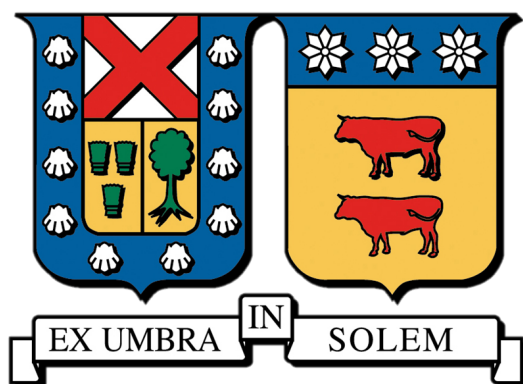


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WHERE ARE ALL THE STRONGLY MAGNETIC AM CV_n STARS?

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Abstract

AM CVn stars are not only uncommon binary systems but also among the most important for different areas in astrophysics. They allow us to calibrate low-frequency gravitational wave detectors. However, their formation and evolution are still not well understood as some processes, such as magnetic braking, common envelope evolution, and mass transfer stability, are currently largely unconstrained. A directly related subject that remains an enigma is the absence of strong magnetic fields in AM CVn, as none has been found in observations so far, which is in stark contrast to other samples of white dwarf binary stars.

In this thesis, we used the BSE code for evolving an initial population of 1 240 857 binaries obtained from a Monte Carlo simulation and combined these simulations with predictions of the crystallization and rotation-driven dynamo proposed scenario for magnetic field generation in white dwarfs. The studied AM CVn formation channels were the WD/WD and the WD/He channel, each one from a single common envelope phase (St-CE) or two common envelope phases (CE-CE), while the CV formation channel could not be analyzed due to limitations of BSE.

The results have revealed that the WD/WD channel is highly predominant over the WD/He channel in the formation of AM CVn systems, making up $\approx 80 - 100\%$ of the predicted binaries. Among the systems forming AM CVn through the WD/WD channel the CE-CE path dominates with $\approx 79 - 100\%$ over the St-CE path. Combining the binary evolution calculations with magnetic field generation according to the crystallization and rotation driven dynamo, we find that at least one-third of AM CVn are predicted to host a strongly magnetic white dwarf. This result is in disagreement with the observations. We propose two possible scenarios that could be the reason of this contradiction. First, the CV formation channel which we ignored might be the dominating over the WD/WD and the WD/He channels, based also on recent postulates, and supposing that AM CVn systems coming from that channel may not form magnetic fields. As a second possibility, as the white dwarfs in AM CVn accrete helium, an originally formed magnetic field might end up being completely buried by the accreted material, a scenario that has been proposed for accreting neutron stars in binaries.

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Nomenclature

Symbol	Meaning, units
M	Stellar Mass, $M_{\odot}$
R	Stellar Radius, $R_{\odot}$
a	Orbital Separation, $R_{\odot}$
Initials	Meaning
AGB	Asymptotic Giant Branch phase
AM CVn	AM Canum Venaticorum-type star
CE	Common Envelope phase
CE-CE	Double Common Envelope pathway
CV	Cataclysmic Variable star
C/O WD	Carbon-Oxygen core White Dwarf
He WD	Helium core White Dwarf
IMF	Initial Mass Function
IMRD	Initial Mass-Ratio Distribution
IOSD	Initial Orbital Separation Distribution
MS	Main Sequence star
RGB	Red Giant Branch phase
SN Ia	Thermonuclear Supernova
St-CE	Single Common Envelope pathway
WD	White Dwarf star
WD/WD	Double White Dwarf formation channel
WD/He	White Dwarf + Helium Star formation channel
ZAMS	Zero Age Main Sequence star

Chapter 1

Introduction

Binary stars, systems consisting of two stars orbiting their common center of mass, constitute one of the most important and studied topics in stellar astrophysics, as it is estimated that about 50% of the sun-like stars in our galaxy are part of multiple systems, with more than 30% being binary systems. Their complex nature makes them valuable sources of information, especially through various processes of interaction, whether of a gravitational or magnetic nature or due to exchange of mass. Studying eclipsing binaries allows us to estimate extra-solar distances very accurately and obtain accurate measurements of stellar masses or radii ([Torres et al., 2010](#)) that are extremely hard to measure for single stars, which led to the best observational constraints on the mass-radius relations of WDs currently available ([Parsons et al., 2017](#)).

Among the most interesting, and in the general astrophysical context most important binary star systems are binaries that contain WDs. More than 99% of all stars will end their life as a WD ([Kalirai et al., 2008](#)) and, according to theoretical estimates, more than 30% of the WDs in our solar neighborhood are part of binary systems ([Holberg, 2009](#)). Added to that, the degenerate nature of WDs leads to varied and unique behaviors compared to other types of binaries. For example, WD binaries are the progenitors of thermonuclear supernovae (SN Ia) which permit the calibration of the extra-galactic distance scale. This led to the Nobel prize-winning discovery of the accelerated expansion of the Universe, usually explained as a consequence of dark energy. In addition, close WD binary stars will dominate the low-frequency gravitational wave signal expected to be detected with space interferometers such as LISA.

Unfortunately, despite their importance for astrophysics, we still do not fully understand the evolution and formation of close WD binary stars. When low-mass or medium-mass stars in binary systems evolve into red giants, mass transfer between the two stars can be unstable which leads to common envelope evolution. It remains still unclear how much orbital energy is lost during this process which makes it very difficult to predict the outcome of common envelope evolution ([Ge et al., 2022](#); [Belloni et al., 2019, 2024](#); [Zorotovic et al., 2010](#); [Zorotovic and Schreiber, 2022](#)). Even if

mass transfer between two stars in a binary is dynamically stable, parameters such as mass transfer efficiency and the corresponding angular momentum loss remain largely unconstrained. Even the systemic angular momentum loss, defined as angular momentum loss that occurs independent of mass transfer, is currently not well understood. The main systemic angular momentum loss mechanisms are magnetic braking and gravitational radiation. While the latter is easy to calculate, current models predict angular momentum loss rates through magnetic braking that differ by more than four orders of magnitude (Schreiber et al., 2023). Finally, and very important in the context of this thesis, the impact of the generation of WD magnetic fields on the evolution of close WD binary stars is largely unexplored despite the fact that it might play a fundamental role (Schreiber et al., 2021b).

One of the classes of cataclysmic variable stars that generated significant scientific interest in the last decades and that illustrates our ignorance of WD binary formation and evolution corresponds to AM Canum Venaticorum-type (AM CVn) stars. These ultra-compact binary systems with extremely short orbital periods, spanning a range from 5 to 65 minutes (Solheim, 2010), are composed of a carbon-oxygen core WD accreting helium from a donor star that might be degenerate or not. AM CVn systems are characterized by the lack of hydrogen features in their spectra, which separates them from all other types of cataclysmic variables. The first AM CVn was observed by Humason and Zwicky (1947), and since its discovery by Greenstein and Matthews (1957) in spectral analysis, later classified as a close binary system by Smak (1967), around 60 AM CVn systems have been identified in photometric and spectroscopic surveys (Ramsay et al., 2018). These systems can be observed in optical bands as very faint blue sources, with varying luminosity due to fluctuations in their accretion disks. They can also be observed in the UV band and X-rays (Ramsay et al., 2005). Three very different formation paths for AM CVn have been suggested and it is currently unclear whether significant numbers of AM CVn form through all of them or if one of the formation channels is clearly dominating. This uncertainty converts theoretical population studies of AM CVn into rather futile exercises. In this thesis, we used a particular feature of the observed AM CVn population towards a better understanding of their formation pathways: the absence of strongly magnetic WDs in AM CVn.

A characteristic that is widely observed in the study of single WDs and WDs in binaries is the existence of strong magnetic fields. It is estimated that about one-third of the WDs in CVs (Pala et al., 2020; Inight et al., 2021) and approximately one-fourth of single WDs are strongly magnetic (Bagnulo and Landstreet, 2021). Furthermore, both among single stars as well as in close binaries, magnetic fields seem to appear late, that is when the WD cooling age exceeds ~ 2 Gyr (Parsons et al., 2021; Bagnulo and Landstreet, 2021).

Despite the fact that AM CVn stars are considered to be rather old WD binaries, there is an apparent absence of magnetic AM CVn systems. So far, astrophysicists have not been able to

find an AM CVn system containing a WD with a strong magnetic field. The reason behind the lack of strongly magnetic AM CVn systems remains a mystery that needs further investigation into the evolution of magnetic fields during the formation process of these binary star systems. At the same time, for a given scenario for the generation of WD magnetic fields, the absence of strongly magnetic WDs in AM CVn might provide hints towards their formation history and perhaps contribute to identify their main formation channel.

In this thesis we assume that WD magnetic fields are generated through the crystallization and rotation-driven dynamo (Isern et al., 2017; Schreiber et al., 2021b, 2022, 2023) which is currently the only scenario that explains the observed late appearance of strong WD magnetic fields. We combine this scenario for magnetic field generation with binary population synthesis considering two formation channels of AM CVn. We find that both these channels predict a large fraction of AM CVn to contain strongly magnetic WDs. This means, that either the third channel is the dominant one, or that WD magnetic fields in AM CVn are efficiently buried below the accreted helium.

Chapter 2

Literature

2.1 Formation channels of AM CVn stars

AM CVn systems are believed to be formed through three possible channels. Knowing that these binaries are characterized by their ultra-short orbital periods and the presence of a WD that is actively accreting material, those paths involve approaching and mass transfer events between the stars. [Belloni and Schreiber \(2023b\)](#) explain that for the formation of an AM CVn at least two episodes of Roche-lobe overflow are required, one to form the accreting WD and another one to form the donor star, also called primary star and secondary star respectively. Each channel is characterized by the characteristics of the required mass transfer phases and the nature of the direct progenitor systems. These three formation channels are visually depicted in the left side of figure [2.1](#).

2.1.1 Double White Dwarf channel

The WD/WD channel explains the evolution of a zero-age MS-MS binary when the primary star expands and fills its Roche-Lobe radius and the systems start transferring material, this transfer may be dynamically stable or unstable, so the secondary star may accrete the material or the system may form a common envelope. In both cases this event leads to the formation of a C/O WD, which would become the accretor star in the AM CVn. After the first mass transfer event, the system has to end up losing orbital angular momentum, so the orbital period decreases before the secondary star evolves as a red giant, filling its Roche-Lobe and forming a common envelope, here the secondary star evolves as a He WD and, later, the system loses angular momentum through gravitational wave radiation, so the C/O WD starts stably accrete mass from the He WD, with an ultra-short orbital period, i.e the system has become an AM CVn.

2.1.2 White Dwarf + Helium Star channel

The WD/He channel is very similar to the WD/WD channel, regarding their evolution, which is essentially the same. But the main difference is after the last common envelope, where the secondary star evolves as a naked He-burning star instead of a HeWD, and the primary star remains as a C/O WD. Subsequently, angular momentum loss reduces the separation between the two stars, and thus the primary accretes helium-dominated material from the (stably) Roche lobe filling secondary, forming an AM CVn. As in the WD/WD channel, the AM CVn may also have formed rather from two consecutive CE phases, or a stable transfer of matter followed by a CE phase. In what follows we denote these pathways as CE-CE (for two common envelope phases) and St-CE for stable mass transfer followed by a common envelope.

2.1.3 Cataclysmic Variable channel

The last pathway that has been proposed to lead to the formation of AM CVn is the CV channel. In this case, the first mass transfer phase, when the initially more massive star fills its Roche-Lobe, leads to dynamically unstable mass transfer which causes common envelope evolution.

In contrast to the formation scenarios described above, in the CV channel, the second mass transfer phase is dynamically stable which leads to the formation of a CV. If the donor star in a CV is an unevolved main sequence star, that is, the composition of the core is still hydrogen-dominated, this mass transfer is entirely driven by systemic (gravitational radiation and magnetic braking) and potentially also consequential angular momentum loss ([Schreiber et al., 2016](#)). In this case, the binary follows the standard CV evolution which means that it evolves towards shorter periods until the still hydrogen-dominated donor star becomes partially degenerate. When this happens, at an orbital period of ~ 80 min, the mass-radius exponent of the donor star changes and the binary starts evolving towards longer orbital periods. In contrast to the classical angular momentum loss-driven CV evolution, if the donor star is significantly evolved at the onset of the second mass transfer phase, mass transfer can still be stable but the binary diverges (which means that the orbital period increases) as the expansion of the donor star dominates the evolution.

If the donor star is neither on the main sequence nor already significantly evolved, the CV can evolve into an AM CVn star. For only slightly evolved donor stars, depending on the assumed strength of magnetic braking, the binary evolves towards shorter periods despite the donor star having developed a helium-rich core. While the system evolves towards shorter periods similar to standard CVs, the period bounce at ~ 80 min does not occur. In contrast, the binary evolves towards shorter periods with the donor star becoming more and more hydrogen-poor. When the entire hydrogen envelope has been stripped from the donor, the system becomes an AM CVn.

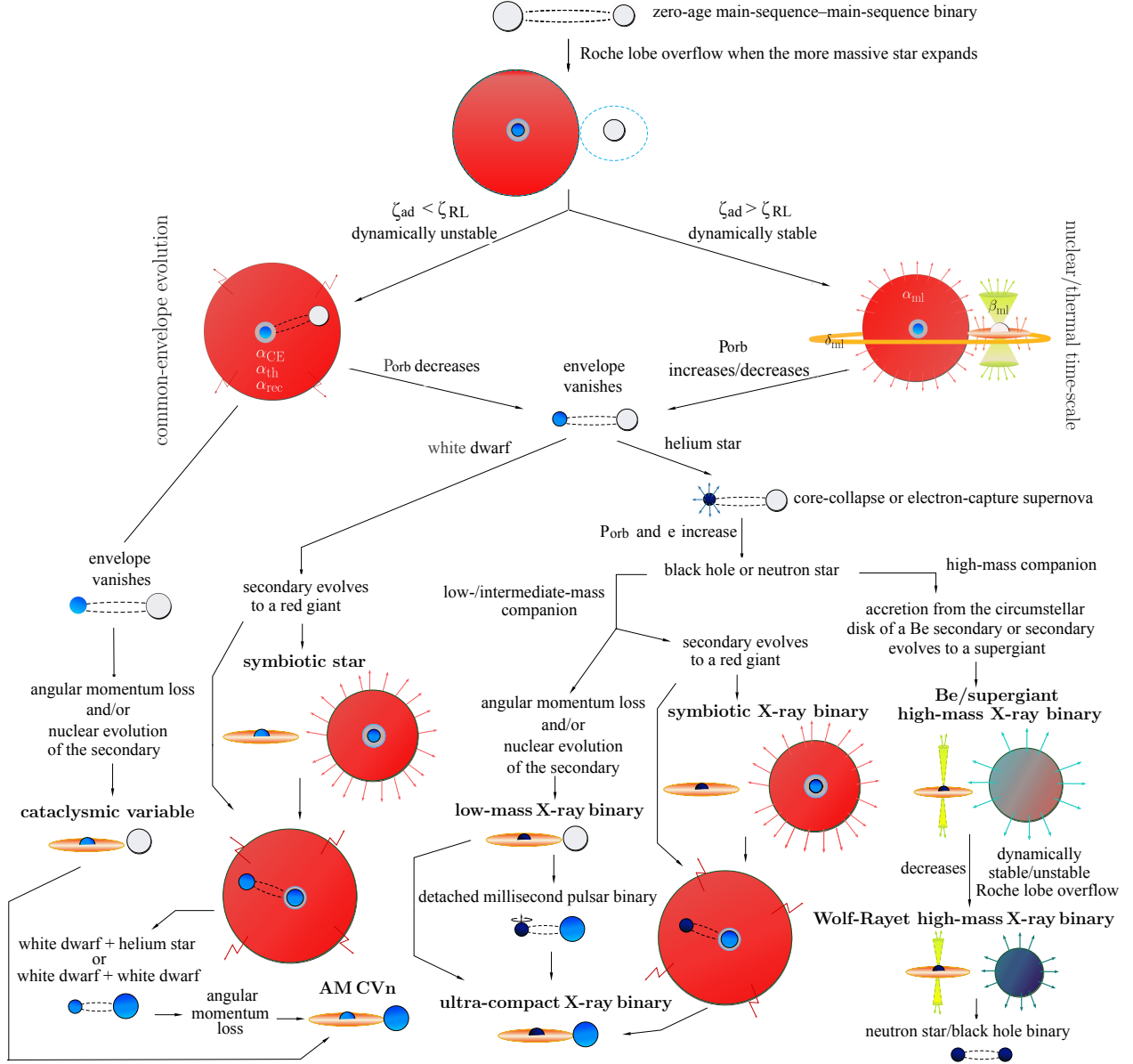


Figure 2.1: Different evolution channels from an initial zero-age MS-MS binary system. The left side of the figure shows the possible formation channels for an AM CVn. Starting from the zero-age MS-MS binary, the diagram shows the two possible scenarios of mass transfer with their corresponding evolution: CV from CE phase and WD/WD or WD/He from CE-CE or St-CE. In this thesis, the original diagram was corrected according to the analysis of Belloni and Schreiber (2023b) for the CV channel

Source from original: Belloni, D. & Schreiber, M. R. (2023). Formation and Evolution of Accreting Compact Objects. https://doi.org/10.1007/978-981-16-4544-0_98-1

2.2 Magnetic fields in white dwarfs

In this thesis, we combine the formation of AM CVn binaries and magnetic field generation in WDs with the aim to progress with our understanding of both processes. In this context, it is important to review our current knowledge of magnetic fields in WDs. In what follows we therefore discuss both observational constraints and theoretical scenarios concerning the origin of magnetic fields in WDs.

2.2.1 Observations of magnetic white dwarfs

Several decades ago, [Blackett \(1947\)](#) postulated that the presumed fast rotation of WDs can drive a dynamo, generating a strong magnetic field. The first detection of a magnetic WD, however, was obtained more than twenty years later ([Kemp et al., 1970](#)). Ever since this groundbreaking discovery, the question of why some WDs become strongly magnetic, while others do not, represents an unsolved question of stellar evolution.

While we have discovered and characterized large numbers of magnetic WDs, especially through spectroscopic surveys such as the Sloan Digital Sky Survey, we still struggle to understand the origin of these magnetic fields. Important information might be provided by the fact that the fraction of strongly magnetic WDs among single stars and in different binary star settings is significantly varying.

The volume-limited sample of magnetic single WDs established by [Bagnulo and Landstreet \(2021\)](#) shows that the fraction of magnetic WDs increases with age and is about 20 %. A high incidence of magnetic WDs, i.e. around 20-40 %, is seen among cataclysmic variables (CVs), semi-detached close binary stars in which a WD accretes from a Roche-lobe filling main sequence star ([Pala et al., 2020](#); [Inight et al., 2023](#)). In contrast, among the progenitors of CVs, detached WD plus main-sequence star binaries, the fraction of strongly magnetic WDs is very small, probably less than 1-2 % ([Liebert et al., 2005, 2015](#); [Parsons et al., 2021](#); [Schreiber et al., 2021b](#)). Different again is the situation for close detached binary stars consisting of two WDs as only one strongly magnetic WD is known among these systems ([Kawka et al., 2017](#); [Schreiber et al., 2022](#)). Finally, the key information on WD magnetic fields for this thesis is that only very recently, the first potentially weakly magnetic WDs have been detected among semi-detached double WDs, so-called AM CVn binaries ([Maccarone et al., 2024](#)). Strong magnetic fields seem to be entirely absent in these systems.

2.2.2 Theories for magnetic fields generation

Several ideas have been put forward to explain the origin of strong magnetic fields in WDs. The three most popular scenarios that have been suggested in the last decades are (i) the fossil field scenario in which it is assumed that the magnetic flux of the progenitor of the WD is conserved during the WD formation (e.g. [Angel et al., 1981](#); [Braithwaite and Spruit, 2004](#); [Wickramasinghe and Ferrario, 2005](#)); (ii) a dynamo generated during common-envelope evolution in close binaries ([Regós and Tout, 1995](#); [Tout et al., 2008](#); [Wickramasinghe et al., 2014](#)) and (iii) a dynamo process related to the merger of two degenerate cores or WDs ([García-Berro et al., 2012](#)). However, all three scenarios fail dramatically when their predictions are compared to observations. The fossil field scenario predicts far too few strongly magnetic WDs ([Kawka and Vennes, 2004](#)). In contrast, the common envelope dynamo scenario predicts far too many strongly magnetic WDs in close binary stars ([Belloni and Schreiber, 2020](#)). The double degenerate merger scenario cannot explain a large number of magnetic WDs among CVs as this would require stellar systems consisting initially of three stars. In addition, and perhaps most importantly, all three scenarios do not offer an explanation for the absence of young detached magnetic WD binaries (e.g. [Liebert et al., 2005](#)) and the late appearance of the magnetic fields in single WDs ([Bagnulo and Landstreet, 2021](#)).

The only proposed scenario that naturally explains the late appearance of WD magnetic fields, is the so-called crystallization and rotation-driven dynamo. The original idea has been put forward by [Isern et al. \(2017\)](#) for single WDs and was applied to WDs in binaries by [Schreiber et al. \(2021b\)](#). According to this idea, crystallization and rotation can drive a dynamo in C/O WDs that then generate strong magnetic fields. After a WD cooled for $\sim 1 - 2$ Gyr, depending on its mass, the carbon and oxygen in its core start to freeze in a lattice structure. In other words, the core starts to crystallize. During crystallization, the chemical potential, temperature, and pressure of the liquid and solid phases must remain equal. In crystallizing WDs this condition causes the solid phase to become richer in oxygen while the carbon excess mixes with the outer liquid envelope. The released gravitational energy causes convection in the liquid zone and, the situation resembles that of and some planets in our solar system: A solid core surrounded by a liquid and convective outer region. It is this configuration that, together with rotation, is supposed to generate the magnetic field of the Earth. It is therefore reasonable to assume that rotating and crystallizing WDs might be able to generate strong magnetic fields through a similar mechanism.

This scenario has been shown to explain a large number of observations of magnetic WDs in binaries: the increased occurrence rate of magnetic WDs in CVs, the paucity of magnetic WDs in the sample of observed double WDs, the large number of detached but close to Roche-lobe filling cold magnetic WD plus M-dwarf binaries, the existence of radio-pulsating WDs ([Schreiber et al., 2021b,a, 2022](#)), as well as the absence of high accretion rate polars in globular clusters ([Belloni et al., 2021](#)) and period bouncers in observed samples of CVs ([Schreiber et al., 2023](#)).

Chapter 3

Methods

Currently only two magnetic AM CVn have been discovered, none of which display a strong magnetic field. This is in strong contrast to other samples of WD binary stars. This investigation aims to find out whether AM CVn systems with strong magnetic fields are predicted to exist by state of the art population synthesis. This was achieved by evaluating two out of the three proposed channels of formation of these systems using the Binary Star Evolution (BSE) code.

3.1 Binary Star Evolution code

The BSE code is a rapid computational tool designed to simulate the evolution of binary star systems. It can model a wide range of physical processes such as mass transfer, angular momentum loss, and single stellar evolution to analyze and characterize the changes occurring within binary stars as they evolve through time. In the context of this thesis, we used BSE to simulate the evolution of approximately 1.2 million binary star systems, intending to find potential AM CVn stars and to evaluate if the predicted primary stars should be magnetic. The BSE code allowed us to explore the different scenarios and parameters involved in the formation of AM CVn systems, enabling a wide study of the influence of each star's properties on the mass transfer rate, orbital variations, and overall evolution of these systems. Nevertheless, when it comes to completing a detailed analysis of some processes such as dynamically stable mass transfer in cataclysmic variables, the BSE code might produce incorrect outcomes. During dynamically stable (angular momentum loss driven) mass transfer the detailed response of the donor star needs to be calculated which the BSE code is unable to do. The Binary Star Evolution (BSE) model may thus not provide a fully trustworthy analysis for AM CVn forming from CVs. Therefore, in this study, our focus is solely on the double WD (WD/WD) and the WD - He-burning Star (WD/He) formation channels. One of the inputs for the BSE code is the parameter α , which is associated with the orbital energy-transferring efficiency needed to unbind the hydrogen envelope during the common envelope phase

(so-called CE efficiency). We executed the same simulation using BSE but with a mid-low value for α ($\alpha = 0.3$, that is suggested for WD binaries (Scherbak and Fuller, 2023), as well as a higher value ($\alpha = 1.0$) to examine the differences and similarities that might affect the comparison with observed data.

3.2 Mass Transfer Stability

We simulated the evolution of WD binary stars up to the point where helium mass transfer onto a WD starts. In an AM CVn system, the mass transfer between the two WD stars needs to be dynamically stable. In order to categorize the candidate binaries for AM CVn systems, we utilized the results obtained by Marsh et al. (2004) on the stability of mass transfer between WDs. Their analysis indicates that the stability mostly depends on the mass ratio of both stars and the orbital separation between them, as described by the following equations.

$$q > 1 + \frac{\zeta_2 - \zeta_{r_L}}{2} - kr_1^2(1 + q)\lambda \quad (3.1)$$

$$q < 1 + \frac{\zeta_2 - \zeta_{r_L}}{2} - \sqrt{(1 + q)r_h} \quad (3.2)$$

$$q < 1 + \frac{\zeta_2 - \zeta_{r_L}}{2} - \sqrt{(1 + q)r_1} \quad (3.3)$$

Equation 3.1 describes the conditions for unstable mass transfer, while the equation 3.2 describes stable mass transfer in the case of direct impact accretion, and the equation 3.3 is the same but with r_1 instead of r_h , describing the stable transfer for disc-fed accretion case, that is, when a disc is formed on the accretor due to the transfer of mass. The switch between the last two cases occurs at $M_1 \approx 1M_\odot$. All variables and parameters from these equations are described in table 3.1.

Variable	Description
$M_1; M_2$	Mass of WD ; Mass of donor star
$R_1; R_2$	Radius of WD ; Radius of donor star
q	M_2/M_1
a	Orbital Separation
ζ_2	$\frac{d \log R_2}{d \log M_2}$
ζ_{r_L}	$\frac{(1+q)}{3} \frac{2 \ln(1+q^{1/3}) - q^{1/3}/(1+q^{1/3})}{0.6q^{2/3} + \ln(1+q^{1/3})}$
λ	$1 + 2 \frac{d \log R_1}{d \log M_1} + \frac{d \log k}{d \log M_1}$
k	$0.1939(1.44885 - M_1)^{0.1917}$
r_1	R_1/a
r_h	$\approx 0.0883 + 0.04858 \log(q^{-1}) + 0.11489 \log^2(q^{-1}) - 0.020475 \log^3(q^{-1})$

Table 3.1: Description of variables for mass transfer stability equations 3.1, 3.2, 3.3. The last variable (r_h) was described by Verbunt and Rappaport (1988), as $r_h = R_h/a$, where R_h is the equivalent radius of the matter orbiting the accreting star, i.e the radius that the accreting matter would have around the WD before forming a disk, from the inner Lagrangian point to the neighborhood of the accreting star.

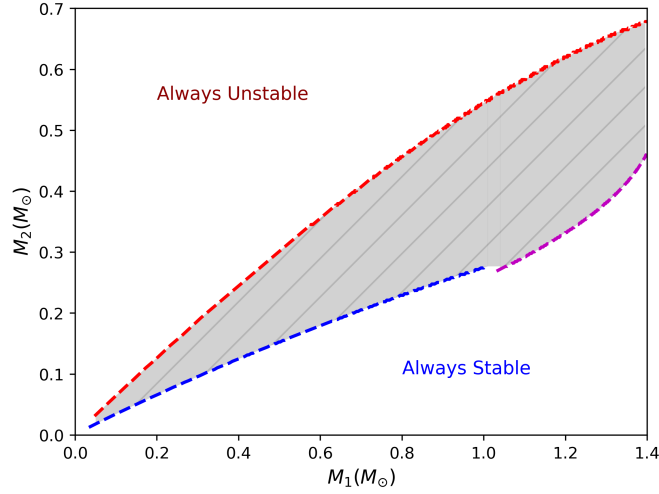


Figure 3.1: Graphical depiction of the mass ratio conditions for stability in the process of mass transfer between two WDs. The red dashed line represents the lower limit for guaranteed instability in the transfer of material. The blue dashed line represents the upper limit for guaranteed stability in the direct impact case, whereas the magenta dashed line represents the upper limit for guaranteed stability in the disc-fed accretion situation. The grey region represents the range of mass ratios where the transfer of mass may be dynamically stable or unstable, in this thesis, we refer to this zone as the Uncertainty Region.

As is described in figure 3.1, some simulated systems might have mass ratios that are located in the Uncertainty Region defined by the difference between the two cases. For our statistical analysis, we considered both the certainly stable cases and the stable + uncertain ones, distinguishing them as distinct categories.

3.3 Binary Population Synthesis

In order to obtain a statistically significant sample of stars with a wide and realistic range of properties, we started by generating a population of 50 million binary star systems with randomly assigned values for mass, age, and orbital separation. Then we applied the Monte Carlo method to filter them based on the following equations.

$$\xi(m) \propto m^{\alpha_i} \begin{cases} \alpha_1 = 0.3 & 0.01 \leq m/M_\odot < 0.08 \\ \alpha_2 = 1.8 & 0.08 \leq m/M_\odot < 0.5 \\ \alpha_3 = 2.7 & 0.5 \leq m/M_\odot < 1.0 \\ \alpha_4 = 2.3 & 1.0 \leq m/M_\odot \end{cases} \quad (3.4)$$

Equation 3.4 represents the Initial Mass Function (IMF) described by Kroupa (2001). The variable α_i from IMF is a dimensionless exponent and is not related to the CE efficiency parameter α from BSE. The behavior of IMF is visually depicted in figure 3.2.

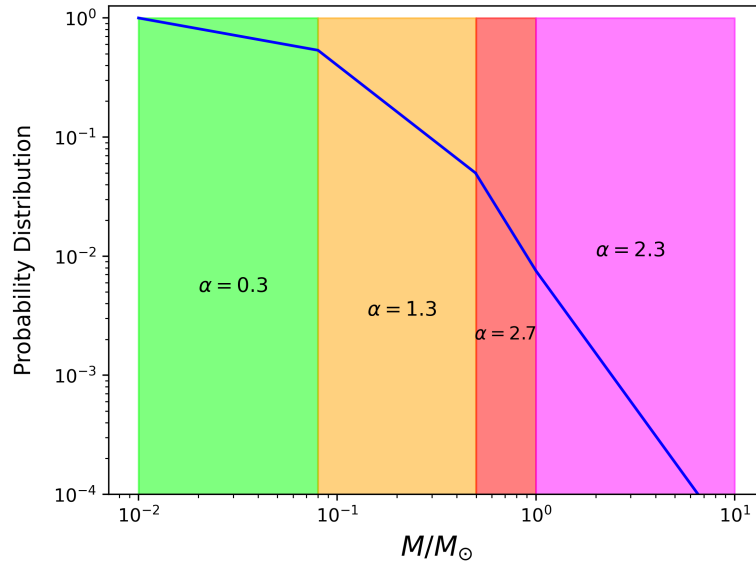


Figure 3.2: Behaviour of mass distribution based on Kroupa’s IMF at each value of exponent α . The original simplified equation commonly uses $\alpha = 2.3$ in the red area, but the change to $\alpha = 2.7$ was described by Kroupa (2001) as a correction from observed binaries, so we used this version.

$$n(q) = \left\{ \begin{array}{ll} \mu q^\nu & 0 < q \leq 1.0 \\ 0 & q > 1 \end{array} \right| \quad (q = M_2/M_1) \quad (3.5)$$

Initial Mass-Ratio Distribution (IMRD) described by [Davis et al. \(2008\)](#) in equation 3.5. we assumed a flat distribution based on the investigation made by [Zorotovic and Schreiber \(2013\)](#). Thus the IMRD is simplified as $q < 1$.

$$\begin{aligned} M_1 &\geq 0.87 && \text{Minimum Mass for C/O WD evolution} \\ M_2 &\geq 0.08 && \text{Minimum Mass for He WD evolution} \end{aligned}$$

We used the simplified IMRD relation for filtering the initial mass of the companion star (M_2), in combination with the two minimum mass conditions for WD evolution. As He-burning stars have higher initial masses than He WD stars, the He WD mass condition also works for He-burning star evolution.

$$h(a) = \left\{ \begin{array}{ll} 0 & a/R_\odot < 3 \quad \text{or} \quad a/R_\odot > 10^6 \\ 0.078636a^{-1} & 3 \leq a/R_\odot \leq 10^6 \end{array} \right. \quad (3.6)$$

Initial Orbital Separation Distribution (IOSD) described by [Davis et al. \(2008\)](#) as in equation 3.6. We used it to obtain realistic orbital distances between both stars at the formation of the binary.

We applied the equations 3.4, 3.5 and 3.6 in the process of filtering the initial randomly generated data to get a realistic population of binary systems. Finally, we assumed a flat distribution for the assignment of the age of each binary, considering the maximum age as $\sim 13.7 \cdot 10^9$ years, i.e at the time when the first stars were formed at $\sim 10^8$ years after the Big Bang ([Bromm et al., 2009](#)).

3.4 In search of magnetic AM CVn

Once the simulation was concluded, the output data was carefully analyzed, aiming to identify any events of AM CVn evolution. Furthermore, the formation paths of these systems were also investigated, in order to get a better understanding of the processes that result in the formation of AM CVn stars. This part of the analysis aimed to determine the relative prevalence of each channel and their respective tendency to host a strongly magnetic WD, via statistically evaluating the results. The presence of strong magnetic fields in the simulated AM CVn systems was determined using the age of the primary star (WD) in combination with its mass. These two parameters allow us to determine whether the accreting WD started to crystallize and therefore could have generated

a strong magnetic field according to the crystallization and rotation-driven dynamo idea described by [Schreiber et al. \(2021b\)](#). Table 3.2 describes the mass-age correlation for crystallization in WDs.

$M_{WD}(M_{\odot})$	Age (Gyr)	$M_{WD}(M_{\odot})$	Age (Gyr)
0.45	3.601090	0.90	1.141814
0.50	3.362254	0.95	0.977598
0.55	3.014729	1.00	0.846713
0.60	2.629549	1.05	0.707408
0.65	2.275663	1.10	0.597439
0.70	2.023202	1.15	0.484545
0.75	1.741295	1.20	0.391335
0.80	1.502254	1.25	0.301358
0.85	1.319653	1.30	0.216126

Table 3.2: Mass-Age relation conditions for the onset of crystallization of the C/O WD in the AM CVn system

The age of the WD's was determined by calculating the time difference between the age of the system when the primary star evolved into a C/O WD, and the age of the system when the AM CVn is formed.

Chapter 4

Results

4.1 AM CVn binaries with BSE

In order to study and check the correct evolution of AM CVn systems simulated with the BSE code, we analyzed the time evolution of the structural parameters, mass, radius and orbital separation for four different AM CVn test-systems, representing the four formation channels, i.e. the WD/WD (CE-CE), WD/WD (St-CE), WD/He (CE-CE) and WD/He (St-CE) channels respectively. The correct understanding and verification of each channel is crucial for a precise theoretical investigation of the formation of AM CVn binaries, as we know that the BSE code has limitations when evolving CV stars, due to the complexity of their formation phases.

We focus specifically on the mass-time evolution, as we are looking for strongly magnetic AM CVn, which is estimated according to the mass-age relation conditions for crystallization from table 3.2. It is also crucial to check the correct evolution and variations of the radius and orbital separation between the stars, as they are important for various processes such as mass transfer events and period changes along the evolution, which play a critical role in the formation of potential AM CVn systems.

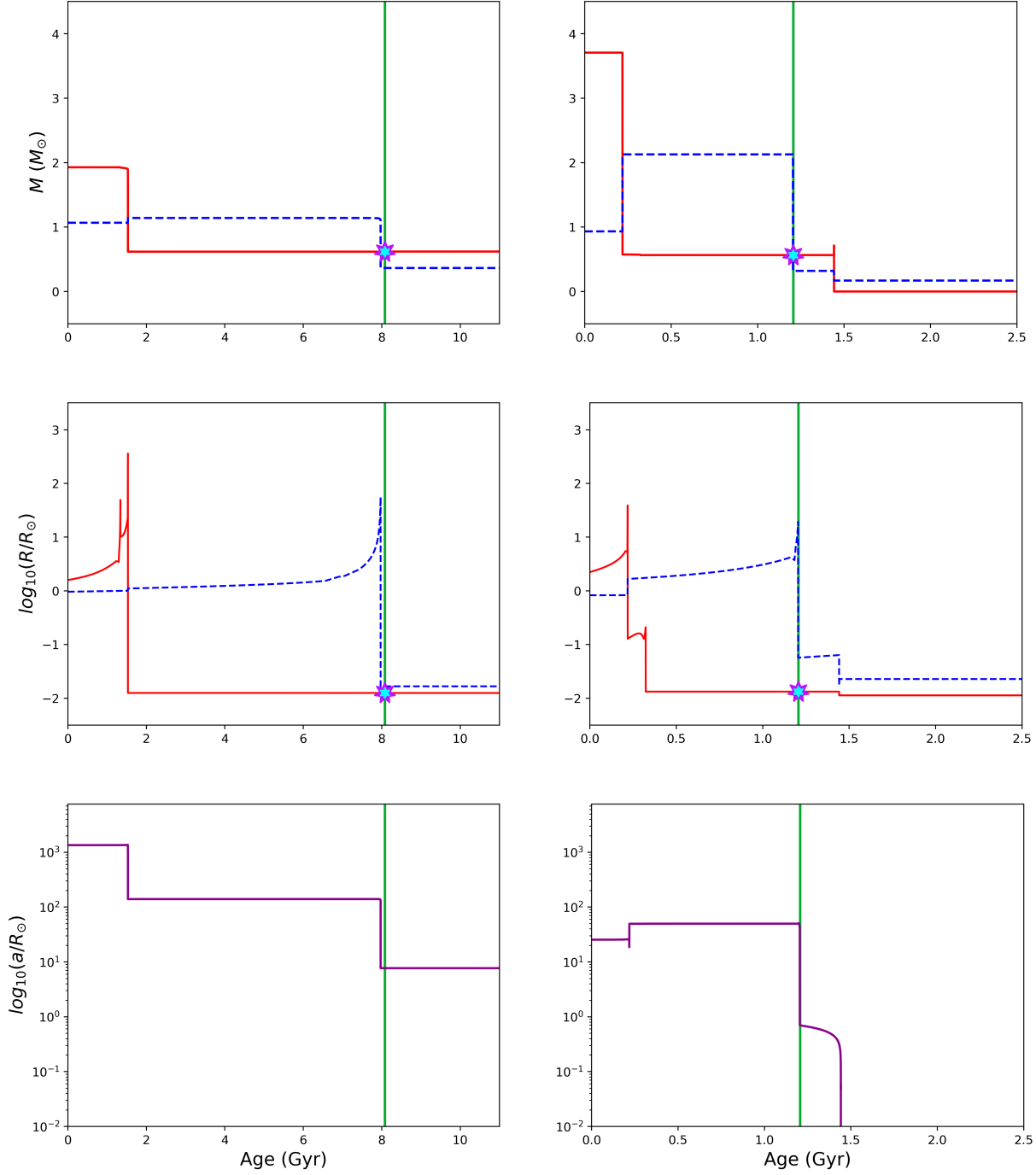


Figure 4.1: Evolution of the analyzed parameters of two sample systems from the simulation population for the WD/WD formation channel, using $\alpha = 0.3$. The left panels display the evolution of the CE-CE path, whereas the right panels represent the evolution of the St-CE pathway. The red line is the evolution of the C/OWD and the dashed blue line illustrates the evolution of the He WD. The star-like symbol denotes the instant when the correspondent star collapses as SN Ia, whereas the green region shows the system's age when it was an AM CVn.

The evolutionary analysis of AM CVn binaries formed through the WD/WD channel and the WD/He channel are shown in figures 4.1 and 4.2, respectively. After examining both analyses, we observed that the AM CVn stage is too short (less than $\sim 1 \text{ Myr}$) for most of the found systems before ending as an SN Ia or merging (this case is unsure), so we can not fully trust on the methods and calculations used by the BSE code for some processes, such as angular momentum loss-driven mass transfer, this is the same reason why we do not analyze the CV formation channel, as for CVs with hydrogen-accreting WDs, the mass angular momentum loss represents a crucial process for the onset of mass transfer phases. For this investigation, we are analyzing the evolution of the systems before and during the AM CVn stage, so these unsure results would not affect our statistical analysis.

Evolutionary tracks for AM CVn formation are illustrated in Figs. 4.1 and 4.2 for the WD/WD and the WD/He channel respectively. In both figures, the left panels show an example of AM CVn formation through the CE-CE formation pathway. The right panels illustrate AM CVn formation including a phase of stable mass transfer (St-CE pathways). When analyzing the evolution of the mass of the stars from the WD/WD channel, for both pathways the primary star loses mass when becoming a C/O WD and a fraction of that material is transferred to the secondary star. However, there is a difference in the fraction of matter that is accreted. During CE phases most of the total mass lost from the donor is not accreted by the other star because the material heats up due to viscous friction, and consequently, it vanishes. In contrast, during stable mass transfer phases a significantly larger fraction of the lost matter is successfully accreted as the transfer of mass is slower and self-controlled. The inverse process occurs at the second mass transfer phase. Subsequently, the system becomes an AM CVn and finally the accretor star explodes as a SN Ia (we do not consider the possibility of a SN Ia explosion in our analysis of the AM CVn population).

In the analysis of the radius (middle panels of figures 4.1 and 4.2), the evolution from MS to WD becomes more self-evident for both stars, as the primary shows two radius peaks corresponding to abrupt fusion processes of hydrogen and then helium, during the onset of the RGB and AGB phases, respectively. For the case of the secondary star, there is only one peak corresponding to the hydrogen layer fusion (there is no helium fusion as a He WD is formed).

The main difference between the CE-CE and the St-CE pathways appears in the evolution of the orbital separation between the stars (bottom panels of figures 4.1). For the CE-CE path the stars become closer during the evolution before finally becoming an AM CVn. In the St-CE path, the orbital separation increases during the first stable mass transfer event, and then decreases abruptly (through CE evolution) right before the AM CVn formation. This is logical as during a CE event, orbital energy is used to unbind the envelope and thus the separation between both stars always decreases. In contrast, during stable mass transfer, it is more uncertain if the separation increases or decreases as it depends on the angular momentum loss of the system.

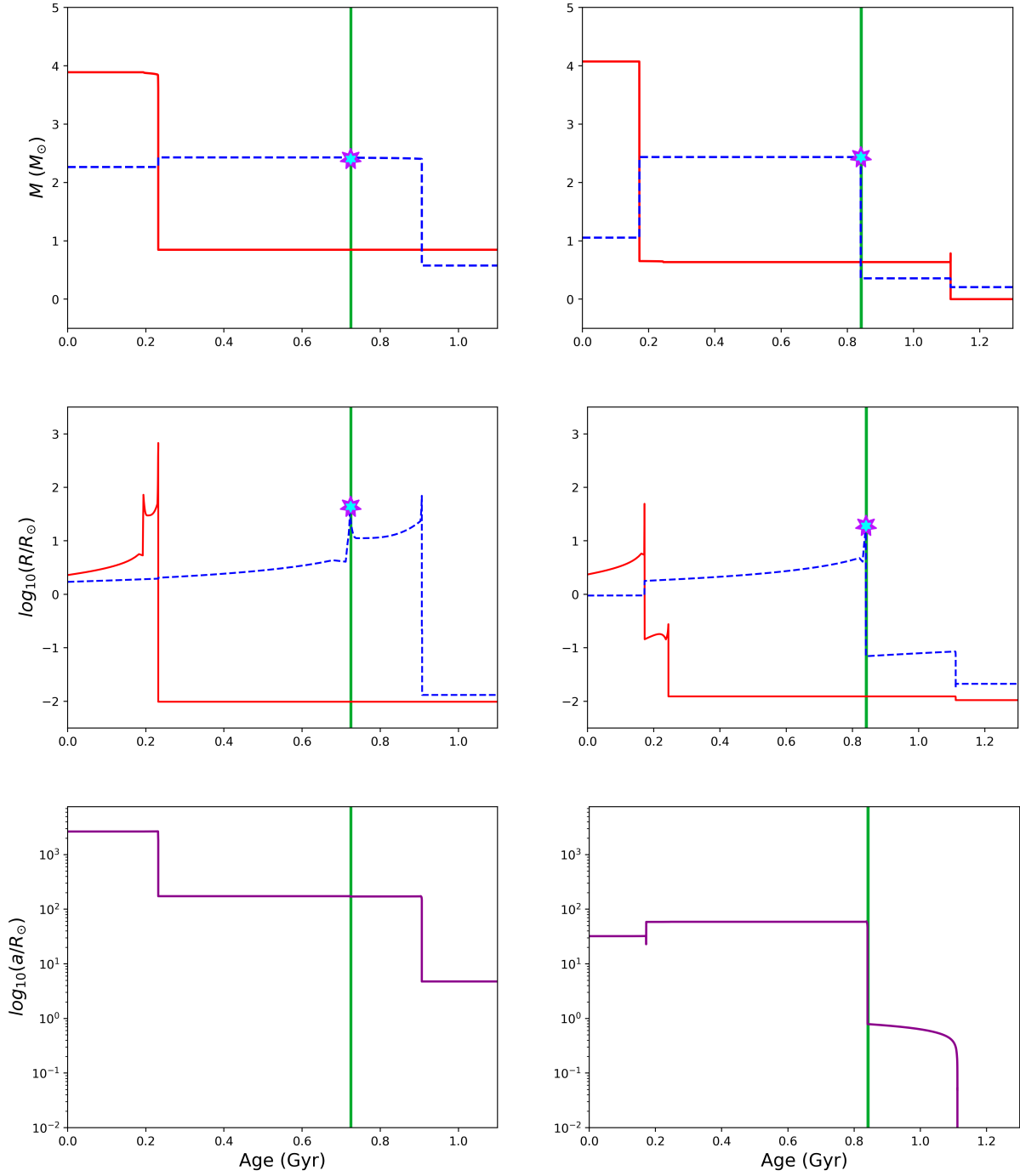


Figure 4.2: Evolution of the analyzed parameters of two sample systems from the simulation population for the WD/He formation channel, using $\alpha = 0.3$. The left panel displays the evolution of the CE - CE path, whereas the right panel represents the evolution of the St - CE pathway. The red line is the evolution of the C/OWD and the dashed blue line illustrates the evolution of the He WD. The star-like symbol denotes the instant when the stars coalesce, whereas the green region shows the system's age during the AM CVn phase.

Similarly to the WD/WD evolution, the mass of the primary decreases abruptly during the first mass transfer event, while the secondary star’s mass slightly increases at first but then abruptly decreases during the final CE phase. The radius evolution shows the two peaks corresponding to the formation of the C/O WD in both paths, but for the case of the He-burning star, the CE-CE path shows that the radius of the secondary star increases after an apparent coalescence and merge between the WD and the He-burning donor star, according to BSE, and then the radius abruptly decreases to $\sim 0 R_{\odot}$. While the St-CE path shows an always-decreasing radius of the secondary after the presumed coalescence. Both cases would require further detailed analysis of the BSE code’s evolutionary calculations and equations, as the He-burning star keeps evolving after, apparently, merging with the accreting WD. Regarding this thesis, those unsure results are negligible as we only analyzed the systems until the beginning of the AM CVn phase. As in the WD/WD case, the orbital separation evolution (bottom panels of figure 4.2) is different in both pathways, due to the CE and stable mass transfer initial phases. Again, the orbital separation increases for the St-CE path at first, and decreases then in the CE phase, while it is always decreasing for the CE-CE pathway.

As it was examined, in this case, the evolution of the system from the WD/He channel (figure 4.2), shows an important difference in comparison with the evolution from the WD/WD channel (figure 4.1), as the WD does not collapse as SN Ia, instead is the He-burning donor star that gets tidally disrupted by the accreting WD and both end up merging, according to BSE. As we can not fully trust on the calculations of the BSE code of mass transfer stability after the AM CVn phase, some predicted coalescence and merging events may not be realistic in these scenarios. A better understanding of these issues would require future further analysis with a more precise evolutionary code as Modules for Experiments in Stellar Astrophysics (MESA) (Paxton et al., 2010). Then, having analyzed the formation of AM CVn binaries from each channel that we consider in this work, we can conclude that the calculations of the BSE code are sufficiently accurate at least until the beginning of the AM CVn phase, which is our subject of interest for this study.

4.2 Initial Binary Population

As the BSE code can accurately describe the formation of AM CVn binaries through the WD/WD and WD/He channels, we used the initial population equations described in section 3.3 to predict a representative sample of AM CVn binaries using Monte Carlo techniques and BSE.

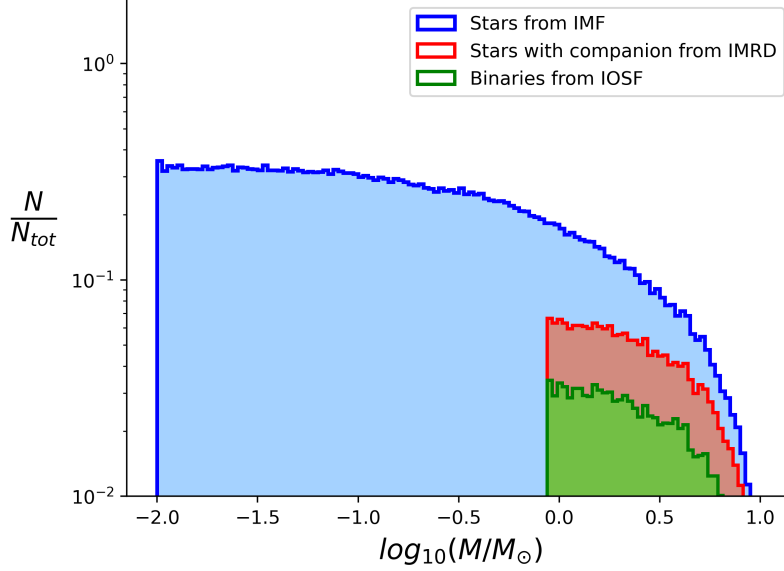


Figure 4.3: Number distribution of an initial 500 000 stars sample, resulting from the initial binary population synthesis. The blue histogram represents the distribution of stars obtained with [Kroupa \(2001\)](#) IMF for single stars. The red histogram shows only the same previous stars that passed the filter using [Davis et al. \(2008\)](#) IMRD and the green histogram represents the resulting stars after passing the last filter from [Davis et al. \(2008\)](#) IOSF.

The initial population used for the simulation in this thesis follows the same type of distribution as the one represented in Figure 4.3, but for an initial 50 000 000 population instead of 500 000, the final population (represented as the green histogram in Figure 4.3) after applying Monte Carlo method is 1 240 857 binary systems.

4.3 AM CVn formation analysis

After evolving our initial binary population of 1 240 857 systems using the BSE code with the different values for the CE efficiency for CE phase, i.e. $\alpha = 0.3$ and $\alpha = 1.0$, we analyzed the resulting data, looking for AM CVn systems and classifying them according to their formation channel. We also displayed all of them in the mass transfer stability plot, described in figure 3.1, according to the respective mass-ratios of each AM CVn system, to illustrate the different formation channels and the corresponding mass transfer stability.

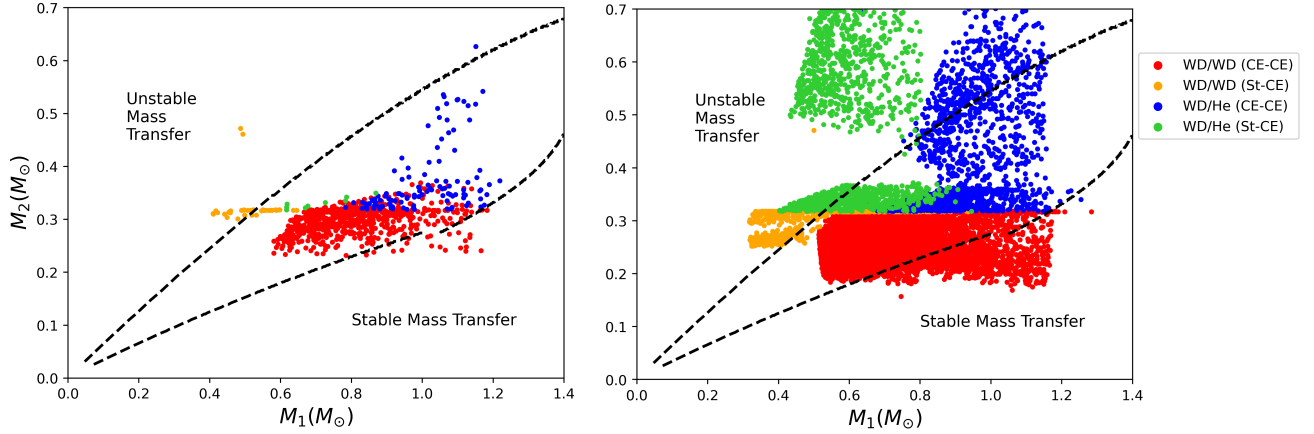


Figure 4.4: The left panel shows the mass ratio distribution for each channel in the simulation using $\alpha = 0.3$ while the right panel represents the distribution obtained by assuming $\alpha = 1.0$. Each dot represents a found candidate to AM CVn in the simulation. The WD/WD channel is represented by red and orange circles for the CE-CE path and the St-CE, respectively. Blue and green circles represent the WD/He(CE-CE), and the WD/He(St-CE) channel respectively. Some binaries from the WD/He channel are not shown in the right panel because it was limited to $0.0 - 0.7 M_\odot$ for M_2 , higher masses for the donor produce unstable mass transfer so they are not relevant in the context of AM CVn.

As we are studying AM CVn systems, we focus on the binaries that are expected to enter stable mass transfer, this means that they should have mass ratios locating them in the region for stable mass transfer or at least in the Uncertainty Region. We called the sample of systems found in the Uncertainty Region plus in the certainly stable mass transfer region *candidates to AM CVn*. The sample consisting of only those located in the region that certainly leads to stable mass transfer is called *AM CVn systems*. Figure 4.4 shows the distribution of the binaries from each channel, in the mass transfer stability diagram, where the AM CVn binaries coming from the WD/WD channel are dominant at lower donor star masses, while those from the WD/He channel are dominant at higher donor masses. This is easy to understand as donor stars from the WD/He channel are still burning helium in their cores, so their masses are higher than those of HeWD's. In the figure the limit between both cases is evident at $M_2 \sim 0.3$.

Donor stars from WD/He channel also exhibit a distribution with masses higher than $\sim 0.7 M_\odot$ and an apparent gap between $0.35 \lesssim M_2 \lesssim 0.45 M_\odot$, this is a consequence of the core-ZAMS mass relation for He-burning stars (Han et al., 2002).

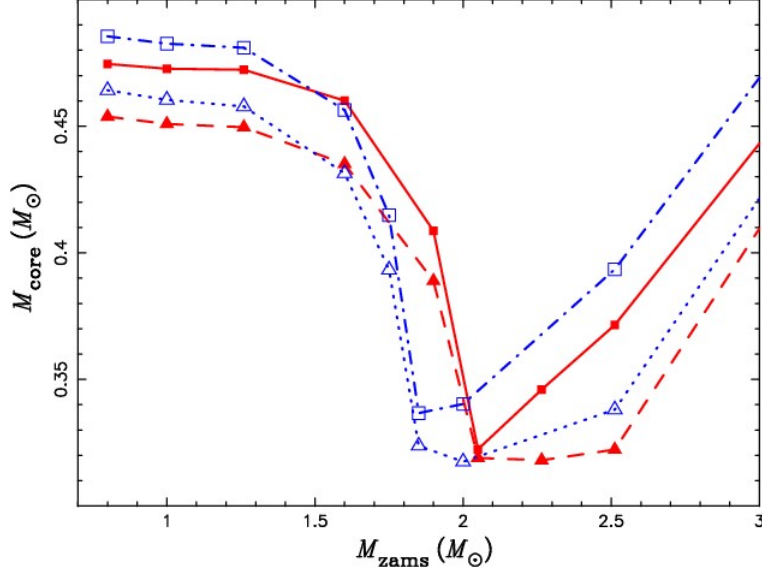


Figure 4.5: Core-ZAMS mass relation for He-burning stars. The range of core masses for the occurrence of a He flash varies as a function of initial ZAMS mass. The dashed and solid lines represent the curves for stars with $Z = 0.02$ (used in this thesis), while the dotted and dot-dashed curves represent stars with $Z = 0.004$. The lower curve for each set gives the minimum core mass above which a star burns helium, and the upper curve gives the core mass at the normal tip of the RGB.

Source: Han, Z. et al. (2002). The origin of subdwarf b star (i): the formation channels. <https://doi.org/10.1046/j.1365-8711.2002.05752.x>.

Figure 4.5 shows the relation between the He-burning core mass and the initial ZAMS mass, being constant for $M_{ZAMS} \lesssim 1.5 M_{\odot}$, fast-decreasing at $1.5 \lesssim M_{ZAMS} \lesssim 2.0 M_{\odot}$ and then increasing at $M_{ZAMS} \gtrsim 2.0 M_{\odot}$, as small variations of M_{ZAMS} between $\sim 1.5 - 2.0 M_{\odot}$ produce considerable differences in the He-burning core mass between $0.33 \lesssim M_{core} \lesssim 0.41 M_{\odot}$, is less probable for a binary to end up having a naked He-burning star in that range of masses, what produces a gap, similarly as in figure 4.4. But we also detected an error from BSE when calculating the masses of the resulting naked He-burning star, as the vast majority of stars have low masses ($\leq 1 M_{\odot}$), as in figure 4.3, then most of the He-burning star in our simulation should have masses about $\sim 0.47 M_{\odot}$, and the gap should be between $\sim 0.33 - 0.41 M_{\odot}$ instead of $\sim 0.4 - 0.5 M_{\odot}$ as in figure 4.4. However, this doesn't affect the results in this thesis as those naked He-burning stars would exhibit unstable mass transfer, so they wouldn't be considered for our analysis.

When comparing the two panels in figure 4.4, the overall distribution is similar for both values of α , but for the case of $\alpha = 1.0$ the number of found *candidates to AM CVn* systems is considerably higher because a higher value of α implies a higher CE efficiency at transferring orbital energy and unbinding the hydrogen envelope. Consequently, assuming a larger value of α implies a larger probability for a the binary to survive CE evolution and become a close post-CE binary. Besides,

in both cases, the vast majority of AM CVn stars candidates with stable mass transfer, come from the WD/WD (CE-CE) channel, while the WD/He (CE-CE) is mostly located in the Uncertainty Region, and both the WD/WD (St-CE) and the WD/He (St-CE), show the tendency to lead to unstable mass transfer (as the third mass transfer phase). The detailed statistical analysis from figure 4.4 is described in tables 4.1 and 4.2.

α	WD/WD		WD/He		Total AM CVn candidates
	CE - CE	St - CE	CE - CE	St - CE	
0.3	683	16	112	10	821
1.0	8 119	195	1 386	375	10 075

Table 4.1: Number distribution of all *candidates to AM CVn* stars at each analyzed channel of formation, including the systems with a stable mass transfer and the systems in the Uncertainty Region as well

When considering the *AM CVn candidates* found with stable mass transfer and those in the Uncertainty Region as well, the observations from figure 4.4 are more evident, for an CE efficiency $\alpha = 0.3$, the total possible AM CVn systems are $\approx 0.066\%$ out of the initial binary population (1 240 857), whereas for $\alpha = 1.0$, the possible AM CVn binaries are $\approx 0.812\%$. For both values of α , the WD/WD channel dominates over the WD/He channel, with more than 80% of the total *AM CVn candidates* forming through this channel. Independent of the CE efficiency during CE phases, the CE-CE path dominates over the St-CE channel. More than 95% of *AM CVn candidates* coming from the WD/WD channel and $\approx 92\%$ and $\approx 79\%$ coming from the WD/He channel (for $\alpha = 0.3$ and $\alpha = 1.0$) evolved through two CE.

α	WD/WD		WD/He		Total AM CVn found
	CE - CE	St - CE	CE - CE	St - CE	
0.3	21	0	0	0	21
1.0	1 072	0	1	0	1 073

Table 4.2: Number distribution of found AM CVn stars, only for those that have been verified to exhibit a stable mass transfer for each analyzed formation channel

As the mass transfer stability is still not well understood for the Uncertainty Region (table 4.2), we also analyzed the distribution considering only the AM CVn with certainly stable mass transfer. The results of this analysis show that for $\alpha = 0.3$ AM CVn systems form from $\approx 1.7 \cdot 10^{-3} \%$ of the 1 240 857 initial binaries and $\approx 0.086\%$ for $\alpha = 1.0$. The WD/WD channel remains dominating over the WD/He channel ($\approx 100\%$). Only one AM CVn was found to come from the WD/He channel with $\alpha = 1.0$. For $\alpha = 0.3$ all the AM CVn came from the WD/WD channel. Evolution

through the CE-CE channel again dominates as 100% of systems in both channels and for both values of the α parameter evolved through two CE phases.

4.4 Crystallization Analysis

In our final study, we re-analyzed the AM CVn binaries found in the analysis made in section 4.3 and used the mass and age of each identified AM CVn system and determined whether the primary star should have reached the conditions for crystallization described in table 3.2. This way we found the fraction of strongly magnetic AM CVn binaries predicted by our investigation to exhibit a magnetic field produced through the crystallization and rotation-driven dynamo model.

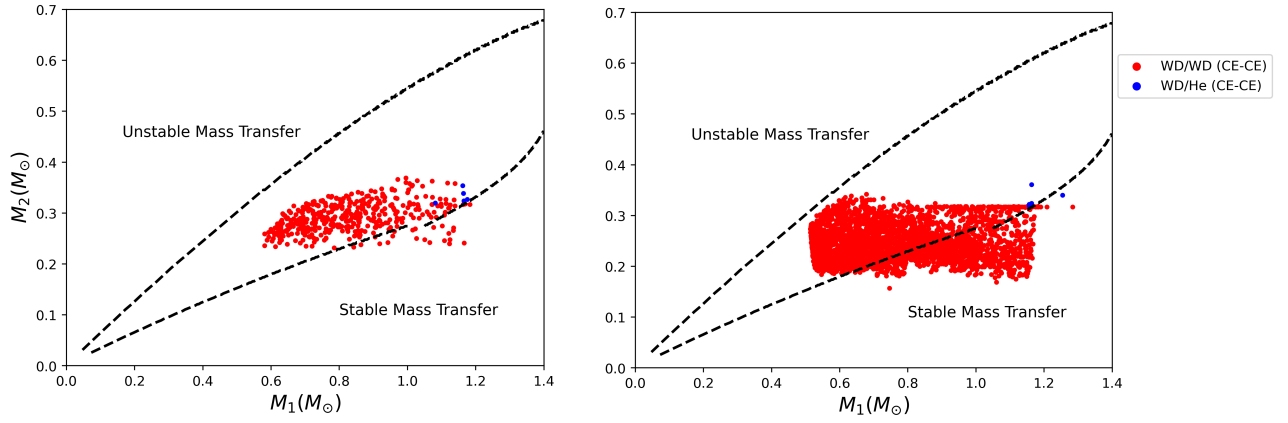


Figure 4.6: Mass transfer stability distribution for crystallized *candidates to AM CVn*. The left panel shows the mass ratio distribution for each channel in the simulation using $\alpha = 0.3$, while the right panel represents the distribution for the simulation using $\alpha = 1.0$. The WD/WD (CE-CE) channel is represented by red circles. Blue circles represent the WD/He (CE-CE) channel.

When analyzing the *AM CVn candidates* systems that are crystallized in figure 4.6 we again found that most form through the WD/WD (CE-CE) channel and only a few through the WD/He (CE-CE) channel. In addition, most systems are located in the Uncertainty Region. As in section 4.3, our detailed statistical analysis of the data shown in figure 4.6 is described in tables 4.3 and 4.4.

α	WD/WD		WD/He		Total crystallized AM CVn candidates
	CE - CE	St - CE	CE - CE	St - CE	
0.3	431	0	5	0	436
1.0	3 218	0	6	0	3 224

Table 4.3: Distribution of all *candidates to crystallized AM CVn* stars at each analyzed channel of formation, including the systems with a stable mass transfer and the systems in the Uncertainty Region as well

The dominance of the WD/WD and CE-CE channel is even more evident in this analysis than in the formation channel analysis from section 4.3. $\approx 99\%$ of the total *candidates to AM CVn* that crystallize according to our analysis come from the WD/WD (CE-CE) path while the other small fraction comes from the WD/He (CE-CE) channel. No *candidates to AM CVn* from any St-CE path meet the requirements for crystallization. Most importantly in the context of this thesis, comparing with the analysis from section 4.3, $\approx 53\%$ of the total *candidates to AM CVn* (i.e systems with certainly stable mass transfer plus systems in the Uncertainty Region) may crystallize for $\alpha = 0.3$ while 32% for $\alpha = 1.0$.

α	WD/WD		WD/He		Total crystallized AM CVn found
	CE - CE	St - CE	CE - CE	St - CE	
0.3	21	0	0	0	21
1.0	946	0	1	0	947

Table 4.4: Distribution of crystallized AM CVn, considering only certainly stable mass transfer, at each analyzed formation channel

For the case of the systems that certainly experience stable mass transfer (table 4.4) the comparison with the analysis from section 4.3 shows that $\approx 100\%$ of total AM CVn systems meet the requirements for crystallization if $\alpha = 0.3$ and $\approx 88\%$ if $\alpha = 1.0$. In other words, (almost) all AM CVn binaries from this simulation should present strong magnetic fields according to the crystallization theory.

From all our simulations and taking into account the uncertainties related to the stability of mass transfer, we conclude that at least about one-third of AM CVn binaries should be magnetic.

Chapter 5

Conclusions

We performed a theoretical binary population investigation of two channels proposed for the formation of AM CVn using the BSE code. The two channels we considered are the double WD channel according to which the direct progenitors of AM CVn are detached binaries consisting of two WDs (WD/WD channel) and the helium star channel in which the AM CVn forms from a binary composed of a WD with a helium core burning star companion (WD/He channel). A third channel, the CV formation channel, was not considered because of limitations of the BSE code that do not allow to properly calculate the evolution of CVs.

We used two different values of the CE efficiency (α) parameter for CE phases in the simulation. We assumed $\alpha = 0.3$, which is the value derived from observations of post-CE binaries, and $\alpha = 1.0$ which is a high-efficiency CE value frequently assumed in studies of SN Ia progenitors. For both channels we considered AM CVn formation through two CE phases as well as through a pathway consisting of a stable mass transfer phase followed by CE evolution.

As one of the criteria for AM CVn binaries is dynamically stable mass transfer between the two stars, we used a mass ratio condition to exclude unstable mass transfer systems. This also required a detailed analysis because this mass ratio criterion contains a so-called Uncertainty Region. Therefore, we made individual studies for all the systems that are potentially experiencing stable mass transfer (so-called *candidates to AM CVn*) and for systems that are certainly going to experience stable mass transfer. The latter clearly represents a more strict filter for AM CVn systems.

The analysis revealed that the WD/WD channel is predominant over the WD/He channel, with more than 80% of the total *candidates to AM CVn* binaries forming from double WDs. Assuming the stricter condition of mass transfer stability, this prevalence increases even to $\approx 100\%$. In both channels, the CE-CE pathway is the most common pathway with more than 95% of the AM CVn forming from two CE phases.

Our investigation finally demonstrated that strong magnetic fields in AM CVn binaries are

predicted to be produced by the crystallization and rotation-driven dynamo model. Taking into account uncertainties in the CE efficiency (α) parameter and the mass transfer criterion, we found that $\sim 30 - 100\%$ of the AM CVn systems would exhibit strong magnetic fields in their WD. This is in stark contrast with the observed absence of strongly magnetic AM CVn systems.

A plausible reason for these discrepancies is that in this thesis we did not analyze the CV formation channel. Since recent studies suggest that the CV channel could be the dominant formation channel of AM CVn, our results might be biased if the prevalence of that channel is remarkably high and supposing that the CV channel does not lead to the formation of strongly magnetic AM CVn. Another potential explanation is a model proposed for neutron stars that we think might be applicable for WDs in binaries as well. According to this model, during the accretion of He-dominated matter in the AM CVn, the previously detectable magnetic field of the WD may be completely buried by the accreted material because of screening currents in the surface.

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