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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-Naturwissenschaftlichen Fakultät

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Rheinische Friedrich-Wilhelms-Universität Bonn

Deutschland

October, 2019

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

Date

Signature

1. Gutachter: Prof. Dr. Norbert Langer
2. Gutachter: Prof. Dr. Michael Kramer

To my Loved Ones

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τί δὴ τοῦτό ἐστι Πυθαγόρας ἐρωτώμενος,
ἔτὸ θεάσασθαι ἔειπε ἔτὸν οὐρανόν

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

ΔΡΑΦΤΗ

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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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.

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 \(2012\)](#).

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](#)).

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 center. The ignition of core Helium burning signifies the transition to the Helium main sequence (He-MS) as a He-ZAMS star (see [Fig 1](#)). The last two concepts are defined in a similar way to the (Hydrogen) main sequence and ZAMS respectively.

Mixing mechanisms

convection, overshooting, thermohaline

Effects of rotation

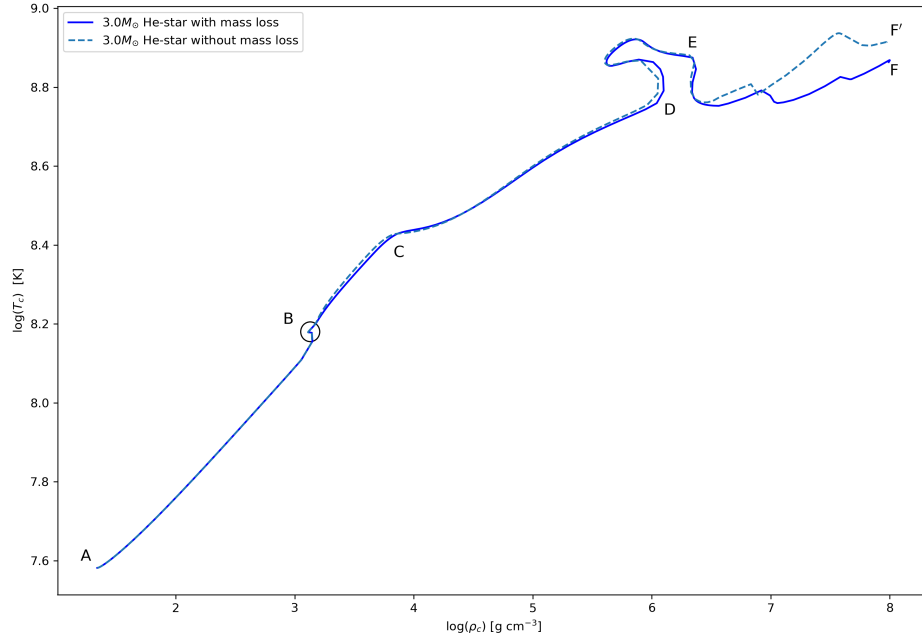
Rotational mixing

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 $-j$ connection to angular momentum losses.

Figure 1.1: $T - \rho$ plane

Evolution of binary systems

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

Interaction and orbital parameters

Cases A/B/C etc

Mass transfer

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

Common envelope

Explain a little bit in more detail the basics of CE

Angular momentum transfer

Effects of angular momentum transfer + magnetic braking

Gravitational waves

The very basics for GWs and their impact on binary mergers

Stellar transients

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

Classification of Supernovae

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

Type Ib/c Supernovae

Explain in details this particular branch

X-ray binaries

HMXB, LMXB, UCXB

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METHODS

Explain shortly what MESA is.

Modules for Experiments in Stellar Astrophysics

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

Physical assumptions

Mention which physical assumptions we used

Single stars

For single helium stars

Binary systems

For the binary systems

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RESULTS

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

Single Helium stars

Neutron star + Helium star binaries

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CONCLUSIONS

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

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DISCUSSION

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

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