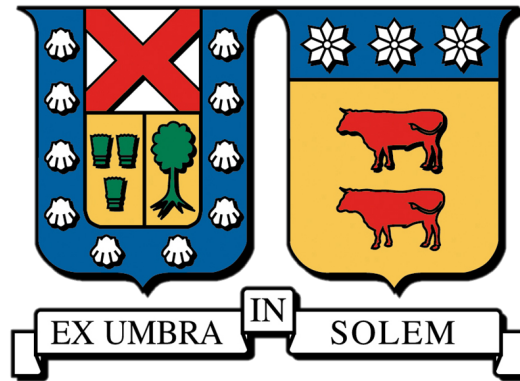


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DEPARTAMENTO DE FÍSICA



The Effect of Irradiation on Period Bouncers: Simulations in
Post-Minimum Period Systems

Xaviera Julio Carvajal

THESIS TO OBTAIN THE DEGREE OF BACHELOR IN ASTROPHYSICS

Tutor: Matthias R. Schreiber.

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Abstract

Cataclysmic variables that have evolved beyond their minimum orbital period, known as period bouncers, constitute fundamental interactive binary systems for our understanding of stellar evolution in compact systems. These systems, composed of a white dwarf accreting material from a degenerate substellar companion, represent a critical evolutionary phase that allows us to explore mass transfer mechanisms, angular momentum loss, and irradiation effects under extreme physical conditions.

However, there exists a striking discrepancy between theoretical models and observations: while population synthesis simulations predict that between 40-75% of all cataclysmic variables should be in this phase, current observations identify only 1.54% of systems in this state. This fundamental disparity challenges our understanding of the physical processes governing the evolution of these systems.

In this thesis, we implement numerical simulations using the MESA stellar evolution code to model the complete evolution of period bouncer systems from their pre-bounce phase to their final stage. We develop a new module that incorporates, for the first time, a quantitative treatment of mass loss induced by X-ray irradiation from the accreting white dwarf. The model considers the interaction between high-energy radiation and the donor star's atmosphere through an efficiency coefficient (c) that relates the mass loss rate to the mass transfer rate. Additionally, we formulate a new parametrization of CAML that incorporates both the traditional mass flow toward the white dwarf and an inverse component due to the ejection of irradiated material, thus establishing a more realistic treatment of these systems' orbital evolution.

The results reveal the existence of a critical value for the irradiation efficiency coefficient ($c \approx 0.05$) that determines a fundamental transition in system evolution. Above this threshold, systems experience rapid destabilization leading to a common envelope phase and to the merger of both stars.

We propose that this accelerated evolution, driven by the coupling between irradiation, mass loss, and angular momentum, provides a natural explanation for the observed scarcity of period bouncers.

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Chapter 1

Introduction

Cataclysmic variables (CVs) are compact binary systems in which a white dwarf (WD) accretes material from a companion that has filled its Roche lobe. Historically, the term cataclysmic was applied to these variables due to their seemingly random photometric behavior, derived from the Greek “kataklysmos”, meaning flood or storm (Rodriguez et al., 2020). In most CVs, the donor is a low-mass main-sequence star; however, as the system evolves and the donor loses mass, it may ultimately transform into a brown dwarf (BD). These systems, called “period bouncers”, represent an advanced evolutionary phase of CVs in which the system has reached a minimum orbital period, typically around 78 minutes (Galiullin et al., 2024).

At the “period bouncers” stage, the timescale on which the secondary star loses mass becomes much shorter than its thermal timescale. As a result, the secondary, now potentially a brown dwarf, ceases to contract in response to mass loss and begins to expand due to its degenerate nature. This expansion, driven by the properties of degenerate matter, causes a gradual increase in the orbital period (Patterson, 1998). Consequently, systems that have surpassed the minimum period evolve toward longer orbital periods, and for this reason, they are called “period bouncers”. During this process, interactions between the white dwarf and brown dwarf continue to modify the system’s dynamics (Pala et al., 2018).

Population synthesis models predict that a substantial proportion, between 40% and 75%, of CVs should consist of these period bouncers, where the donor is a brown dwarf (e.g., (Kolb, 1993); (Belloni et al., 2020)). However, observations reveal a starkly different reality. According to the Ritter and Kolb catalogue (Ritter and Kolb, 2016), a total of 1,429 cataclysmic variables have been identified. Among these, Muñoz-Giraldo et al. (2024) report that only 22 systems have been confirmed as period bouncers, representing approximately 1.54% of the total catalogued CVs. This figure falls far short of theoretical predictions, creating a significant discrepancy between estimates and observational data. This discrepancy has been attributed to various factors, including observational biases and the inherent difficulty of detecting these intrinsically faint systems.

While period bouncers are intrinsically faint due to their low accretion rates, and this makes their detection challenging in visible light surveys, the dramatic discrepancy between theoretical predictions and observations suggests a fundamental problem in our understanding of these systems, beyond mere observational biases (Pala et al., 2020). The confirmation of several systems through various detection methods, including eclipse-based surveys, demonstrates that these objects are detectable when they exist (Echevarría et al., 2023). The key problem appears to lie in the fact that most CV evolution simulations do not account for a crucial phenomenon: the intense irradiation of the companion star by X-rays from the white dwarf. In these systems, the energy released during the accretion process produces significant X-ray emission that strongly impacts their brown dwarf companions (Schreiber et al., 2019; Owen and Alvarez, 2016). This X-ray irradiation can dramatically alter the donor’s atmospheric structure and, consequently, the complete evolution of the system. The importance of this effect becomes particularly relevant in the context of period bouncers, where the brown dwarf’s low surface gravity makes it especially susceptible to irradiation effects (Rappaport et al., 2017; Lothringer and Casewell, 2020).

Recent studies have shown that irradiation can have significant effects on the atmospheric properties of brown dwarfs in compact binary systems. For example, Santisteban et al. (2016) reported the direct spectroscopic detection of an irradiated substellar donor in an accreting white dwarf binary system. Such systems provide a unique opportunity to study how substellar atmospheres respond to intense short-wavelength irradiation, a phenomenon not widely observed or modeled in detail (Lothringer and Casewell, 2020). Understanding this effect within period bouncers may reveal key insights into their detection challenges and apparent scarcity.

The primary aim of this research is to examine how irradiation-induced mass loss influences the angular momentum evolution and demographic distribution of period bouncer systems. Through detailed numerical simulations using the MESA code, this study seeks to develop a model that addresses the discrepancy between predicted and observed period bouncer populations. Specifically, we explore the extent to which white dwarf irradiation can explain the scarcity of observed period bouncers. Before presenting our analysis, we will briefly review the fundamental concepts related to cataclysmic variables and period bouncers, thus establishing the theoretical framework necessary for our investigation

Chapter 2

Evolution of Cataclysmic Variables

Cataclysmic Variables (CVs) are interacting binary systems that have been studied by astronomers for decades due to their rich evolutionary diversity. As illustrated in Figure 2.1, these systems can follow multiple evolutionary paths depending on their initial conditions and physical parameters (Belloni and Schreiber, 2023).

The evolutionary process begins with a primordial binary system composed of two main-sequence stars. When the more massive star evolves off the main sequence and expands its outer layers during the red giant branch (RGB) or asymptotic giant branch (AGB) phase, the system enters a critical common envelope phase (Patterson, 1984; Warner, 1995). After this phase, the system emerges as a cataclysmic variable, where mass transfer plays a crucial role. Mass transfer in CVs occurs when the donor star fills its Roche lobe, a region defined by the gravitational potential where matter is bound to the star. When the star expands to completely fill this lobe, material from its surface can flow through the L1 Lagrangian point towards the white dwarf (Rodriguez et al., 2020). The stability of this mass transfer process is fundamental to the system's evolution and is governed by the mass ratio (Marsh et al., 2004):

$$q = M_2/M_1 \tag{2.1}$$

where M_2 is the mass of the donor star and M_1 is the mass of the white dwarf. Mass transfer is stable when the following condition is satisfied:

$$q < 2/3 \tag{2.2}$$

This is a widely used simplified expression derived from a detailed analysis of mass transfer stability, which takes into account additional effects such as the feedback of angular momentum to the binary system. This approximation was originally derived by Marsh et al. (2004) in their study on mass transfer between white dwarfs. When $q > 2/3$, mass transfer becomes unstable,

causing the donor star to expand faster than its Roche lobe, potentially leading to another common envelope phase or even the merger of the two stars.

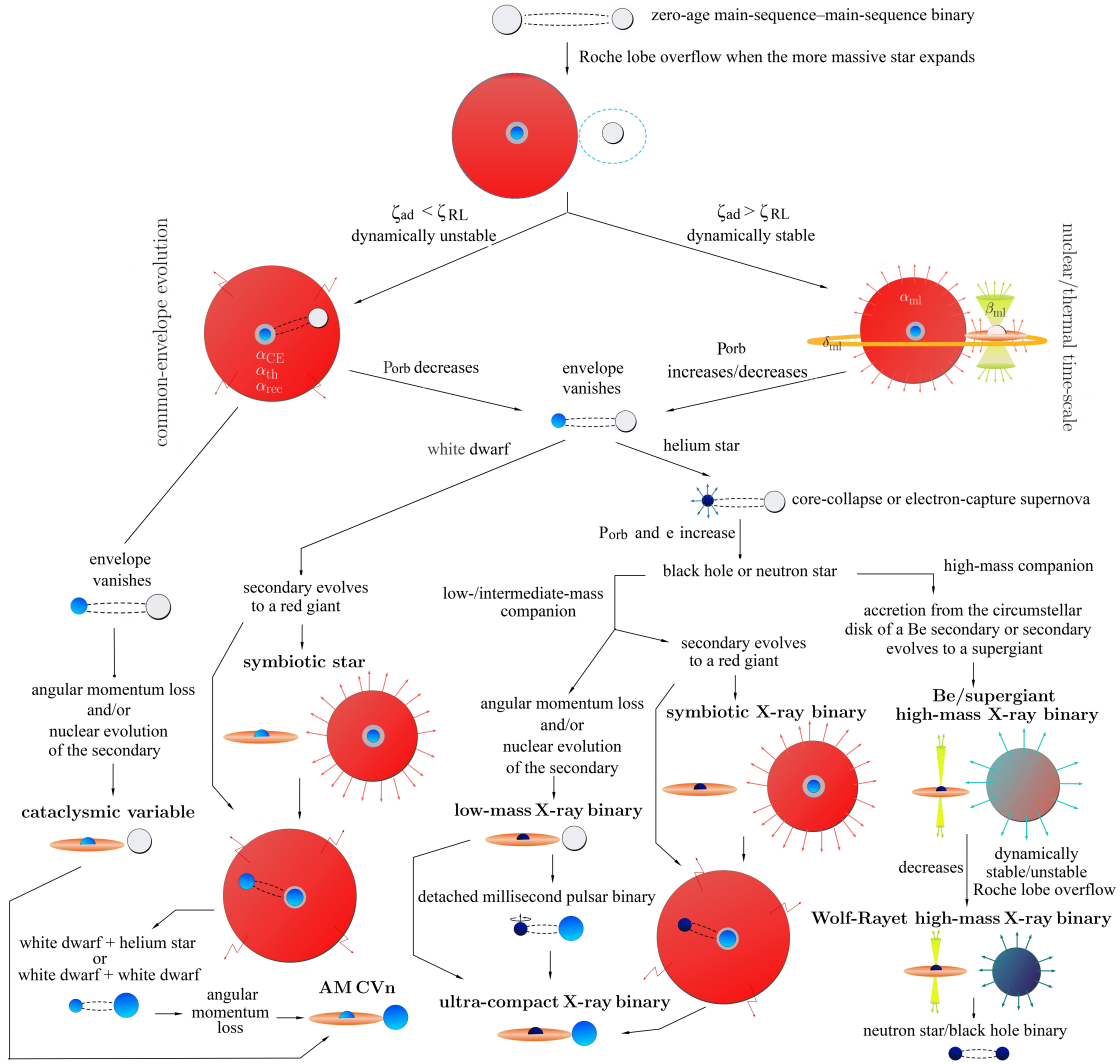


Figure 2.1: Schematic evolutionary diagram illustrating the diverse pathways of binary systems containing a white dwarf. The diagram traces multiple evolutionary sequences from initial main-sequence binaries (top) through various intermediate stages to their final configurations. Red circles indicate critical phases of mass transfer through Roche lobe overflow or common envelope evolution. White circles represent main-sequence or evolved companion stars, while blue dots represent white dwarfs, with their relative sizes indicating mass ratios. Solid arrows show the direction of evolution, with branching points determined by initial mass ratios (q) and orbital separations. The left branch, highlighted in this study, shows the classical CV formation pathway through common envelope evolution, while other branches lead to alternative outcomes such as X-ray binaries and AM CVn systems. The evolutionary sequences are based on current theoretical models (Belloni and Schreiber, 2023); however, a modification in the CV evolution was made in the work of Joaquín Barraza, which will be used in this study. This comprehensive visualization demonstrates the complexity and diversity of white dwarf binary evolution.

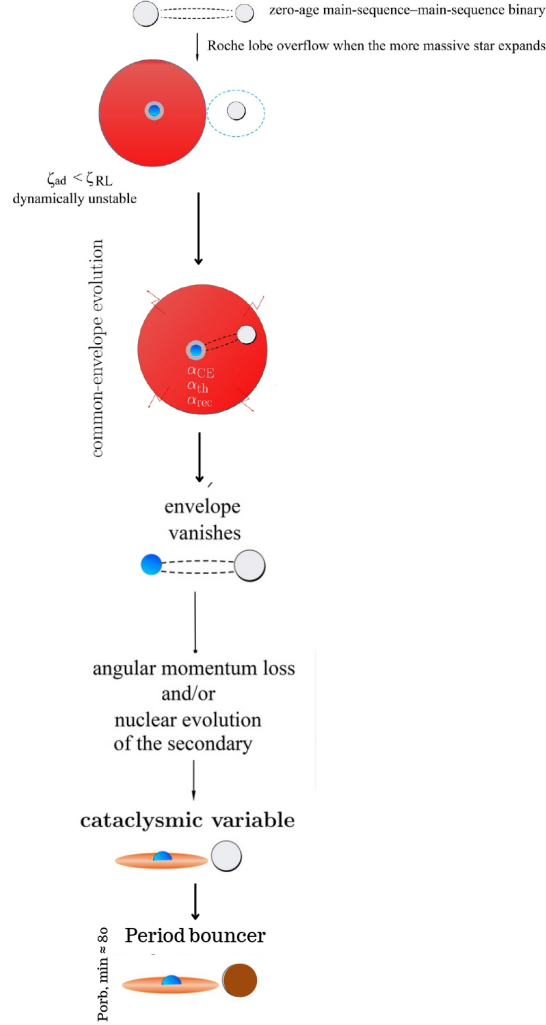


Figure 2.2: Detailed evolutionary sequence depicting the formation pathway of a period bouncer system. This diagram focuses specifically on the CV branch that leads to period bouncers, illustrating key evolutionary stages and physical processes. Red circles mark critical mass transfer events, particularly the common envelope phase and subsequent Roche lobe overflow episodes. Blue dots represent the primary white dwarf, while the companion star’s evolution is tracked from its main-sequence state (white circles, at the top) to its final brown dwarf configuration. The sequence highlights the crucial mass ratio threshold ($q > 2/3$) that triggers the common envelope phase, followed by the stable mass transfer regime ($q < 2/3$) characteristic of CVs (Marsh et al., 2004). Each stage includes approximate timescales and typical orbital period ranges. Particularly noteworthy is the transition through the minimum period (80 minutes) and the subsequent period bounce phase, where the orbital period begins to increase due to the degenerate nature of the donor star. This representation synthesizes the theoretical predictions from Belloni and Schreiber (2023) with recent observational data to provide a comprehensive view of period bouncer formation.

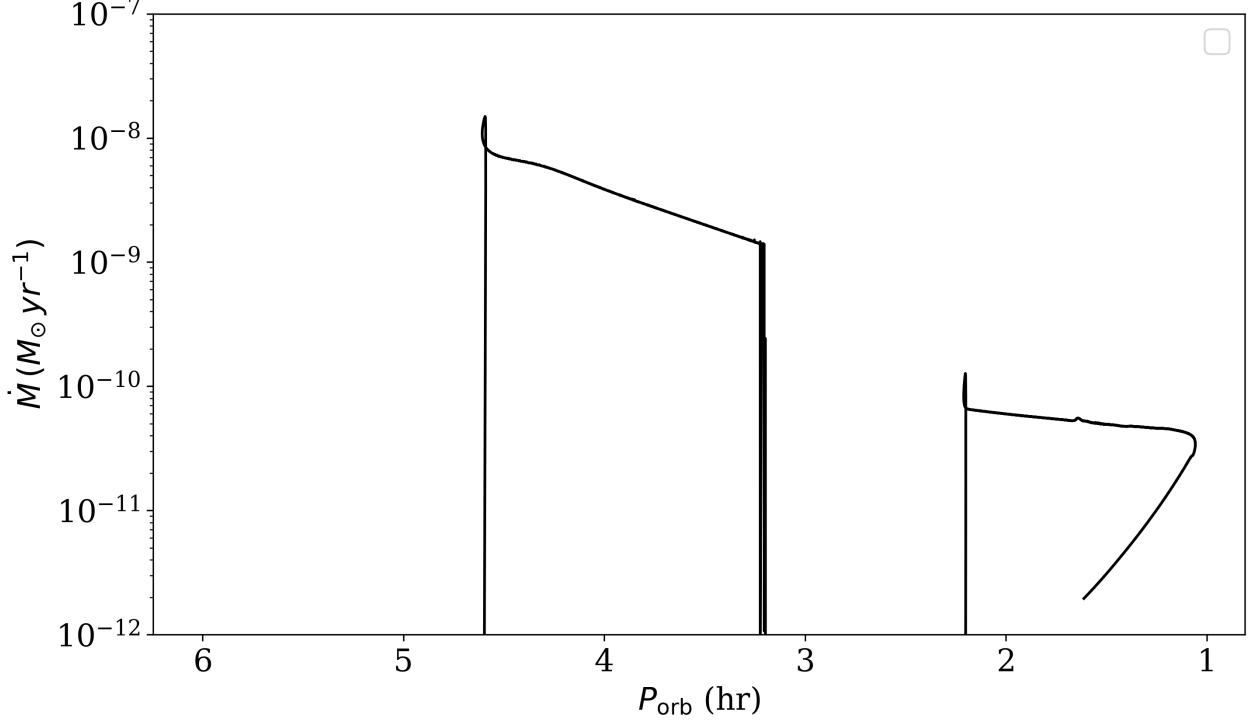


Figure 2.3: Mass transfer rate ($\dot{M}$) as a function of orbital period (P_{orb}) for CV systems. Evolution proceeds from left to right in the diagram. Systems start with high mass transfer rates ($\sim 10^{-8} M_{\odot} \text{ yr}^{-1}$) and long orbital periods (~ 5 hours). The period gap is visible between 2-3 hours as an interruption in mass transfer. After resuming transfer below the gap, the system evolves towards the period bouncer state, characterized by extremely low transfer rates ($\sim 10^{-11} M_{\odot} \text{ yr}^{-1}$).

One of the most interesting evolutionary outcomes for CVs, and the focus of this study, is the “period bouncer”, as shown in Figure 2.2. These systems are characterized by reaching a minimum orbital period of approximately 80 minutes (Gänsicke et al., 2009), after which the period begins to increase. This phenomenon occurs when the donor’s mass decreases to around $0.08 M_{\odot}$, and its core begins to experience partial electron degeneracy (Rappaport et al., 1983).

Figure 2.3 provides a quantitative representation of this evolution, illustrating how the mass transfer rate varies during the system’s lifetime. The evolution proceeds from left to right in the diagram, beginning with longer orbital periods and higher mass transfer rates. A fundamental aspect of this evolution is the period gap, a distinctive feature that occurs when the orbital period is between 2-3 hours, and is intrinsically related to the angular momentum loss mechanisms governing these systems.

In the initial phase, when orbital periods are above 3 hours, angular momentum loss is dominated by magnetic braking. This mechanism operates through the magnetized stellar wind of the secondary star, where the magnetic field, coupled with the stellar wind, acts as an effective “lever arm” that extracts angular momentum from the system. During this phase, the mass transfer rate

is relatively high, on the order of $10^{-8} \text{ M}_{\odot} \text{ yr}^{-1}$, reflecting the efficiency of this mechanism.

When the secondary star’s mass reaches approximately $0.3 \text{ M}_{\odot}$, its internal structure undergoes a dramatic reorganization, becoming fully convective. The term “convective” refers to the energy transport mechanism within the star. When a star is fully convective, energy transport from its interior to its surface occurs primarily through the physical movement of stellar plasma, similar to how water boils in a pot: hot material rises while cooler material sinks (Webbink and Wickramasinghe, 2002). This change in the star’s internal structure has profound implications for its magnetic field, as the fully convective structure significantly alters the stellar dynamo dynamics, the mechanism that generates and maintains the star’s magnetic field. As a consequence, the surface magnetic field substantially weakens, which dramatically reduces the efficiency of magnetic braking that drives mass transfer (Verbunt, 1984). The reduction in magnetic braking efficiency means the system can no longer maintain the same mass transfer rate it had previously.

The period gap, visible in Figure 2.3 as a region where mass transfer practically disappears, represents an “empty space” in the orbital period distribution of CVs (Schreiber et al., 2024). This void is not a statistical coincidence but a direct consequence of the system’s evolution. During this phase, the star contracts within its Roche lobe and mass transfer practically ceases, explaining the scarcity of observed systems with periods between 2 and 3 hours (Schreiber et al., 2024; Webbink and Wickramasinghe, 2002). The transition to a fully convective structure dramatically modifies the efficiency of magnetic braking, leading to a system reorganization that manifests as this characteristic gap in the period distribution (Verbunt, 1984). Below the period gap, in systems with orbital periods less than 2 hours, angular momentum loss becomes dominated by gravitational radiation. This mechanism, although less efficient than magnetic braking, maintains a stable but reduced mass transfer rate, on the order of $10^{-10} \text{ M}_{\odot} \text{ yr}^{-1}$. The system continues evolving towards shorter periods until it reaches the minimum period and becomes a period bouncer.

It is particularly notable that period bouncer systems maintain stable mass transfer (Kalomeni et al., 2016). This is because the donor star’s mass has significantly decreased ($M_2 \lesssim 0.06 \text{ M}_{\odot}$), while the white dwarf’s mass remains relatively constant ($M_1 \sim 0.8 \text{ M}_{\odot}$), resulting in a mass ratio $q \lesssim 0.1$, well below the critical stability threshold of $q < 2/3$ (Marsh et al., 2004). As a result, this configuration ensures that mass transfer remains stable throughout the post-period bounce phase, allowing these systems to evolve smoothly toward longer orbital periods with extremely low mass transfer rates, on the order of $10^{-11} \text{ M}_{\odot} \text{ yr}^{-1}$.

2.1 Period Bouncers

As mentioned previously, period bouncers represent an intriguing stage in the evolution of cataclysmic variables (CVs). These systems, typically composed of a white dwarf (WD) and a brown

dwarf (BD) as the donor star, have evolved beyond the minimum period (Pala et al., 2018). A white dwarf is the dense remnant of a low- or intermediate-mass star that has exhausted its nuclear fuel, supported against gravitational collapse by electron degeneracy pressure (Koester, 2002). In contrast, brown dwarfs are objects with masses between those of giant planets, like Jupiter, and stars, lacking sufficient mass to sustain hydrogen fusion in their cores. These “failed stars” emit most of their energy in the near-infrared and cool rapidly over time, making them intrinsically faint (Burrows and Liebert, 1993).

The orbital period minimum is a fundamental inflection point in the evolution of CVs, occurring when the donor star becomes so low in mass (approximately $0.08 M_{\odot}$) that its interior becomes degenerate. When a star is degenerate, its internal pressure is no longer determined by temperature, as in normal stars, but by a quantum principle known as the Pauli exclusion principle. This principle asserts that no two electrons can occupy the same quantum state within a confined volume (Ostriker, 1971). In degenerate stars, matter is compressed to the extent that electrons are extremely densely packed, forming what is known as a degenerate gas. In this state, the pressure preventing gravitational collapse does not originate from thermal particle motion but rather from the quantum resistance against electrons occupying the same space (Chandrasekhar, 1939).

When the donor star in a CV becomes a brown dwarf, its response to further mass loss changes dramatically: instead of contracting as a main-sequence star would, it begins to expand. This expansion forces the system to evolve toward longer orbital periods to maintain Roche lobe overflow (Paczynski and Sienkiewicz, 1981). The exact position of the minimum period depends on several factors, including the donor star’s chemical composition and the system’s evolutionary history; however, it typically occurs around 70–80 minutes (Kolb, 1993). This evolutionary reversal is a consequence of the unique dynamics that occur in these binary systems as they age.

Then, the formation of a period bouncer occurs when the timescale of mass loss in the secondary star becomes much shorter than its thermal timescale. At this point, the secondary, having lost much of its mass, no longer contracts in response to mass loss and instead begins to expand due to its degenerate nature. This expansion is a direct result of the properties of degenerate stars and leads to a gradual increase in the orbital period (Kimura et al., 2018).

Period bouncers are characterized by very low mass ratios, typically around 0.03, compared to pre-bounce systems with typical mass ratios around 0.13 (Pala et al., 2018). As defined in equation 2.1, the mass ratio q is the ratio between the mass of the secondary (donor) star and the mass of the primary white dwarf.

This low mass ratio in period bouncers reflects the advanced evolutionary stage of these systems, where the secondary has lost a significant amount of its original mass through mass transfer to the white dwarf. In contrast, pre-bounce systems that have not yet reached the minimum period

maintain a more massive secondary relative to the primary, resulting in a higher mass ratio. The donor star in a period bouncer is often eroded to a mass of approximately $0.06M_{\odot}$ or less, at which point nuclear burning ceases, and the star’s structure becomes dominated by electron degeneracy (Inight et al., 2023b).

Due to the low mass of the secondary star, the mass transfer rate in period bouncers is significantly lower than in younger CV systems. The combination of a low-mass primary white dwarf, a brown dwarf secondary, and a low accretion rate renders these systems intrinsically faint. Primary white dwarfs in period bouncers tend to be cooler than those in younger CVs due to reduced accretion heating. Furthermore, the secondary brown dwarfs in period bouncers are extremely cool (Pala et al., 2018).

Recent observational studies have employed various techniques to detect and characterize the period bouncer population, combining photometric surveys, spectroscopic follow-up, and astrometric data (Santisteban et al., 2018; Inight et al., 2023a). These studies have provided constraints on their spatial density in the solar neighborhood ($\lesssim 2 \times 10^{-5}, \text{pc}^{-3}$) and revealed their characteristic position in the HR diagram, where they cluster near the cooling sequence of solitary white dwarfs. This location is consistent with their spectral properties: the flux is dominated by the primary white dwarf, while contributions from the accretion disk and brown dwarf donor are minimal, making their identification particularly challenging.

Theoretical understanding of CV evolution predicts that a substantial fraction of the current galactic CV population should consist of period bouncers. However, observational evidence has consistently been lower than these predictions, creating one of the most significant discrepancies in our understanding of CV evolution. Various population synthesis models agree that period bouncers should constitute a significant fraction of the total CV population. Although specific estimates vary, all point to these systems being abundant. For instance, Kolb (1993) suggested they could represent 70% of all CVs, while Goliašch and Nelson (2015) estimated a fraction between 38% and 60%, and more recently, Belloni et al. (2018) raised this estimate to 75%. Despite differences in exact percentages, these models converge on a fundamental conclusion: period bouncers should be a dominant component in the CV population.

It is important to note that, contrary to intuition, period bouncers are not evolutionarily old systems. In fact, the time for a CV to reach the period bouncer state is relatively short in evolutionary timescales, typically on the order of a few Gyr (Knigge et al., 2011). Therefore, the observed scarcity of these systems cannot be simply explained as a consequence of the CV population’s age, which makes the discrepancy between theoretical predictions and observations even more intriguing.

2.2 The Population Paradox

These predictions are based on our understanding of Cataclysmic Variable (CV) evolution. Theoretical models indicate that CVs evolve towards progressively shorter orbital periods until they reach the minimum period (Paczynski and Sienkiewicz, 1981), after which the period begins to increase very slowly. During this post-bounce phase, the system’s evolution becomes extremely slow because mass transfer significantly decreases and the donor star gradually degenerates into a brown dwarf-like object (Howell et al., 2001). Evolutionary calculations suggest that a typical CV could spend up to 70% of its lifetime in this post-bounce phase, implying that we should observe a large population of these objects, known as period bouncers (Kolb and Ritter, 1990; Knigge et al., 2011). However, despite these well-founded theoretical predictions, observational studies have consistently found a significantly lower proportion of period bouncers. For instance, Patterson (2011) identified only 22 period bouncer candidates among approximately 1429 known CVs, according to the catalog by Ritter and Kolb (2016), representing just 1.5% of the sample. Pala et al. (2020) estimated a fraction of period bouncers of only 7-14% within their CV sample within a radius of 150 pc, and Inight et al. (2023b) concluded that only 0.7% of all CVs observed in the SDSS I to IV campaigns were period bouncers.

The significant discrepancy between theoretical predictions and observational data suggests that our current understanding of CV evolution may need revision (Goliašch and Nelson, 2015). While observational biases exist due to the fact that period bouncers are inherently faint due to their low accretion rates and the low luminosity of both the white dwarf and brown dwarf companion (Littlefair et al., 2008), these biases alone may not fully explain the observed scarcity. Instead, the low number of identified period bouncers might reflect a real phenomenon in CV evolution, indicating that these systems could become unstable or undergo processes that prevent them from remaining in the period bouncer phase for as long as current theories predict (Gänsicke et al., 2009).

This apparent deficiency of period bouncers challenges our conventional models of CV evolution (Kalomeni et al., 2016) and suggests that additional physical mechanisms, possibly related to the stability of these systems, may play a crucial role in determining their fate after reaching the period minimum (Schreiber et al., 2016). Understanding these mechanisms is essential for resolving the population paradox and developing a more complete model of CV evolution.

2.3 White Dwarf Irradiation

In period bouncer systems, white dwarfs significantly affect the atmosphere of the companion brown dwarf, primarily through X-ray radiation produced by accretion (Muñoz-Giraldo et al.,

2023). While the white dwarfs themselves may have relatively low effective temperatures, the accretion process generates substantial X-ray radiation that interacts with and modifies the thermal and chemical structure of the brown dwarf’s atmosphere (Lothringer and Casewell, 2020; Owen and Alvarez, 2016). Although the UV spectrum (10-400 nm) can affect planetary atmospheres, in period bouncers the dominant radiative process is X-ray emission from accretion. This X-ray radiation is particularly effective at heating and ionizing the brown dwarf’s upper atmosphere, leading to significant structural modifications and potential mass loss.

The impact of accretion-generated X-ray radiation on the brown dwarf’s atmosphere is substantial, causing ionization and heating of its upper layers (Muñoz-Giraldo et al., 2023). These effects have important observational implications for both the thermal and chemical structure of the atmosphere. Given the complexity of these atmospheric processes and the difficulty in studying them directly, it is useful to seek analogies with other better-studied astrophysical systems that present similar characteristics.

2.4 Analogy with Hot Jupiters

In this context, the comparison between period bouncers and hot Jupiters serves multiple important purposes in our understanding of irradiated brown dwarfs. Hot Jupiters represent the most well-studied cases of highly irradiated hydrogen-rich atmospheres in astronomy. The extensive theoretical framework and sophisticated atmospheric models developed for hot Jupiters provide a valuable starting point for modeling period bouncer atmospheres. While the irradiation source differs, many of the basic physical processes and computational methods remain applicable.

Furthermore, the methods developed to detect and characterize hot Jupiter atmospheres, including spectroscopic techniques and the interpretation of emission and transmission spectra, can be adapted for studying brown dwarfs in period bouncers. Period bouncers and hot Jupiters share several key physical characteristics that make this comparison useful, including their proximity to the primary object, high atmospheric temperatures, hydrogen-rich compositions, and the presence of significant internal heat flux (Lothringer and Casewell, 2020; Showman, 2016).

However, the radiation environments are fundamentally different. Hot Jupiters receive primarily stellar radiation across a broad spectrum from their main sequence host stars, while period bouncers are dominated by X-ray radiation from accretion onto the white dwarf (Lothringer and Casewell, 2020). This distinction is crucial, as X-rays are particularly efficient at causing atmospheric mass loss through direct heating of the upper atmosphere, leading to hydrodynamic escape where the atmospheric gas expands and flows outward as a pressure-driven wind (Owen and Alvarez, 2016; Schreiber et al., 2019).

Understanding these similarities and differences is crucial because it allows us to identify which

physical processes from hot Jupiter models can be directly applied to period bouncers, helps us anticipate where new theoretical developments are needed to account for the unique aspects of X-ray irradiation, and provides context for interpreting observations and distinguishing between different atmospheric phenomena.

2.5 Mass Loss and Atmospheric Structure

As we have discussed, the dominant mechanism driving atmospheric evolution in these systems is the intense X-ray radiation from accretion onto the white dwarf (Owen and Alvarez, 2016). While observations of white dwarf-giant planet systems have revealed mass loss rates in the range of $\dot{M} \sim 10^{-18} - 10^{-15} \text{ M}_{\odot} \text{ year}^{-1}$ (Schreiber et al., 2019; Salz et al., 2015; Santos et al., 2023), period bouncers are expected to experience significantly higher mass loss rates due to three main factors: more intense X-ray flux from ongoing accretion, the inflated nature of the brown dwarf, and the extremely close orbital separation. This enhanced susceptibility to mass loss is further amplified by the modified structure of the brown dwarf, a consequence of its mass transfer history (Rappaport et al., 1983). The brown dwarf in a period bouncer has a considerably larger radius than an isolated brown dwarf of similar mass, resulting in a wider effective area exposed to X-ray irradiation. The presence of metals in white dwarf atmospheres, observed in several studies, provides indirect evidence of ongoing accretion (Lothringer and Casewell, 2020), suggesting a feedback loop where X-ray induced mass loss contributes to continued accretion and further X-ray emission.

In this work, we propose that mass loss through irradiation could induce significant consequential angular momentum loss (CAML) in period bouncers. CAML, traditionally considered as an additional source of angular momentum loss associated with mass transfer (King and Kolb, 1995; Zorotovic and Schreiber, 2019), could have a different origin in these systems. In cataclysmic variables, the total rate of angular momentum loss is expressed as:

$$\dot{J} = \dot{J}_{\text{sys}} + \dot{J}_{\text{CAML}} \quad (2.3)$$

where $\dot{J}$ represents the total angular momentum loss rate of the system, $\dot{J}_{\text{sys}}$ represents systemic loss through magnetic braking and gravitational radiation, and $\dot{J}_{\text{CAML}}$ represents the additional angular momentum loss through mass transfer. For nova eruptions, the specific angular momentum loss rate is proposed by Schreiber et al. (2016) as:

$$\frac{\dot{J}_{\text{CAML}}}{J} = \nu \frac{\dot{M}_{\text{BD}}}{M_{\text{BD}}} \quad (2.4)$$

where J is the total angular momentum of the system, $\dot{M}_{BD}$ is the mass loss rate from the brown dwarf, M_{BD} is the brown dwarf mass, and ν is the specific angular momentum parameter defined by [King and Kolb \(1995\)](#); [Zorotovic and Schreiber \(2019\)](#) as:

$$\nu = \frac{M_{BD}^2}{M_{WD}(M_{WD} + M_{BD})} \quad (2.5)$$

where M_{WD} is the white dwarf mass. In period bouncers, we propose that these equations need to be adapted to consider two contributions to CAML: traditional CAML associated with nova eruptions, although these are infrequent in these systems due to the low mass transfer rate, and an additional CAML term produced by direct mass loss due to brown dwarf irradiation. For this, both the parameter ν and the $\dot{J}_{CAML}$ equation must be reformulated to reflect these two contributions, that is, the mass lost through classical mass transfer and the mass lost directly through brown dwarf irradiation. We propose that this combined CAML mechanism could help explain the discrepancy between the predicted and observed number of period bouncers ([Belloni and Schreiber, 2023](#)), as it would modify the stability limits for mass transfer ([Zorotovic and Schreiber, 2019](#)). The exact formulation of these modifications and their implementation will be presented in [section 3](#).

Chapter 3

Methods

This chapter presents the methodology employed to study the effects of irradiation in period bouncer systems. It is important to emphasize that the present work does not develop a detailed model of the irradiation process itself, given the complexity this entails in cataclysmic variable systems, where mass transfer and other physical processes interact with radiation in non-trivial ways. Instead, this study focuses on modeling the observed consequences of irradiation, specifically the induced mass loss and its effects on the system’s orbital evolution, following evidence from similar systems (Owen and Alvarez, 2016; Santisteban et al., 2016). This approach represents a first step toward understanding the role of irradiation in these systems, while more comprehensive models incorporating the detailed physics of radiation-matter interaction are being developed.

The research is developed through a numerical model that considers the additional mass loss produced by irradiation and its effects on the system’s angular momentum, building upon previous studies of angular momentum loss in CVs (Schreiber et al., 2016; Zorotovic and Schreiber, 2019). The implementation was carried out using the MESA stellar evolution code (Paxton et al., 2018), to which specific routines were added to model these physical processes.

The methodological development is structured in three main interrelated components. First, the simulation of binary system evolution is performed using MESA, starting from a pre-bounce CV. Second, a model is implemented that quantifies the additional mass loss induced by irradiation effects, inspired by observations of similar phenomena in white dwarf-planet systems (Schreiber et al., 2019). Finally, the calculation of consequential angular momentum loss (CAML) was modified to incorporate these effects (King and Kolb, 1995).

3.1 Use of MESA

The numerical simulations for this work were performed using MESA (Modules for Experiments in Stellar Astrophysics). The initial parameters were selected to represent a typical CV in its pre-

bounce phase, allowing the study of the complete system evolution up to and beyond the minimum period.

Table 3.1: Initial binary system parameters

Parameter	Value
White dwarf mass (M_1)	$0.8 M_\odot$
Donor mass (M_2)	$0.2 M_\odot$
Initial orbital period	0.1 days (144 min)

The selection of these parameters is grounded in observations and previous theory. The initial white dwarf mass of $0.8 M_\odot$ corresponds to the average mass observed in CVs (Zorotovic and Schreiber, 2019). The donor mass of $0.2 M_\odot$ represents a typical main sequence star in a pre-bounce CV, allowing the study of complete evolution towards the period bouncer phase. The initial orbital period of 0.1 days (144 minutes) was strategically selected to allow the system to evolve naturally towards the observed minimum period of approximately 78 minutes (Galiullin et al., 2024).

This initial configuration, starting with a main sequence secondary star rather than a brown dwarf, allows the study of the complete system transformation and clearly discerns the effects of irradiation during the period bounce phase. The MESA code was specifically selected for its capability to handle the physics of degenerate objects and its flexibility to incorporate new physics through custom subroutines (Paxton et al., 2018). The code simultaneously solves the stellar structure equations and orbital evolution, considering the effects of electron degeneracy that are crucial in the period bounce phase (Rappaport et al., 1983).

3.2 Mass Loss Model Due to Irradiation

Having established the basic configuration of the binary system in MESA, the next crucial step is the implementation of a model that quantifies the effects of irradiation in terms of mass loss. As mentioned previously, this study focuses on the observable consequences of irradiation rather than the detailed irradiation process itself. Therefore, a mass loss model was implemented that considers the effects of white dwarf irradiation on the brown dwarf.

This model activates when the donor star mass reaches $0.055 M_\odot$, at which point, according to Kolb (1993), the star has developed a degenerate core characteristic of a brown dwarf. The decision to activate the mass loss model specifically in the period bouncer phase is based on the particular physical characteristics of these systems. In earlier stages, when the donor is a main sequence star, its internal structure and surface gravity are sufficiently robust to withstand the effects of irradiation. However, once the star evolves into a brown dwarf, its atmosphere becomes

more susceptible to irradiation due to its lower surface gravity and partially degenerate nature (Burrows and Liebert, 1993). This increased susceptibility, combined with the extreme proximity to the white dwarf characteristic of period bouncers, makes the effects of irradiation particularly significant during this evolutionary phase.

A key aspect of this implementation is the feedback mechanism between mass transfer and mass loss (Ehrenreich et al., 2015). In binary systems where initial mass transfer exists, this transfer leads to increased white dwarf luminosity through accretion, which in turn enhances the irradiation of the donor star. The increased irradiation causes the donor star’s atmosphere to expand, potentially resulting in additional Roche lobe overflow and, consequently, an increase in the mass transfer rate (Zhao et al., 2024).

Considering this feedback cycle, the model calculates an additional mass loss proportional to the system’s mass transfer rate, expressed by equation 3.1:

$$\dot{M}_{\text{loss}} = c \cdot \dot{M}_{\text{transfer}} \quad (3.1)$$

where $\dot{M}_{\text{loss}}$ represents the rate of mass loss due to irradiation, $\dot{M}_{\text{transfer}}$ is the mass transfer rate through Roche lobe overflow, and c is an efficiency factor that determines what fraction of the transferred mass is ultimately lost from the system due to irradiation effects.

While previous studies like Salz et al. (2015) have found that only between 0.001 and 0.3% of the mass lost from white dwarfs is due to irradiation-driven mass loss in systems without mass transfer, in our case we are considering binary systems with active mass transfer.

In these systems, the increased irradiation of the donor star due to accretion onto the white dwarf is expected to significantly enhance the irradiation-driven mass loss rate. Therefore, we have used a wider range of 0.1 to 0.002 (10 to 0.2%) for the efficiency factor c in the mass loss equation. This broader range allows us to explore the effect of higher irradiation-driven mass loss efficiency in binary systems with mass transfer, as the observational evidence suggests that these systems may exhibit significantly higher mass loss rates. In this way, we can evaluate the impact of this feedback between mass transfer and irradiation on the long-term evolution of these systems.

It is important to acknowledge the limitations present in this model. First, spherically symmetric mass loss is assumed, which may not accurately represent the true geometry of the outflow. Second, a simplified calculation of the irradiation profile across the donor’s surface was implemented. Additionally, potential shielding effects from the accretion disk are omitted. Finally, a constant efficiency factor is used that could actually vary with system parameters.

Despite these limitations, this implementation provides a first approximation to understanding how irradiation-induced mass loss affects the long-term evolution of period bouncer systems. The additional mass loss not only affects the system’s mass evolution but also impacts its angular momentum through non-conservative mass loss, generating an additional consequential angular

momentum loss beyond that known from nova eruptions (Schreiber et al., 2016). This consideration naturally leads to the next component of the model: the modification of the consequential angular momentum loss (CAML).

3.3 Modification of CAML

The treatment of consequential angular momentum loss (CAML) was modified to consider the direct relationship between mass transfer, irradiation-induced mass loss, and angular momentum loss. The traditional CAML model, originally developed by King and Kolb (1995), has been fundamental in understanding the evolution of cataclysmic variables. However, the effects of irradiation in period bouncers require an extension of this treatment.

The model developed in this work includes two components that act simultaneously once the system reaches the period bouncer phase. The first component corresponds to classical CAML, associated with nova eruptions, expressed by equation 3.2:

$$\nu_{\text{classic}} = \frac{M_2^2}{M_1(M_1 + M_2)} \quad (3.2)$$

where ν_{classic} is the classical specific angular momentum parameter, M_1 is the white dwarf mass, and M_2 is the donor mass.

The second component, specifically developed for this work, represents the inverse CAML derived from irradiation-induced mass loss:

$$\nu_{\text{inv}} = \frac{M_1^2}{M_2(M_1 + M_2)} \quad (3.3)$$

In both equations 3.2 and 3.3, M_1 and M_2 represent the white dwarf and donor masses respectively, whose initial values are given in Table 3.1. The inversion in the functional form of ν_{inv} with respect to classical CAML represents a novel contribution of this study. This inversion is justified considering that, while classical CAML describes angular momentum loss in the direction of mass transfer flow from the donor star to the white dwarf, inverse CAML models angular momentum loss in the opposite direction, caused by mass expulsion due to irradiation from the white dwarf towards the donor star.

The total angular momentum loss is calculated as the sum of both contributions:

$$\dot{J}_{\text{CAML}} = \dot{J}_{\text{CAML}_1} + \dot{J}_{\text{CAML}_2} \quad (3.4)$$

where $\dot{J}_{\text{CAML}}$ is the total rate of angular momentum loss, and each component is expressed as:

$$\dot{J}_{\text{CAML}_1} = \nu_{\text{classic}} \cdot \frac{J\dot{M}_{\text{transfer}}}{M_2} \quad (3.5)$$

$$\dot{J}_{\text{CAML}_2} = \nu_{\text{inv}} \cdot \frac{J\dot{M}_{\text{loss}}}{M_2} \quad (3.6)$$

where J is the total angular momentum of the system, $\dot{M}_{\text{transfer}}$ is the mass transfer rate, and $\dot{M}_{\text{loss}}$ is the rate of mass loss due to irradiation.

This formulation establishes a chain of proportional relationships that can be mathematically expressed as:

$$\dot{M}_{\text{transfer}} \propto \dot{M}_{\text{Irradiation}} \propto \dot{M}_{\text{loss}} \propto \dot{J}_{\text{CAML}_2} \quad (3.7)$$

These proportionality relationships demonstrate how white dwarf irradiation initiates a chain of physical effects: it first induces mass loss proportional to the mass transfer rate, and this mass loss in turn generates additional angular momentum loss. This interrelation is fundamental to understanding how irradiation can affect the system's long-term orbital evolution.

The inclusion of the inverse CAML term and its specific formulation represents a fundamental innovation of this study. This new CAML treatment is particularly relevant in the period bouncer phase, where white dwarf irradiation can have a significant impact on the system's orbital evolution. The inversion in the functional form of CAML is physically motivated by the bidirectional nature of the mass loss process in these systems: traditional mass transfer from the donor to the white dwarf, and irradiation-induced mass loss in the opposite direction. This modification of CAML is expected to have fundamental implications for our understanding of period bouncer evolution, potentially providing an explanation for the observed scarcity of these systems compared to current theoretical predictions.

Chapter 4

Results

This chapter presents the results obtained through the implementation of the simulation described in Chapter 3. Using the initial parameters listed in Table 3.1, the implementation focused on developing a model capable of capturing the effects of white dwarf irradiation on the donor star in post-minimum period cataclysmic variable systems. As detailed in Section 3.2, the model incorporates these effects through an efficiency coefficient c , which relates the mass loss rate to the mass transfer rate according to equation 3.1. This coefficient represents the fraction of mass lost due to the effects of irradiation relative to the mass transferred through the Roche lobe.

Following the CAML modification methodology described in Section 3.3, the study systematically explores how different intensities in the effect of irradiation, specifically mass loss, influence the evolution of post-minimum period systems. This exploration was conducted by varying the efficiency coefficient c over a range that spans from conservative values based on previous studies of similar systems to higher values that could be relevant in the specific context of cataclysmic variables with active mass transfer. The simulation was initialized at the start of the post-bounce phase and, as detailed in Section 3, the irradiation model was activated when the donor mass reached $0.055 M_{\odot}$.

The results are presented in a series of panels that allow direct comparison of how different irradiation efficiency values affect the system’s evolution. It is important to clarify that when we refer to the system “ending its evolution” in different cases, this does not represent a real physical end of the binary system, but rather the point where the computational limitations of the MESA code are reached. This distinction is fundamental for the correct interpretation of the results presented in the figure.

4.1 Impact of Irradiation effect on Donor Star Radius Evolution

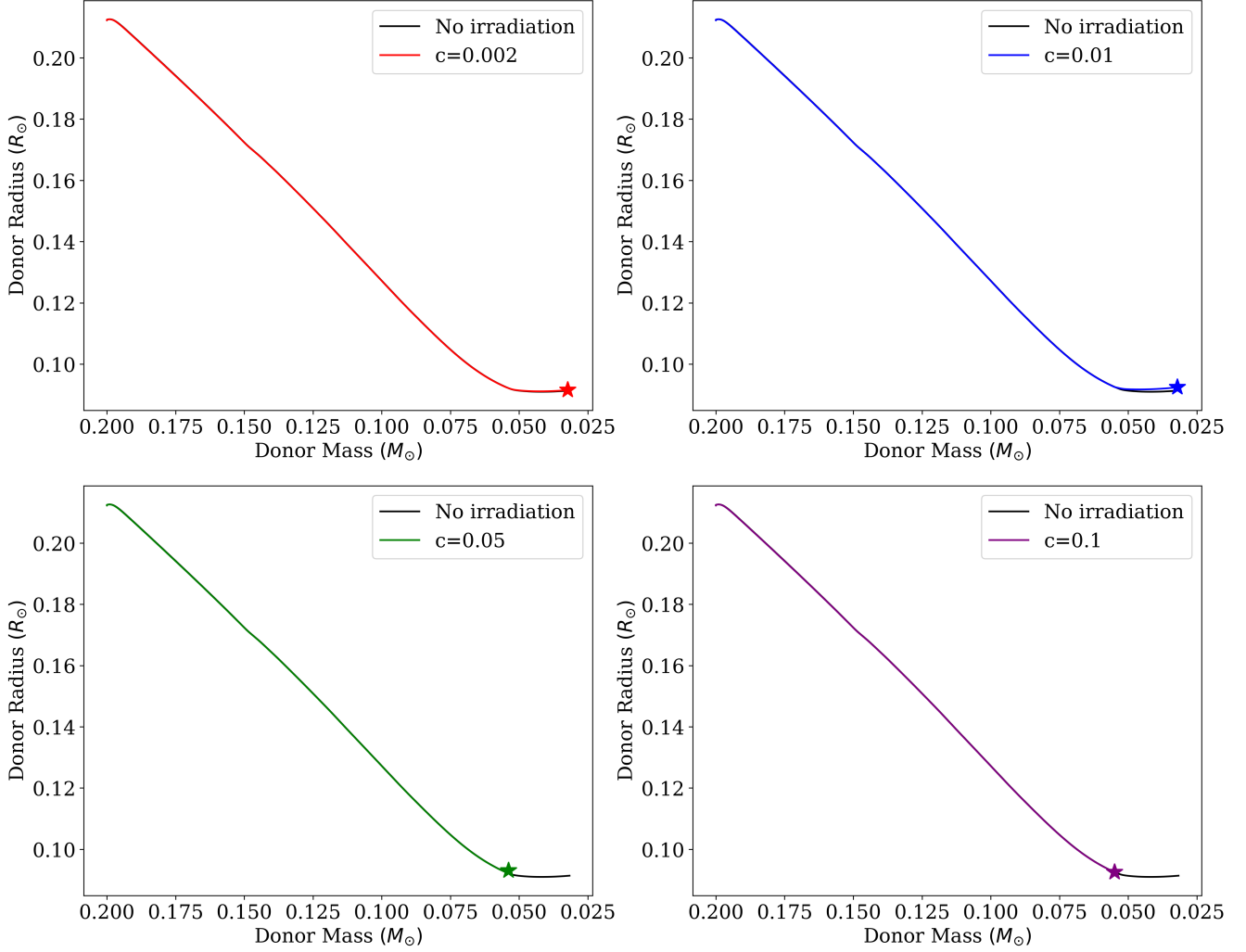


Figure 4.1: Evolution of the donor’s radius as a function of its mass for cataclysmic variable systems under different irradiation efficiencies. The panels show the comparison between the standard evolution without irradiation (black line) and cases with irradiation, using efficiency coefficients c . Star symbols mark the endpoint of evolution for each trajectory. The horizontal axis represents the donor mass in solar units ($M_{\odot}$), while the vertical axis shows the donor radius in solar units ($R_{\odot}$). Evolution begins with a mass of $0.2 M_{\odot}$, and differences in radius evolution are observed as the donor loses mass, particularly after $0.055 M_{\odot}$, where the irradiation model is activated. Notably, systems with higher irradiation efficiency end their evolution earlier than the standard case.

The analysis of the donor’s radius evolution under irradiation effects shows a clear dependence on irradiation intensity, as observed in Figure 4.1. In the first panel, where standard evolution is compared with an efficiency factor of $c = 0.002$, we observe that the brown dwarf evolution follows nearly the same path as the previous model. This result suggests that such a low efficiency factor has minimal impact on the system’s evolution, which is consistent with values found by Salz et al. (2015) for hot Jupiters, albeit under different conditions.

In the second panel, with an efficiency factor of $c = 0.01$, the evolution shows slight differences from the standard case. The most notable change occurs when the donor mass reaches 0.05 solar masses, where a small increase in radius is observed. This phenomenon does not imply an increase compared to the non-irradiated model but reflects the effects of X-ray irradiation on the expansion of the donor’s outer atmospheric layers. This atmospheric expansion is not sufficient to trigger greater mass transfer but is more associated with a thermal adjustment of the donor’s atmosphere (Owen and Alvarez, 2016).

In the third panel, with $c = 0.05$, a more significant deviation is observed. Although initial evolution follows the non-irradiated model’s path, the system ends its evolution before the radius can increase, marked by the green star at approximately 0.05 solar masses. This behavior suggests that an increase in irradiation efficiency causes more dramatic changes in the brown dwarf’s structure, but evolution halts before a significant radius expansion occurs.

The fourth panel, with the highest efficiency factor $c = 0.1$, shows similar behavior to the third case. Evolution ends before the radius can increase, indicating that the intense irradiation effects cause such a pronounced alteration in the donor’s structure that it prevents its expansion, leading to an early end to the evolution. In these highly irradiated systems ($c \geq 0.05$), the combination of modified internal structure and enhanced atmospheric escape can induce a positive feedback cycle. This phenomenon implies that the radius increase leads to greater mass transfer, which in turn causes more accretion onto the white dwarf and stronger irradiation.

4.2 Mass Transfer Variations Induced by the Effect of Irradiation

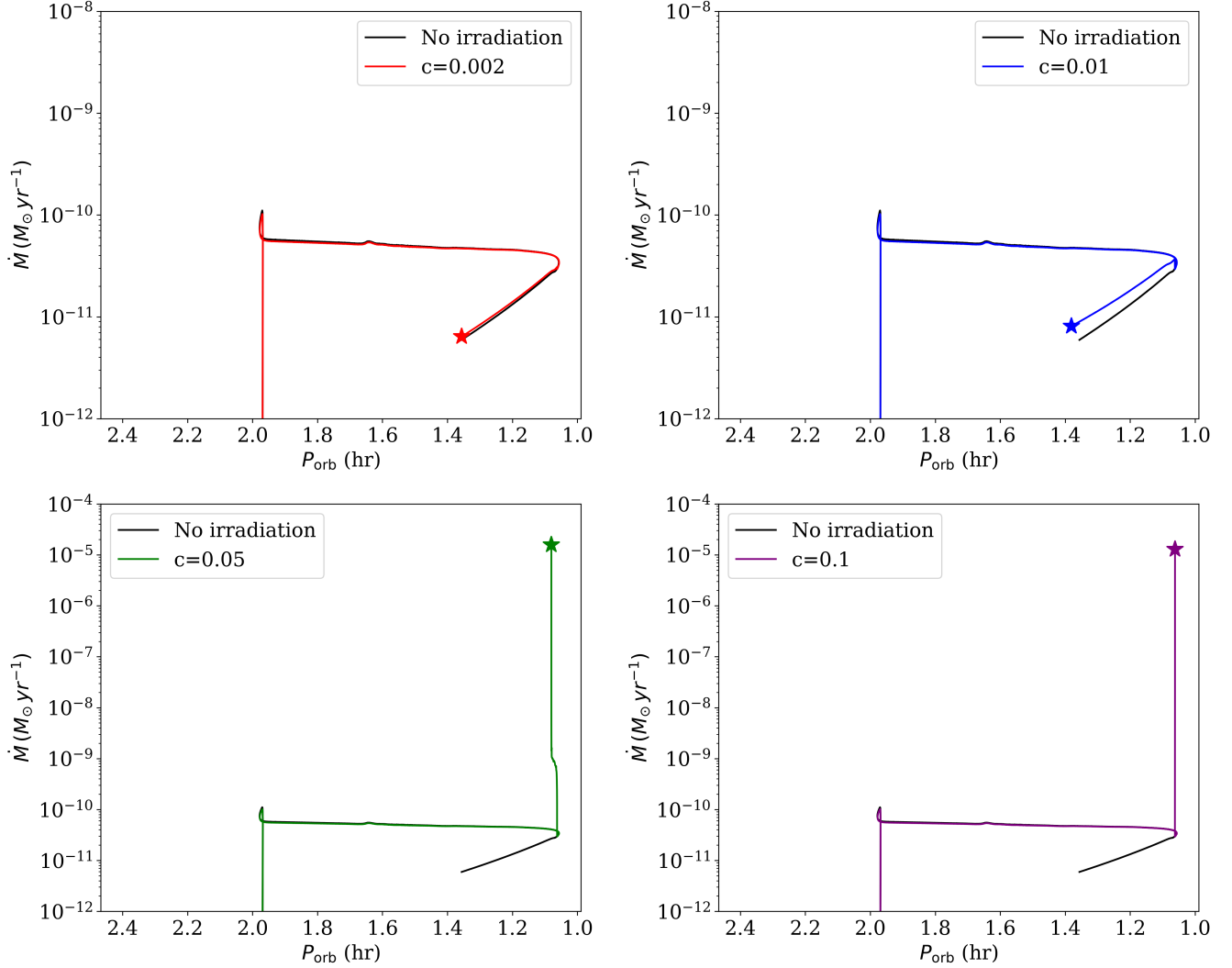


Figure 4.2: Mass transfer rate ($\dot{M}$) evolution as a function of orbital period (P_{orb}) for close binary systems under varying irradiation regimes. The panels show comparisons between the standard model (black lines) and models with irradiation efficiency coefficients c . Star markers denote evolutionary endpoints for each trajectory. Calculations terminate when the system reaches a critical mass transfer phase exceeding MESA computational capabilities.

The evolution of mass transfer under different irradiation regimes reveals distinctive patterns depending on irradiation intensity, as illustrated in Figure 4.2. For $c = 0.002$, the system maintains evolution practically identical to the non-irradiated standard model, with mass transfer rates following classical predictions for conservative systems. In the case of $c = 0.01$, a moderate increase in mass transfer rate is observed, directly correlated with the stellar radius expansion

documented in Figure 4.1.

For values of $c \geq 0.05$, systems exhibit an extreme increase in mass transfer rate that exceeds MESA’s computational limits (Paxton et al., 2018). This occurs because MESA’s calculations cannot find acceptable models that preserve the continuity of the star’s internal structure. In the specific case of $c = 0.05$, before reaching this instability, orbital period alterations can be observed as a consequence of angular momentum conservation: material flowing from the brown dwarf to the white dwarf redistributes its angular momentum, resulting in orbital period adjustment to maintain dynamic equilibrium (Ricker and Taam, 2012). For $c = 0.1$, the system reaches this instability phase more rapidly.

4.3 Temporal Evolution of Irradiated Systems

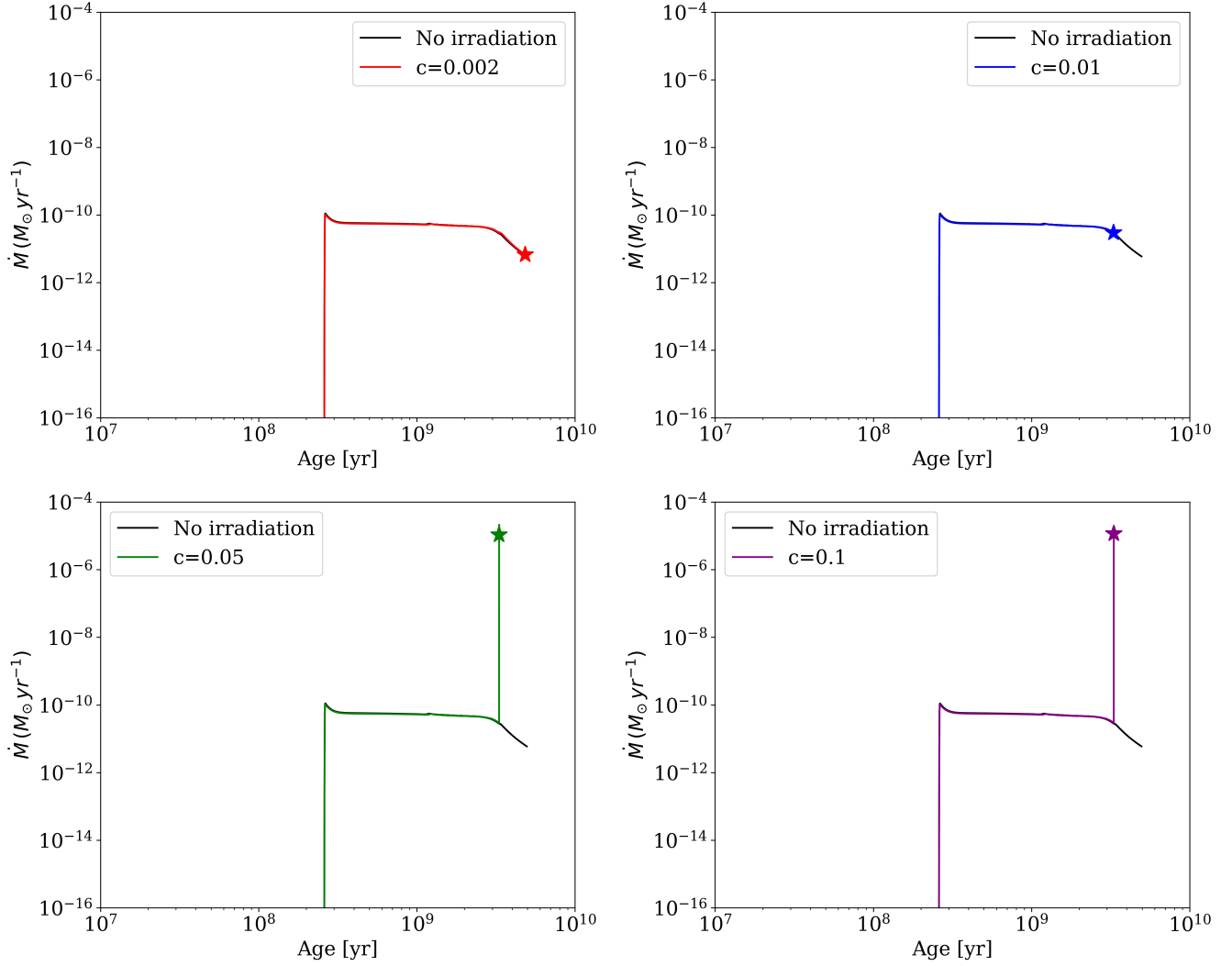


Figure 4.3: Temporal evolution of mass transfer rate for close binary systems under different irradiation regimes. Panels show comparisons between the standard model (black lines) and models with irradiation efficiency coefficients c . Stars mark points where calculations reach MESA’s computational limitations. Calculations terminate when the system reaches a critical mass transfer phase exceeding the code’s computational capabilities.

The temporal evolution of mass transfer, presented in Figure 4.3, reveals crucial aspects about the long-term stability of these systems. The non-irradiated case, which serves as the baseline reference, shows the most prolonged evolution, maintaining a stable mass transfer rate of approximately $10^{-10} M_{\odot}/\text{year}$ and continuing beyond 10^9 years. This behavior reflects the “natural” evolution of the system, without significant external perturbations.

For the case ($c = 0.002$), the observed behavior is very similar to the non-irradiated case,

with comparable mass transfer rates. However, even at this level of low irradiation effect, subtle differences can be detected, suggesting that radiation does influence the system’s structure. This indicates that, although irradiation does not generate large effects, there is a minimum threshold required for irradiation to significantly impact the system’s evolution.

In the case of a moderate irradiation effect ($c = 0.01$), we observe that calculations stop earlier than expected because MESA can no longer continue with numerical integration (Paxton et al., 2018). While maintaining a mass transfer rate similar to the non-irradiated case, the system reaches MESA’s computational limits much earlier, around 10^9 years. This result is significant because it shows that even moderate irradiation levels can substantially modify the temporal evolution of the system without necessarily causing dramatic instabilities.

For high irradiation effect ($c \geq 0.05$), termination occurs much earlier due to extremely high mass transfer rates. In these situations, structural changes happen so quickly that they exceed the code’s computational capabilities.

The transition to high irradiation effect regimes ($c \geq 0.05$) marks a dramatic change in system behavior. In these cases, the evolution shows an initial phase similar to the low irradiation cases, until approximately 10^9 years, at which point a catastrophic increase in mass transfer rate occurs. This abrupt change, happening roughly 900 million years earlier than in low irradiation cases, suggests the existence of a critical irradiation threshold that triggers a fundamental instability in the system. The most extreme case ($c = 0.1$) exhibits behavior similar to $c = 0.05$. The similarity in the instability onset time between these two cases suggests the existence of a critical irradiation value around $c = 0.05$, above which the system inevitably evolves toward an unstable configuration on relatively short timescales.

Chapter 5

Discussion

The detailed analysis of the results presented in Figures 4.1, 4.2 and 4.3 reveals fundamental findings about how irradiation-induced mass loss affects the evolution of close binary systems. The system’s dynamics are profoundly affected by a complex mass loss process. When the brown dwarf begins to lose mass due to irradiation from the white dwarf, a chain of effects is triggered. The system’s center of mass progressively shifts toward the white dwarf due to the brown dwarf’s reduced “weight” in the system (Verbunt and Zwaan, 1981). To maintain angular momentum conservation, both stars’ orbits must expand (Webbink, 1976). This orbital expansion, combined with mass reduction, weakens the brown dwarf’s surface gravity, which in turn decreases its surface escape velocity. As a result, a feedback cycle is created where lower gravity facilitates further atmospheric mass loss.

As evidenced in our results, simulations with a coefficient $c = 0.01$ showed the first signs of irradiation effects on the donor’s structure. This initial atmospheric expansion, though slight, represents the first indication of a more complex mechanism that can eventually lead to dramatic changes in the system’s evolution. The response mechanisms involve a complex interaction between mass loss and the stellar envelope structure, where the absorbed energy increases the temperature of the outer layers and reduces the effective surface gravity (Kolb and Baraffe, 1999). This modification in the envelope structure not only affects the mass loss dynamics but also has profound implications for the system’s angular momentum.

Indeed, our results indicate that angular momentum loss in these systems presents significantly greater complexity than traditional CAML, manifesting through two simultaneously operating mechanisms. The first mechanism corresponds to traditional CAML, which describes the angular momentum loss associated with mass transfer from the donor to the white dwarf (King and Kolb, 1995). However, our simulations have revealed a second mechanism, which we term inverse CAML, operating in the opposite direction. This new mechanism originates when material, once processed by the white dwarf, is expelled back toward the donor due to irradiation effects. The

relative importance of this inverse CAML increases significantly with irradiation intensity, primarily because the expelled material originates from a position further away from the system’s center of mass which means that the specific angular momentum of the expelled material is much larger. Consequently, the interaction of these two CAML mechanisms produces a net effect on the system’s total angular momentum that significantly exceeds the predictions of models considering only traditional CAML (Knigge et al., 2011).

The transition to higher coefficients ($c \geq 0.05$) marks a critical point where we observe a dramatic increase in mass transfer rate. The intensified angular momentum loss, combined with the high mass transfer rate, destabilizes the system (Paczynski, 1976). This destabilization occurs because the mass loss from the donor is faster than the system can dynamically adjust, leading to unstable mass transfer. As a result, the transferred material cannot be efficiently accreted by the white dwarf, accumulating around both stars and forming a common envelope. During this common envelope phase, the orbital friction between the stars and the surrounding gas dissipates orbital energy, causing the stellar cores to orbit increasingly closer to each other in a decreasing trajectory (Ivanova et al., 2013). This process creates a feedback cycle: the loss of angular momentum brings the stars closer, intensifying mass transfer, which in turn increases angular momentum loss. This orbital energy loss is transferred to the envelope gas, heating and expanding it. As the distance between the cores decreases, friction increases and the process accelerates, inevitably leading to the complete merger of both stars. Although our current model cannot follow the complete evolution of this phase due to computational limitations, the identification of this threshold provides crucial information about the final fate of the system: the merger of both stars.

A particularly intriguing aspect distinguishes these systems from hot Jupiter systems. In the latter, the central star’s intense UV radiation efficiently expels hydrogen from the planetary atmosphere (Schreiber et al., 2019). However, in our case, we observe a more complex phenomenon: as we already mentioned, the two stars end up merging, and the result is a structure that remarkably resembles a real giant star. This occurs because the hydrogen from the brown dwarf ignites on the white dwarf’s surface. The resulting structure is practically identical to a genuine giant, with three main components: a degenerate core (the former white dwarf), a layer where hydrogen converts to helium through nuclear fusion, and an extensive hydrogen envelope.

This giant product of the merger, although structurally similar to a conventional giant, would have a considerably shorter lifetime. Two factors limit its duration: the finite amount of hydrogen available from the brown dwarf which, being less massive than a normal star, provides a limited fuel reservoir, and the intense surface gravity of the white dwarf’s degenerate core, which would process this fuel at an accelerated rate.

These findings have significant implications for our understanding of the period bouncer population. The identification of the critical threshold at $c = 0.05$ marks a crucial boundary between

stable and unstable system evolution. This transition to runaway mass transfer could explain the apparent scarcity of observed period bouncers compared to theoretical predictions (Gänsicke et al., 2009), as systems with $c \geq 0.05$ would experience rapid evolution, effectively removing them from the observable population.

It is essential to acknowledge the limitations of our current model. While the results provide valuable insights, the use of a constant coefficient (c) represents a significant simplification. In reality, mass loss efficiency depends dynamically on multiple interrelated factors, including stellar density, instantaneous accretion rate, donor radius, and escape velocity, all of which evolve continuously (Lothringer and Casewell, 2020). These limitations point to several crucial areas for future research.

A more complete treatment would require more sophisticated models incorporating the coefficient's dependence on these variable physical parameters and a more detailed analysis of instability phases. The incorporation of three-dimensional hydrodynamic simulation results, such as those conducted by Sgró et al. (2022), could provide a more realistic description of mass loss processes and their coupling with orbital evolution. These improvements would not only refine our predictions for individual system evolution but also provide deeper insights into the observed distribution of period bouncers and other evolutionary states in the cataclysmic variable population.

The observational validation of our theoretical predictions will require a systematic search for systems at different evolutionary stages, with particular attention to those near the identified critical threshold. Multi-wavelength observations, especially in X-ray, will be crucial for characterizing irradiation intensity and its effects on the donor's atmosphere. Such observations would provide essential constraints for future theoretical models and help bridge the gap between theoretical predictions and observational evidence.

Chapter 6

Conclusions

The detailed analysis of irradiation effects in post-minimum period binary systems has revealed its critical role as a regulatory mechanism in the evolution of cataclysmic variables (Belloni et al., 2023). Through numerical simulations implemented in the MESA code, we have discovered that irradiation not only modifies the donor’s structure, but can determine the complete evolutionary fate of the system, including its potential merger into a giant-like structure, providing a possible explanation for the observed scarcity of these objects (Muñoz-Giraldo et al., 2024).

The research has identified a critical value of the irradiation efficiency coefficient ($c \approx 0.05$), which marks a fundamental transition in the system’s behavior. Below this threshold, systems maintain stable evolution with moderate mass transfer rates. However, when the coefficient exceeds this critical value, systems experience rapid destabilization that leads to a common envelope phase (Paczynski, 1976), dramatically altering their subsequent evolution. This critical behavior is intimately linked to the angular momentum loss mechanisms operating in the system and, in extreme cases, leads to the complete merger of both stars.

A particularly significant finding is that this merger results in a structure that remarkably resembles a real giant star, with a degenerate core, an active hydrogen fusion shell, and an extensive envelope. This structure, although transient due to its limited fuel reservoir and high surface gravity, represents a unique evolutionary state that could provide a missing link in our understanding of post-merger evolution in binary systems.

To understand and characterize these mechanisms, our development of a new CAML treatment represents another significant contribution of this work. The incorporation of two components, the classical CAML associated with traditional mass transfer (King and Kolb, 1995) and an inverse CAML originated by material ejection due to irradiation, provides a more complete and accurate description of angular momentum loss in these systems. This dual formulation has proven essential for understanding the complete dynamics of system evolution, particularly because the inverse CAML acts in the opposite direction to traditional mass flow, significantly modifying previously

calculated angular momentum loss rates (Zorotovic and Schreiber, 2019).

The interaction between these two CAML mechanisms reveals a fundamental positive feedback cycle: while classical CAML governs mass transfer to the white dwarf, inverse CAML intensifies mass loss due to the resulting irradiation. This cyclical process, where increased accretion leads to greater irradiation and therefore to greater mass loss (Schreiber et al., 2019), can dramatically accelerate system evolution. Such a mechanism, not considered in previous models, provides a natural explanation for the discrepancy between theoretical predictions and observations of the period bouncer population, as it could significantly reduce the time these systems remain in the post-minimum period phase.

A crucial finding of this research has implications that revolutionize our understanding of stellar evolution, from individual to population scales. At the individual system level, our model modifies the traditional conception of cataclysmic variable lifetimes in their post-minimum period phase (Kolb and Baraffe, 1999), suggesting that irradiation can dramatically shorten this evolutionary stage. At the population scale, this fundamentally transforms our understanding of cataclysmic variable demographics as a whole, affecting everything from the expected rates of formation and destruction of these systems to their spatial distribution in the galaxy.

Our results demonstrate that a significant fraction of systems experience accelerated evolution, prematurely moving away from the period bouncer phase due to intense irradiation effects. This discovery represents a significant advance in resolving one of the most persistent problems in the field: the marked discrepancy between the theoretically predicted abundance of period bouncers (40-75% according to Kolb (1993); Goliašch and Nelson (2015)) and the small number of observed systems (barely 1.54% according to Muñoz-Giraldo et al. (2024)).

The simulations conducted present certain limitations that must be acknowledged. The use of a constant efficiency coefficient represents a simplification that could be improved in future models. Additionally, the incorporation of three-dimensional hydrodynamic simulations (Sgró et al., 2022) could provide a more detailed description of mass loss processes. Observational validation of model predictions, particularly near the identified critical threshold, will also be crucial.

The next steps in this line of research are clear and promise significant advances. The development of more sophisticated models incorporating temporal dependence of the efficiency coefficient and a systematic observational search for systems near the identified critical threshold are required. Particularly promising is the development of a model that considers the additional loss of angular momentum caused by ejected material temporarily remaining in orbit around the system, as well as a more detailed study of the resulting merger products and their subsequent evolution. This material, before being re-accreted, could generate significant friction effects that would amplify the total angular momentum loss (Ricker and Taam, 2012), potentially further accelerating the system's evolution away from the period bouncer phase.

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