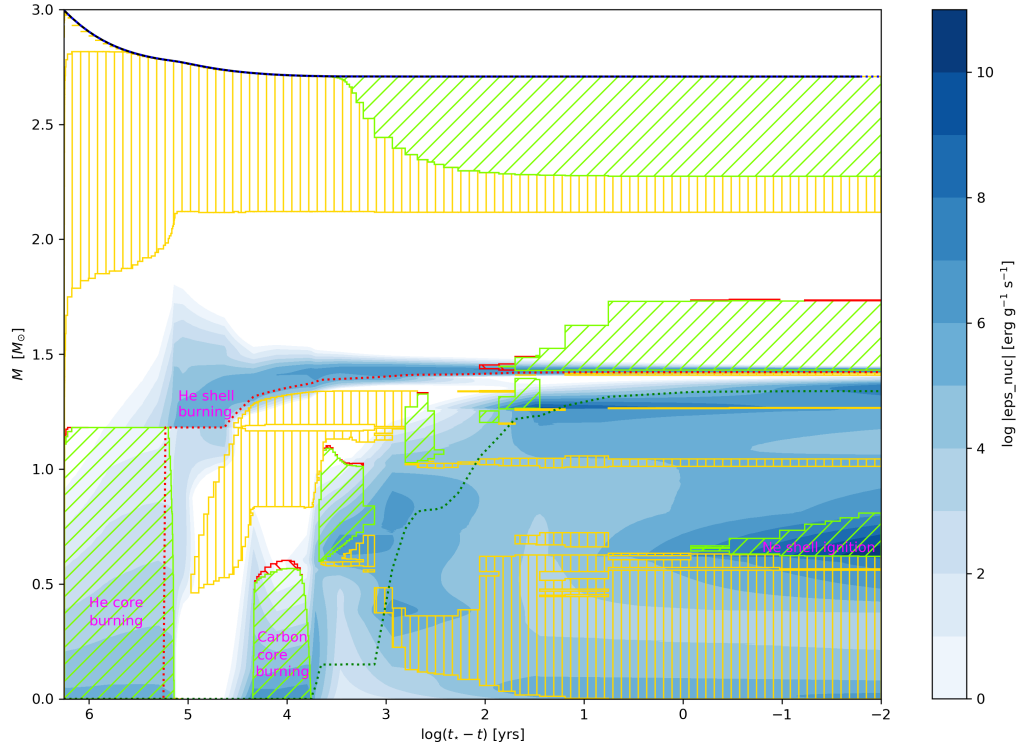
Figure 1.2: Kippenhahn diagramm for a $3.0 M_\odot$ He-star with mass loss. The green and gold hatched areas denote convective and thermohaline mixing respectively. Red solid lines represent areas with semi-convective mixing. The black, red, and green dotted lines show the build-up of Helium, Carbon, and Oxygen core mass respectively

later discussion.

Maybe the most effective way to transfer material is with *convection*. Thermal variations across different shells of the star will lead to density variations and, consequently, to buoyancy driven flows of the fluid. Essentially, what this means is that a hot parcel of fluid will rise due to buoyancy forces and a colder parcel will sink. This process is very efficient for transporting more heavy elements produced in the deep interior of the star towards the surface via bulk motions (dredge-up) and vice versa. The stability of a layer against convection is given by the *Ledoux* criterion

$$\nabla_{\mathrm{rad}} < \nabla_{\mathrm{ad}} - \frac{\chi_\mu}{\chi T} \nabla_\mu \tag{1.1}$$

which, in the case of chemically homogeneous layers ($\nabla_\mu = 0$), reduces to the *Schwartzschild* criterion

$$\nabla_{\mathrm{rad}} < \nabla_{\mathrm{ad}} \tag{1.2}$$

For a detailed explanation of the symbols and the implications of those criteria, see Kippenhahn et al. (2012).

The composition gradient in the Ledoux criterion acts as a stabilizing agent in weakly, thermally unstable regions leading to a slower mixing rate. These zones are not mixed by convection but rather by another process, called *semi-convection* (see Spruit 2013; Langer 1991).

Another mechanism that has an important consequence in stellar evolution, is *convective overshooting*. During this phenomenon, a parcel of fluid carried away by convection will overshoot beyond the boundary of the unstable region and into the stable region. This is caused by the inertia of the convective material and thus, it travels some distance further than the region in which it was accelerated until it loses all of its momentum. For this reason, convective overshooting introduces a large uncertainty in the extent of mixed regions.

The fourth major mixing process is called *thermohaline* mixing. It occurs when the molecular weight decreases with depth, e.g. a Helium layer on top of a hydrogen-rich layer due to accretion in a binary system. The heavier elements will eventually sink in whilst the lighter material will rise, re-establishing the mean molecular weight being larger as we move towards the centre of the star. However, thermohaline mixing is believed to play a lesser role in the evolution of single stars and becomes important in accreting binaries (see also Cantiello, M. & Langer, N. 2010; Charbonnel, C. & Zahn, J.-P. 2007).

Effects of rotation

Rotational mixing

Transportation of angular momentum

Eddington-Sweet circulation etc

Winds and mass loss

Importance of mass loss in the evolution of stellar winds and Wolf-Rayet stars + magnetic braking –> connection to angular momentum losses.

1.2   Evolution of binary systems

Few words about how most stars form in binary systems, detached, semi-detached and contact binaries

1.2.1   Interaction and orbital parameters

Cases A/B/C etc

1.2.2   Mass transfer

Few words about mass transfer in binary systems (wind mass accretion + Roche lobe overflow)

1.2.3   Common envelope

Explain a little bit in more detail the basics of CE

1.2.4   Angular momentum transfer

Effects of angular momentum transfer + magnetic braking

1.2.5   Gravitational waves

The very basics for GWs and their impact on binary mergers

1.3 Stellar transients

Couple of words for the different types of stellar transients and how can we observe them

1.3.1 Classification of Supernovae

Explain in details the difference between core collapse SNe and type Ia and different subdivision

1.3.2 Type Ib/c Supernovae

Explain in details this particular branch

1.3.3 X-ray binaries

HMXB, LMXB, UCXB

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Chapter 2

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METHODS

Explain shortly what MESA is.

2.1 Modules for Experiments in Stellar Astrophysics

Write 2-3 pages of the MESA basics and how it works (Newton iterations etc). Consider possible subsections

2.2 Physical assumptions

Mention which physical assumptions we used

2.2.1 Single stars

For single helium stars

2.2.2 Binary systems

For the binary systems

DRAFT

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Chapter 3

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RESULTS

Mension the mesa reader Python module for the extraction and analysis of MESA data

3.1 Single Helium stars

3.2 Neutron star + Helium star binaries

DRAFT

CONCLUSIONS

Write the conclusions we arrived at for all cases and what are they implying for the formation of DNS binaries

DISCUSSION

Write a page or two for your findings, future work etc

BIBLIOGRAPHY

Abbott, B. P., Abbott, R., Abbott, T. D., et al. 2017, Phys. Rev. Lett., 119, 161101

Cantiello, M. & Langer, N. 2010, Astronomy and Astrophysics, 521, A9

Charbonnel, C. & Zahn, J.-P. 2007, Astronomy and Astrophysics, 467, L15

Chiosi, C. & Maeder, A. 1986, Annual Review of Astronomy and Astrophysics, 24, 329

Clayton, D. 1968, Principles of Stellar Evolution and Nucleosynthesis (McGraw-Hill)

Eggleton, P. 2006, Evolutionary Processes in Binary and Multiple Stars (Cambridge University Press)

Habets, G. 1986a, Astronomy and Astrophysics, 165, 95

Habets, G. 1986b, Astronomy and Astrophysics, 167, 61

Han, Z., Podsiadlowski, P., Maxted, P. F. L., & Marsh, T. R. 2003, Monthly Notices of the Royal Astronomical Society, 341, 669

Han, Z., Podsiadlowski, P., Maxted, P. F. L., Marsh, T. R., & Ivanova, N. 2002, Monthly Notices of the Royal Astronomical Society, 336, 449

Heber, U. 2009, Annual Review of Astronomy and Astrophysics, 47, 211

Kippenhahn, R., Weigert, A., & Weiss, A. 2012, Stellar Structure and Evolution, 2nd edn. (Springer)

Langer, N. 1991, Astronomy and Astrophysics, 252, 669

Langer, N. 2012, Annual Review of Astronomy and Astrophysics, 50, 107

Nomoto, K. 1987, The Astrophysical Journal, 322, 206

Prialnik, D. 2000, An Introduction to the Theory of Stellar Structure and Evolution (Cambridge University Press)

Spruit, H. 2013, Astronomy and Astrophysics, 552, A76

Sweigart, A. V. 1997, The Astrophysical Journal, 427, L23