Late evolution of Cataclysmic Variables

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Abstract

In this thesis I will introduce the evolutionary stages of Cataclysmic Variables (CVs) and focus on their late evolution. Evolutionary stages of CVs are not very well understood and the standard model for it seems to not be able to explain all the observed phenomena. Long-term stable mass transfer is a key part of these binary stars and their evolution, but understanding the mechanics that enable the mass transfer is still a big challenge. Active research and new observations have answered some big questions in the last years, for example successfully observing the predicted period spike, but the late stages of CV evolution still need better understanding. Old CVs are believed to inhabit substellar stars, brown dwarfs, as their secondary stars but observing these very old systems has been one of the biggest challenges in the study of CV evolution today.

To understand the evolutionary path these systems follow, we must understand the structure and mass transfer of these systems as described in section 1. In this thesis I will use the observed period distribution of CVs to introduce many of the observed phenomena relating to late evolution of CVs. Possible mechanics behind angular momentum loss (AML) CVs experience will be discussed. Late evolutionary path as it is understood at this time will be provided. Different ways to possibly identify these late type CVs with substellar secondaries and few possible candidates for them are introduced.

Contents

1 Cataclysmic Variables

Cataclysmic Variables (CVs) are semi-detached interacting binary stars in which a white dwarf accretes mass from a low-mass main sequence star or a brown dwarf. Figure 1 shows a very simplistic drawing of what the structure of these systems are thought to look like. A white dwarf, the primary, is a degenerated stellar core remnant. In case of magnetic CVs the magnetic field lines of the white dwarf interact with the transferred material, causing it to fall on to its surface and magnetic CVs usually do not posses an accretion disc. For non-magnetic CVs the accreted material from the secondary star forms an accretion disc around the primary.

CVs are categorized into classical novae, recurrent novae, dwarf novae and nova-like variables. These categories are defined by the frequency of nova eruptions CVs experience. Nova eruptions are thought to be caused when hydrogen-rich material accretes on to the surface of the white dwarf causing thermonuclear runaway. Classical novae have gone through one observed eruption, recurrent novae have regular eruptions and nova-like variables have never been observed to go through eruptions but have similar behaviour to other groups. For dwarf novae the mechanism is thought to be different for they go through reoccurring outbursts caused by instabilities in the accretion disc.

Evolution of CVs has been subject of research for decades but is still not thoroughly understood. Problem with fully understanding the evolutionary path of CVs is that much of the predicted data do not match the observations made. It is theorized that angular momentum loss (AML) drives the mass transfer and evolution of CVs. However, the mechanics behind the AML are still under questioning. Big part of today's research is to try to observe more systems to confirm the predictions made about CVs' late evolution or possibly to find new explanations for the observed phenomena.

In this thesis I will only look at non-magnetic CVs and consider the mass transfer to be conservative.

1.1 Structure

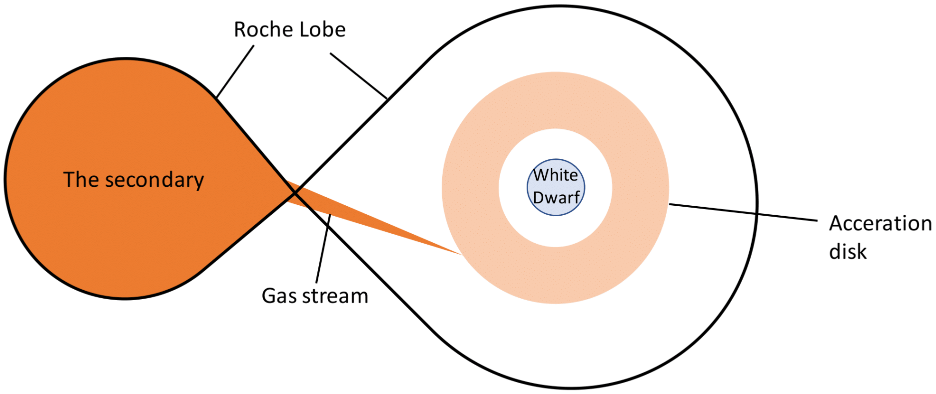

Figure 1: Structure of Cataclysmic Variables

White dwarfs have smaller radius but bigger mass than the secondary star in these systems. Observations of CVs has shown that the white dwarfs in these systems usually have a higher mass than isolated white dwarfs. The average mass of white dwarfs in CVs is around $M_{WD} = 0.83\ M_{\odot}$ [1], while isolated white dwarfs have a mass around $M_{WD} = 0.62\ M_{\odot}$ [2]. It has been theorized that either they gain mass by accretion or CVs form with white dwarfs that already for some reason have a higher mass [3].

The secondary star in CVs is usually thought to be a red dwarf, having the mass of $M_2 \lesssim 0.6\ M_{\odot}$. It has a slightly bigger radius than other main-sequence stars with the same mass due to its rapid mass loss [4]. Due to mass loss the secondary star goes through a lot of evolutionary changes that affect the system as whole. In late evolutionary stages the secondary transforms into a brown dwarf.

For non-magnetic CVs the disc around the primary star forms when material transferring from the secondary will not reach the white dwarf because of its angular momentum. First the material forms a thin ring that will start to expand into a disc around the primary.

1.2 Mass Transfer

Roche Lobe is a region around a star in a binary system in which the material is bound to the star via gravity. Equation for the Roche Lobe is given as:

$$\psi = \frac{GM_1}{(x^2+y^2+z^2)^{\frac{1}{2}}} + \frac{GM_2}{(a-x)^2+y^2+z^2} + \frac{\Omega^2}{2}[(x - \frac{aM_2}{M_1+M_2})^2 + y^2] \tag{1}$$

where a is the binary separation and M_1 and M_2 are the mass of the white dwarf and the secondary star [5]. In the figure 1 Roche Lobe can be seen as teardrop shaped area around both of the stars. Material that exceeds the Roche Lobe of the secondary is no longer attached to the secondary via gravity. In order for the mass transfer to happen in CVs the secondary must come in contact with its Roche Lobe, causing Roche Lobe Overflow. After this the material from the secondary starts transferring to the primary through the systems inner Lagrange point.

If the angular momentum of the system was conserved the binary separation of the CV would increase in response to mass transfer, also increasing the Roche Lobe and ceasing the mass transfer [6]. In CVs their binary separation and therefore orbital period decreases through out the evolution, which lets us conclude that there must be AML acting upon these systems to keep the mass transfer going long-term and stable. The AML shrinks the binary separation of the two stars and therefore shrinks the Roche Lobe of the secondary, enabling the contact between the Roche Lobe and the shrinking secondary. This can be seen from the equation:

$$\frac{R_L}{a} = 0.462(\frac{M_1}{M_1+M_2})^{\frac{1}{3}}, \tag{2}$$

where R_L is the radius of the Roche Lobe [7]. Decreasing binary separation decreases the radius of the Roche Lobe.

Period-density relationship for Roche-lobe-filling stars can be written as:

$$\langle\rho_2\rangle = \frac{3\ M_2}{4\pi R_2^3} \simeq 107\ P_{orb,h}^{-2}\ \mathrm{g\ cm^{-3}}, \tag{3}$$

where M_2 and R_2 are the mass and the radius of the secondary and $P_{orb,h}$ the orbital period of the system in hours.

2 Period Distribution

As mentioned in section 1, CVs lose angular momentum leading to binary separation decrease and therefore orbital period decrease. This lets us conclude that following orbital period decrease we can follow how these systems evolve over time. Looking at period distribution of observed CVs we can see some defining points of their late evolution.

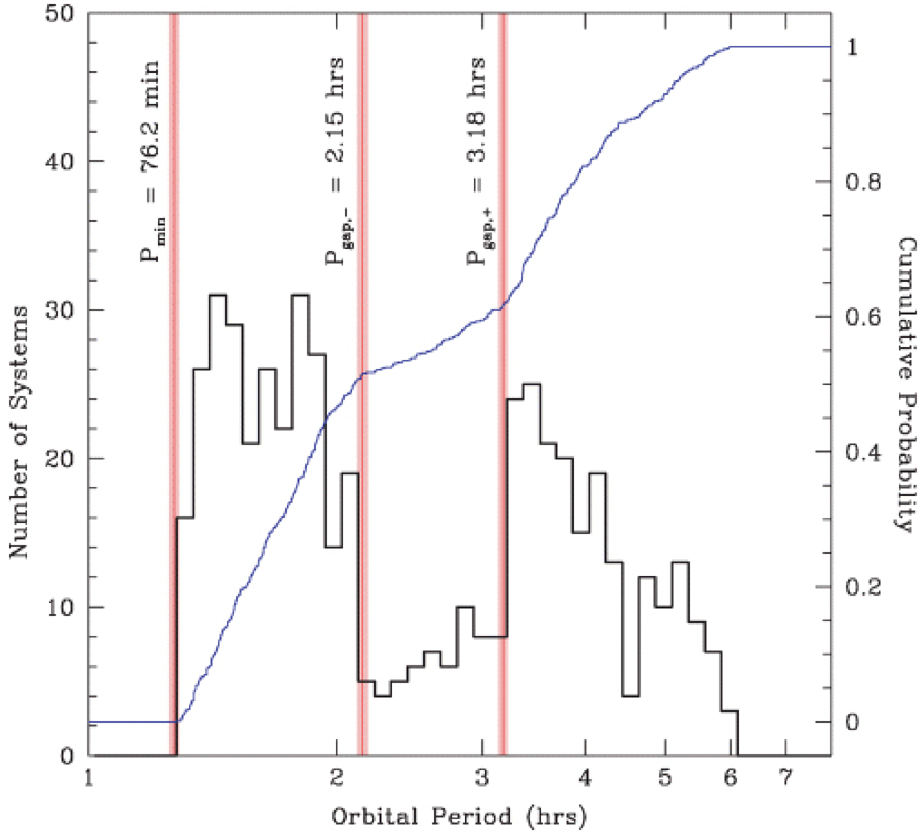

Figure 2: Period Distribution of Cataclysmic Variables taken from Knigge (2006) [8]. This figure shows the amount of systems observed per P_{orb}. The red vertical lines mark the places of the period gap and period minimum.

First thing to note from the distribution is the dearth of systems in between the two red lines marking the so-called period gap at 3.18 and 2.15 hours. Observing CVs has not revealed many systems with the orbital period located between these time points. This phenomenon has been explained by assuming the mass transfer between the components ceases for the duration of the period gap, making them hard to detect. The explanation for the cessation of the mass transfer is that the AML rate these systems experience suddenly drops. This causes the secondary to lose contact with its Roche Lobe temporarily, causing the mass transfer to cease.

A sharp cut-off in the amount of observed systems can be seen in the distribution around 1.3 hours. This suggests the existence of orbital period minimum. When CVs reach this point of their evolution, their orbital period either stops decreasing or none of the systems simply have not evolved further. It is believed that mass loss of the secondary eventually drives it out of thermal equilibrium, causing it to turn into a brown dwarf. Brown dwarfs do not decrease their radius in response to mass loss but increase, which leads to orbital period increasing. This can be seen from equation 3. This turn causes the period minimum and suggests the existence of systems which are evolving back to longer periods.

From the period distribution can also be noted that after the period gap there is an increase in the amount of observed systems. This increase is well in line with theories, but the amount of observed systems after the period gap is in fact way too low. Most of the systems should have already evolved near the period minimum or even past it. This should cause a clear and sharp spike at the period minimum.

In the following sections more specific explanations for the observed phenomena on the period distribution will be provided.

3 AML - mechanics

As stated in section 1.2, AML drives the mass transfer in CVs. It maintains the contact between the Roche Lobe and the secondary star, enabling mass transfer. This lets us conclude that there must be a mechanism that causes the AML [9].

The requirement for the AML is for it to be rapid enough for the mass loss timescale of the secondary ($\tau_{\dot{M}_2} \sim M_2/\dot{M}_2$, where $\dot{M}_2$ is the amount of mass loss the secondary experiences) to be comparable with its thermal timescale ($\tau_{th} \sim GM_2^2/L_2R_2$) [4]. Mass loss will cause the secondary star to shrink in order for it to stay in thermal equilibrium. For this reason the AML needs to shrink the binary separation and therefore the radius of the Roche Lobe rapidly enough, so that the secondary and its Roche Lobe stay in contact. Gravitational radiation (GR) is thought to be the main driving force of AML for all close binaries [6].

3.1 Above the Period Gap

The rate secondary loses mass above the period gap is typically around $\sim 10^{-9}$ to $\sim 10^{-8}$ $M_\odot$ yr^{-1} [10]. The rate secondary star loses mass is slightly too high for the time it needs to shrink back to the radius needed for thermal equilibrium. This means that the star can not quite reach the ideal radius for thermal equilibrium and for this reason the secondary star becomes slightly bloated and will have around 30% bigger radius than other stars with the same mass [4].

GR gives the baseline for AML in CVs. However, AML rate CVs experience is far higher than GR alone would cause. In order to explain the AML rate, which needs to be higher than GR alone, and the existence of the period gap it is thought that above the period gap the main driving force for AML is magnetic braking.

Magnetic braking is caused by a main-sequence star that has a magnetic field which causes the star to lose its orbital angular momentum. Material removed from the surface of the star by stellar wind stays in corotation with the star because magnetically coupled stellar wind interacts with the open field lines of the star. When the star rotates, the rotating material causes a torque that reduces the rotational angular momentum of the star. This is thought to happen with the secondary star, but tidal forces in CVs cause the angular momentum to drain from the CVs orbit instead from the rotation of the secondary [9].

3.2 In The Period Gap

When the secondary star has lost enough mass it becomes fully convective. This happens when the secondary's mass is around $M_2 \approx 0.26\ M_\odot$. At this point the system is usually near the cut-off on the period distribution, at the beginning of the period gap, having the orbital period of ~ 3.18 hours.

It is theorized that when a star becomes fully convective it loses its magnetic field or at least the strength of the magnetic field decreases. Because magnetic braking relays entirely on the magnetic field of the secondary, Spruit and Ritter (1983) proposed that when the secondary becomes fully convective, the sudden weakening of the magnetic field would cause a sudden drop in the AML rate [11].

A sudden decrease in the AML rate, and therefore in the rate the secondary loses mass to the primary, would give the secondary star a chance to contract to the ideal radius for thermal equilibrium. As mentioned at the beginning of this section, above the period gap the secondary star has about 30% bigger radius than it should have compared to its mass. The contraction to smaller radius quite suddenly would cause the loss of contact between the secondary and its Roche Lobe and therefore pause the mass transfer.

Identification of CVs usually happens through emission lines caused by the accreted material. Mass transfer also causes nova eruptions and outbursts that increase the magnitude of CVs and make them more detectable. Since most typical ways to identify CVs require on-going mass transfer, during the period gap their detection is difficult. This is thought to be the cause of the observed period gap.

While the system evolves in the period gap, GR is still causing the system to lose angular momentum. Therefore the AML continues to shrink the binary separation and the Roche Lobe. For this reason the Roche Lobe eventually reaches the secondary star again around $P_{orb} \sim 2.15$ hours, enabling the mass transfer between the components again. The system becomes detectable again, marking the end of the period gap on the period distribution. From this point forward GR is thought to be the main driving force of AML.

Garraffo et al (2018) present a study following the idea from Taam & Spruit (1989) [12], that the secondary's magnetic field does not disappear when it becomes fully convective but instead the magnetic field becomes more complex [13]. Increased complexity of the magnetic field would cause the AML experienced by the secondary to weaken [13]. This would be consistent with X-ray observations made, that suggest the magnetic activity to be as strong as it was before the star becomes fully convective [14]. This could also be able to explain the period gap, because the sudden decrease in AML would still cause the secondary to lose touch with its Roche Lobe as described before. This theory would not discredit the idea of disrupted magnetic braking but offer an explanation for the disruption.

The theory of cessation of the mass transfer for duration of the period gap would suggest that secondary stars above and below the gap would have identical masses but different radii. Patterson et al. (2005) produced a study that showed a discontinuity in the radius of the secondary around $M_2 \approx 0.2\ M_\odot$ which roughly corresponds to the period gap, suggesting that the disrupted magnetic braking theory's prediction is right [15].

3.3 Below the Period Gap

Relying on the theory of disrupted magnetic braking, it would no more affect below the period gap or its contribution would be a lot smaller. This would mean that GR would be the main driving force for the AML below the period gap. The AML rate caused by GR is much lower than the rate caused by magnetic braking and therefore the mass transfer rate is lower. The mass transfer rate below the period gap is $\lesssim 10^{-10}\ M_\odot\ \mathrm{yr}^{-1}$ [10].

Calculations from Knigge et al (2011) show that AML below the period gap could be as high as 2.47 ± 0.22 times the GR rate, suggesting that additional mechanism to GR is needed [4]. McAllister et al (2018) presented a study of 15 CVs components masses, where they presented 6 new estimates and 9 improved estimates. Through these new estimates the study pointed, that the rate for AML that Knigge et al (2011) presented is too high, because they had under predicted the secondaries masses below the period gap [16]. The rate for AML is still higher than GR would alone cause and explanation for the higher AML rate is still needed.

4 Short Period CVs

4.1 Period Minimum

Period minimum is seen in the period distribution as a sharp cut-off in observed systems around 76 minutes. The phenomenon behind the observed orbital period minimum has been explained by the changes happening in the secondary star. When the systems have evolved near the observed period minimum, secondary star's time-scale for mass loss is much shorter than thermal time-scale, $\tau_{th} >> \tau_{\dot{M}_2}$ [4]. Secondary star can not stay in thermal equilibrium anymore, since it can not shrink to the radius needed for thermal equilibrium fast enough. This causes the secondary to turn into a substellar object, a brown dwarf. Even if the mass loss was slow and the thermal time-scale would not exceed the mass loss time-scale, the continuous mass loss of the secondary star will eventually cause it to reach the hydrogen burning limit around $M_2 \approx 0.07$ $\mathrm{M}_\odot$ [4]. After this the star's mass would not be sufficient to support nuclear reactions to burn hydrogen in its core and the star turns into a substellar object.

Brown dwarfs do not shrink in response to mass loss, because they are not trying to stay in thermal equilibrium. Brown dwarf responses to mass loss by increasing its radius. The still on-going mass transfer and increasing radius of the brown dwarf cause the density of the secondary to decrease. From the equation 3 it can be seen, that in response to the decreasing density of the secondary, the orbital period stars to increase [17]. This turn towards longer orbital periods is thought to cause the observed orbital period minimum. The exact place of the period minimum for a CV depends on the total mass of the binary. Gravitational radiation is stronger higher the total mass is, causing the period minimum to be longer [17].

In early 2000's the observed period minimum was around 77 minutes and the predicted one around 65 minutes [18]. Theoretical prediction for the period minimum varies in different studies but it is usually located between 65 minutes to around 80 minutes, usually noticeably shorter than observed one. New observations of the systems and improvements in the predictions have improved these numbers during the years, but still the problem seems to be that the observed and predicted period minimum do not quite match.

Explaining the mismatch could succeed by assuming that below the period gap there is additional AML to GR affecting the systems. As mentioned in section 3, according to calculations of Knigge et al (2011) the rate for AML below the period gap must be 2.47±0.22 times the GR rate [4]. In this study the evolutionary track CVs follow was constructed by using the mass-radius relationship of the secondary as an indicator of evolutionary changes in the system. This seems to work well because it is assumed that the secondary's evolutionary changes affect the system as whole. When this higher AML rate was used to calculate the period minimum in their study, they located the theoretical period minimum that was in good agreement with the observed one [4]. The observed period minimum after a comprehensive study in 2009 to find faint CVs near the period minimum was located at $P_{min} = 82.04 \pm 0.7$ minutes at the time [19].

However, McAllister's et al (2018) study of 15 CVs' components masses estimated the observed period minimum to be at 79.6 ± 0.02 minutes [16]. This prediction was made by fitting Gaussian distribution to the current sample of CVs' orbital periods in the range of $76 - 82$ minutes. The new estimated masses lowered the observed period minimum quite significantly, causing the predicted period minimum by Knigge et al (2011) to be too high and no longer match the observed one [16].

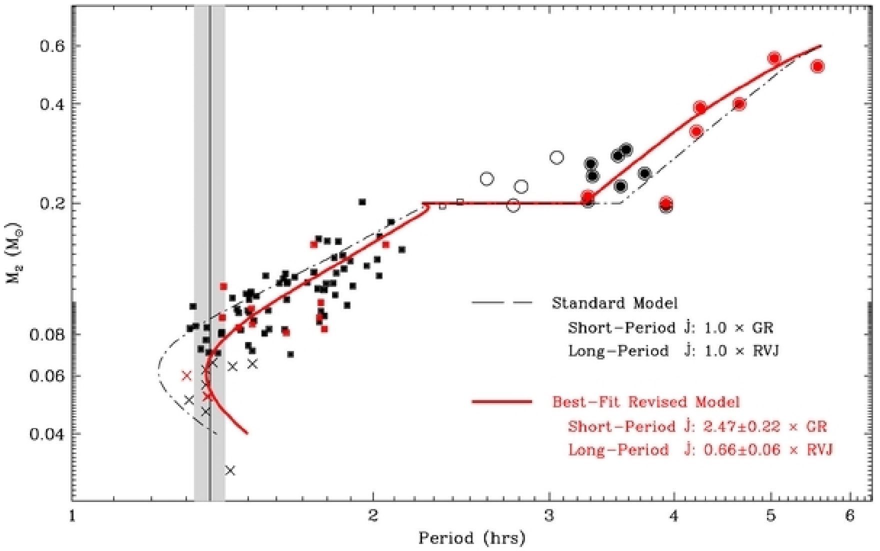

Figure 3: Mass of the secondary star as function of the orbital period of Cataclysmic Variables taken from Knigge et al (2011) [4]. The vertical line marks the place of the period spike, which should correspond to the period minimum of CVs. The red line shows the model created in the paper and the black dotted line shows the prediction made by the standard model. The AML rates used for the best-fit model below the period gap is 2.47 times the one used for the standard model. This is far higher rate and seems to produce the period minimum almost exactly were the spike should be located. The difference between the two models is remarkable.

4.2 Period Spike

The period distribution in section 2 shows an increase in amount of systems after the period gap and near the period minimum. Theories have predicted the existence of a period spike at the period minimum for decades, for calculations have shown that ∼ 99% of CVs should have evolved past the period gap and ∼ 70% of them should be period bouncers [20].

It takes about 10^9 years from CVs to evolve down to $P_{orb} = 2$ hr. Hence most of the CVs should have already evolved near the period minimum. The slowed down mass transfer below the period gap causes CVs to evolve slower and spend a long time near the period minimum. Period bouncers, systems that have already evolved beyond the period minimum, should also be present in the period spike. Observing the period spike was a problem for decades, because even though rise in the amount of systems after the period gap was observed, no clear spike was found. Systems with short orbital periods can be very faint which causes them to be harder to spot than systems with longer orbital periods. This could explain why there are quite a lot systems located above the period gap and not as much as wanted below the period gap.

In 2009 Gänsicke et al carried out a study to look for faint CVs near the period minimum using data from Sloan Digital Sky Survey (SDSS). They succeeded on locating various faint systems around the orbital period range of 80 to 86 minutes, finally producing a period spike near the period minimum [19]. This was a significant find.

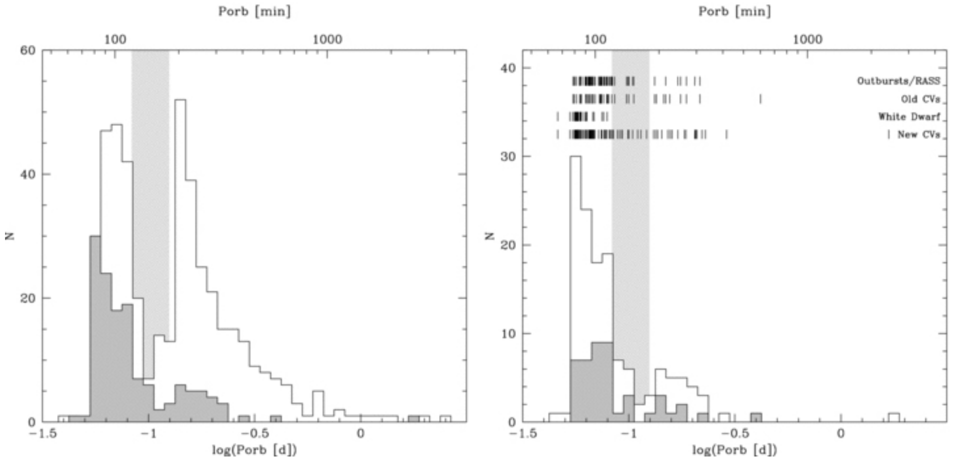

Figure 4: Period Distributions taken from Gänsicke et al (2009) [19]. Left hand chart shows CVs from catalog of Ritter & Kolb (2003) [21] that were not observed in SDSS in white compared to all CVs observed by SDSS in grey. Right hand chart shows all the CVs observed by SDSS, grey ones showing the CVs that had already been identified and white shows the new ones observed by Gänsicke et al (2009). The light grey panel in both charts marks the place of the period gap.

Figure 4 shows how much significance this study had on the orbital period distribution. The now-observed spike is not as sharp and tall as predicted. Finding systems near the period minimum is difficult because of the dominance of the white dwarfs in the observations. If it is assumed that AML acting upon CVs below the period gap would be solely caused by GR, white dwarfs had the same mass and the secondary stars had a chemical composition of Zero Age Main Sequence star the period spike should be extremely visible in the period distribution. Under these assumptions population synthesis made by Goliasch & Nelson (2015) shows that the probability density per P_{orb} to find systems near the period minimum is twice as large as to find them on the orbital period range of 76 - 106 minutes [22]. But the different white dwarf masses and chemical compositions of the secondary would create the spike to be more muted.

4.3 Period Bouncers

Period bouncers are systems that have evolved beyond the period minimum towards longer orbital periods. These systems have a substellar secondary, a brown dwarf, which in response to mass loss expands its radius, causing the expansion of the orbital period.

Mass transfer near the period minimum is fairly slow compared to younger systems. At this point CVs evolve much slower and therefore spend a long time near the period minimum. This should tell us that most of the systems should be near the period minimum in their evolution and most of them period bouncers. The typical theoretical prediction of CVs that would have evolved beyond the period minimum is estimated to be as high as $\simeq 70$ percent [23]. The problem again rises, when the observations do not match the predictions. There are multiple systems detected that are good candidates of being period bouncers, but confirming these systems to actually inhabit a substellar secondary is quite challenging.

While identifying period bouncers a short orbital period is a good indicator for them, but not sufficient to differentiate them from other short period CVs. A good way to differentiate a period bouncers from other CVs is to use the mass ratio of the components, $q = M_2/M_{WD}$. For short period CVs that have yet to reach the period minimum and have an orbital period of 90 minutes, this ratio is about $q = 0.13$

and for post-period minimum systems with the same orbital period the ratio is about $q = 0.03$ [24]. Patterson (2011) showed that the bounce occurs somewhere between $q = 0.065 - 0.080$ [25].

An example of identified period bouncer is QZ Lib. It was already a known CV when Pala et al (2018) analyzed data from the star's super-outburst. The orbital period was located at $P_{orb} = 0.06436$ days which corresponds to 92.7 minutes. Calculated mass ratio was $q = 0.020 \pm 0.017$, which is in line with substellar companion [24]. The reason it was not identified as a period bouncer before was because it was studied in such a limited wavelength range. This is an indication that there could be many more already known CVs that have not been identified as period bouncers yet [24].

The easiest explanation for the lack of observations of period bouncers is thought to be selection effects. White dwarfs are very bright and especially while having a low-mass substellar companion, their brightness and much higher mass makes period bouncers hard to differentiate from isolated white dwarfs. Systems like this might be possible to only observe through their close binary nature, because they might not show any other classic accretion signatures affiliated with CVs, like emission lines [26].

Hernandez Santisteban et al (2018) estimated the upper limit of the period density of post period minimum CVs to be $\rho \lesssim 1.8 \cdot 10^-5 \text{ pc}^{-3}$ [26]. This estimation was made by observing sample of 2264 white dwarf candidates and trying to observe if they had transiting substellar companions, especially looking for "dead" CVs. Dead CVs would have a dark substellar companion and no observed signs of accretion. Some CVs have inclination that causes them to eclipse when observing them and these eclipses would cause dropouts in observed light curves. Many studies before had searched the same data set for variable objects, but this study was first to look for these eclipsing systems, so called dropouts. The search revealed no systems with substellar companions, giving the estimate for the space density. As the paper states [26], this space density is lower than most previous estimates, but it matches recent predictions made by Goliasch and Nelson (2015) [22].

Schreiber et al (2016) presented a study of consequential angular momentum loss

(CAML) where they showed that CAML would be able to explain multiple problems regarding CV evolution, including matching the observed and predicted space densities [27]. CAML refers to AML caused by the mass transfer occurring between the two components, therefore only occurring outside the period gap.

The theory suggests that CAML occurring in CVs increases with decreasing white dwarf masses. This would cause CVs with low-mass primary stars to have unstable mass transfer in the short periods and this means they could possibly disappear as CVs, because the white dwarf and its companion would merge [27]. The explanation for the missing period bouncers would simply be that they do not exist. This could also explain why we have observed many systems in which the white dwarfs have a higher mass than expected. Then there is still the problem on figuring out, what causes the CAML needed for the theory. Most obvious mechanism for CAML tends to be nova eruptions. They could cause significant friction between the secondary star and ejecta [27].

5 Search for Period Bouncers

WZ Sge-type stars are a subgroup of dwarf novae. Their accretion is very slow which causes them to have outbursts quite seldom, several years or even decades between them. They have short orbital periods and their mass-ratio distribution has a peak between 0.07 and 0.08 [28], indicating that they are very good candidates for period bouncers. Many of the known period bouncer candidates are actually WZ Sge-type stars. However, they are very faint CVs and therefor hard to detect. One way to differentiate the period bouncers from other short period CVs is to look at their spectral energy distribution (SED) [29].

5.1 SED

Observing these types of CVs SED in the ultraviolet - optical - near-infrared (NIR) wavelengths can reveal the nature of the secondary star. Because of the low mass transfer rate the disc should not add much contamination on the NIR luminosity. When the secondary turns into a substellar object it is thought that the NIR flux of the secondary drops significantly. So for pre-bounce systems there should be a noticeable amount of red-NIR excess in the spectrum that will not be observed for post-bounce systems.

Neustroev et al (2017) presented a study of WZ Sge-type dwarf novae SSS J122221.7311525 that had gone through a super-outburst [30]. When observing the CV in its quiescence state there were no excess NIR detected. The mass-ratio of the system was determined to be $q \lesssim 0.045$ and the orbital period of the system to be $P_{orb} \approx 109.8$ minutes [30]. All these are very strong indicators for a period bouncer.

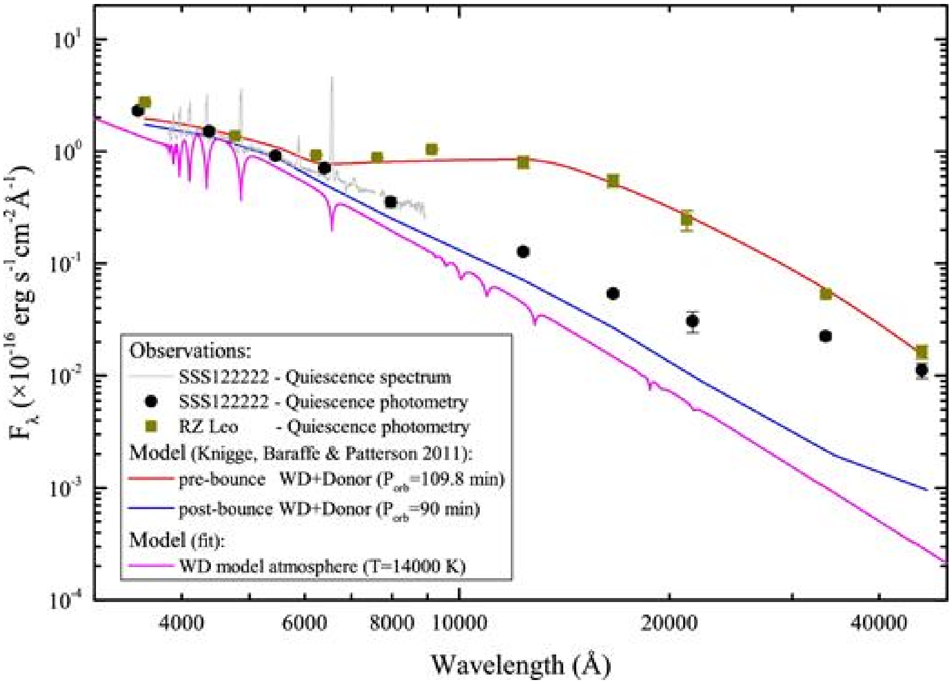

Figure 5: Taken from Neustroev et al (2017) [30]. The red and blue lines show the theoretical values for SED calculated by using a model from Knigge et al (2011) [4]. The red line predicts the energy distribution for pre-bounce systems and the blue line for post-bounce systems. The square marks are from a observed pre-bounce CV. The black dots represent the CV observed in the study. Both systems follow the theoretical lines quite closely, confirming SSS J122221.7311525 as a good period bouncer candidate.

5.2 Superhumps

Superhumps are present in short-period CVs. They are periodic variations in brightness caused by tidal instabilities in the accretion disc. Superhump period is usually a few percents longer than the orbital period of the system [24]. Using superhump periods mass ratio q can be determined. Low mass ratio is a good indicator for a period bouncer. If it is assumed that $M_{WD} = 0.81 M_\odot$, the secondary star's mass can be also determined as shown below.

Kato (2015) listed all known WZ Sge-type stars with their known properties [28]. Using the orbital and superhump periods of these systems as listed in the paper, the period excess of the superhump can be calculated as follows:

$$\epsilon = \frac{P_{SH} - P_{orb}}{P_{orb}}, \tag{4}$$

where P_{SH} is the superhump period. The excess ϵ and the mass ratio of the two stars q, are related as seen by the equation:

$$q(\epsilon) = (0.118 \pm 0.003) + (4.45 \pm 0.28) \cdot (\epsilon - 0.025) \tag{5}$$

Equations 4 and 5 can be found from McAllister et al (2018) [16]. By calculating the mass ratios with these equations and assuming an average white dwarf mass to be $M_{WD} = 0.81\ \mathrm{M}_{\odot}$, the masses of the secondary stars can be calculated. When plotting masses of the secondary stars as a function of the orbital periods, it can be seen from the figure 6 that most of the known WZ Sge-type stars locate near the period minimum with low mass secondary stars. This indicates many of them being good period bouncer candidates.

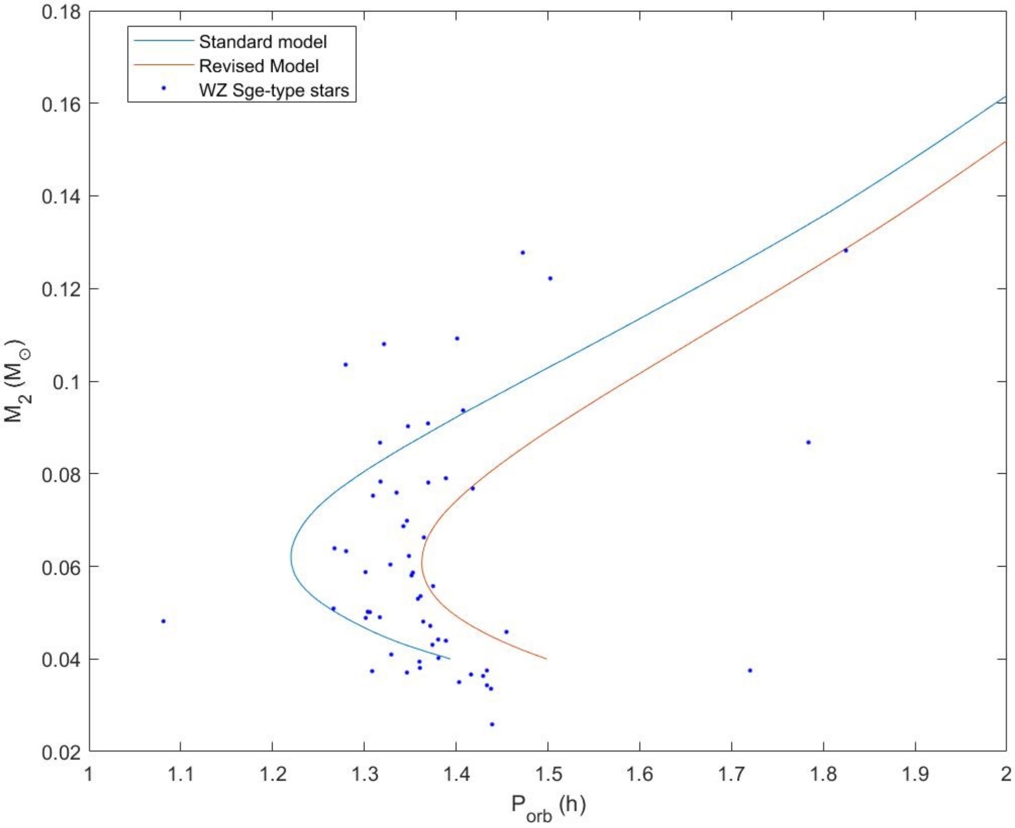

Figure 6: Masses of the secondary stars as function of the orbital period. Data for plotting the standard model and revised model taken from Knigge et al (2011) [4]. Data for the WZ Sge-type stars taken from Kato (2015) [28]. Using the equations 4 and 5 masses for the secondary stars were calculated.

6 Summary

Cataclysmic Variables are interacting binary starts and their evolution is driven by AML that causes long-term mass transfer between the components. The clear evolutionary path CVs follow has yet to be constructed. The standard model offers good explanations for the phenomena seen in the period distribution, but still a lot is missing.

Figuring out the proper cause for AML below the period gap would give us a possibility to solve the period minimum problem and maybe have a better explanation for the observed period gap.

New observations of period bouncers and estimates of their properties would shine light on the most interesting and less-understood part of late CV evolution. Trying to identify period bouncers from already discovered systems has been a good way to discover them.

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