Dwarf Novae

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ABSTRACT

Dwarf novae (DN) are a subclass of cataclysmic variable stars (CVs) composed of a white dwarf accreting matter from a low-mass companion. They are characterized by periodic increases in brightness driven by accretion dynamics within the binary system. These outbursts are dimmer and more frequent than for other types of CVs, like classical novae, due to temporary increases in accretion rates. Dwarf novae were first discovered in 1855 by John Russel Hind, but the class of dwarf novae was only created after the discovery of SS Cyngi by Ms. Louisa Wells in 1896. Some of the first theories explaining DN were geometric variability, a connection with classical novae and thermal variability before they landed on the idea of an accretion disk with a hot spot. Although the outbursts in dwarf novae are well-characterized, their underlying mechanisms remain debated, with the two leading theories being the Disk Instability Model and the Mass Transfer Burst Model. These rely respectively on the dynamics within the accretion disk and on the mass transfer between the two stars. Observational data and outburst modelling provide critical insights into the complex interactions between the white dwarf and its companion star. This paper explores the historical context, theoretical models, and observational techniques that inform our understanding of dwarf novae.

1. INTRODUCTION

In astronomy, cataclysmic variable stars (CVs) are binary systems where a white dwarf, the primary star, accretes matter from a low-mass companion, typically a main-sequence star. The interaction between these stars gives rise to various types of outbursts, depending on the system's properties. These outbursts, which serve as mechanisms for the system to release energy, include supernovae, classical novae, and dwarf novae, each driven by distinct processes. Contrary to supernovae, which are characterized by the star dying after the explosion, dwarf novae and classical novae are both types of CVs where the components of the binary survive the release of energy and can undergo additional recurring outbursts. These are characterized by increases in brightness followed by a longer quiescent (inactive) state. Dwarf novae and classical novae both exhibit periodic outbursts; however, unlike classical novae, dwarf novae are generally dimmer and exhibit more frequent outbursts (Shappee et al. 2017).

Dwarf novae (DN), also known as U Geminorum variables, usually have their brightness increase by 2 to 6 magnitudes during their outbursts, which corresponds to an increase by a factor of 6 to 250 in luminosity. Their outburst phases can last 5 to 20 days and are separated by quiet (quiescent) intervals that last 30 to 300 days (Carroll & Ostlie 2006). Dwarf novae exhibit distinct phases, with a high accretion rate during outbursts followed by a lower accretion rate during quiescence, and can be classified based on the orbital period gap observed in cataclysmic variables. This gap, which contains periods between 2 to 3.12 hours approximately, is marked by noticeably fewer observations of systems within this range (Garraffo et al. 2018). The orbital period can be translated into a mass ratio, q, given by the donor star's mass over that of the white dwarf. Accordingly, dwarf novae are categorized as being either below or above the period gap, with each group exhibiting distinct outburst behaviours. The duration of shorter outbursts is typically related to the orbital period of the binary system, while longer outbursts appear to be independent of the orbital period (Cannizzo 2000).

Although we can characterize the outbursts in dwarf novae, the mechanisms driving them are still a subject of debate, with two primary models proposed: the Disk Instability Model and the Mass Transfer Burst Model (Sion et al. 2008). Both of these models rely on the dynamics of the accretion disk around the white dwarf, with the first model relying on instabilities within the disk and the second model focusing on instabilities in the mass transfer between the two stars. As such, studying dwarf novae and their outbursts through measurements such as light curves could be crucial for understanding the dynamics of accretion disks.

This paper will go over the historical background of dwarf novae and some initial theories in Section 2. Then Section 3 will go deeper into the current theories, and Section 4 will give an overview of some observations of dwarf novae and the current methods used to study them. Finally, a summary of the important points and a few open questions will be given in Section 5.

2. BACKGROUND

2.1. *First Detections*

The first star of the Dwarf Novae type to be observed was U Geminorum – seen in 1855 by English astronomer John Russel Hind (1823 - 1895) (McLeod 1948)(Jensen et al. 1995). That night, Hind had been searching for minor planets when he noticed a ninth-magnitude star where nothing had been observed before (McLeod 1948). He observed the new variable for several nights and noticed that it didn't move, confirming that it couldn't be an asteroid. In the following nights, Hind saw the star fade from a magnitude of 9 to one of 14, as shown in Figure 1 (McLeod 1948). It stayed at this fainter magnitude, almost invisible in Hind's telescope, for several months. As a consequence, astronomer Hind decided to give it the class of *faint nova*.

However, a few months later, U Geminorum was seen following the same cycle (bright outburst and subsequent dimming) by another English astronomer Norman Robert Pogson (1829 - 1891). Following this separate observation, U Geminorum was monitored more systematically such that more cycles were observed, and the period between the outbursts was calculated to be around 100 days. By definition, due to the repeated outbursts, this was not a classical nova. Thus, a new class of variable stars, called dwarf novae, was established, with U Geminorum being the first star belonging to that class (Jensen et al. 1995)(McLeod 1948). At the time of this first observation, the mechanism of U Geminorum was not understood. It remained unique among all other previously detected variable stars for around 40 years – until the detection of SS Cyngi.

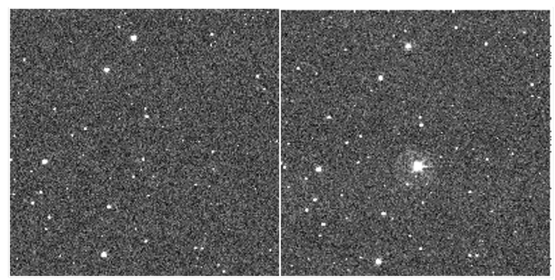

Figure 1. On the left is a 20-second exposure of U GEM before an outburst, and on the right is a 20-second exposure of U GEM after the start of an outburst. A clear increase in luminosity is seen during the outburst. Images were taken by AAVSO member Arne Henden, USRA/USNO (AAVSO 2024).

SS Cyngi, observed in 1896 by Ms. Louisa Wells with the Harvard Observatory as she was scouring photographs of star fields situated in the constellation Cygnus, was the second star of the dwarf nova type to be discovered. Similarly to U Geminorum, its magnitude varies from 12^{th} to 8^{th} magnitude in only 50 days on average. Most of the time SS Cygni is in its dimmer state, such that it is barely visible in a four-inch telescope (McLeod 1948).

The subsequent detections of dwarf novae were mostly done by amateur astronomers. Indeed, due to the unpredictable behaviour of most cataclysmic variables, dwarf novae included, it was very difficult for professional astronomers and big collaborations to monitor these sources. As such, this was a field where amateur astronomers could shine and contribute substantially, allowing the detection of hundreds of dwarf novae in the visual range (Jensen et al. 1995). Nowadays, non-profit scientific organizations composed of amateur astronomers, such as the *American Association of Variable Star Observers* (AAVSO), often have their observations and data available for use on their websites.

2.2. *First Theories*

The first attempts at explaining the nature of dwarf novae were based on the outburst light curves of those first two detections (U Gen and SS Cyg). This proved to be difficult due to the dissimilarities between both light curves; outbursts from SS Cyg were frequent but irregularly spaced (see Figure 2), while those from U Gem occurred at larger intervals and regularly alternated between longer- and shorter-lasting bursts. Moreover, the brief episode in 1907/1908 during which SS Cyg ceased its regular outbursts and instead went through irregular brightness fluctuation caused additional doubts and confusion (La Dous 1994).

Nonetheless, with their few observations, they determined that novae are related to dwarf novae. While this is also the modern belief and can be shown through collected data, at the time of early theories, this assumption was entirely built on the fact that both objects go through outbursts. This link between both object types was supported by a relation Kukarin and Paranego (1934) thought to have found, which linked the outburst amplitude of dwarf and recurrent novae to their frequency and recurrence. The application of that relation to the amplitude of novae led to results compatible with them having been observed only once (La Dous 1994). While there is no physical reason to want to relate the amplitude of dwarf novae to that of novae, historically, the assumption that novae and dwarf novae are related played a role in modern-day understanding of CVs.

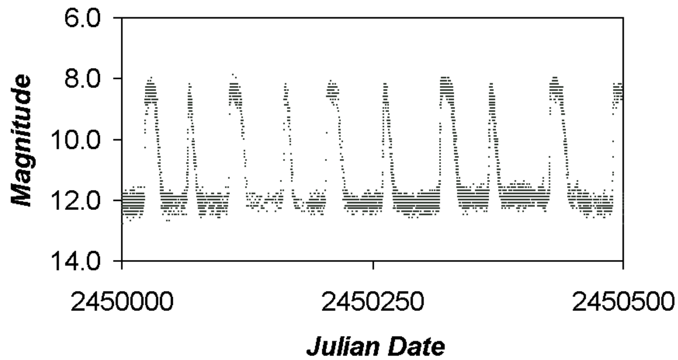

Figure 2. Portion of the SS Cygni light curve from the AAVSO International Database. Interchanging bouts of wide and narrow outbursts, as well as the variability in the period, can be seen (AAVSO 2024).

Even with the accidentally correct assumption that dwarf novae are somewhat similar to novae, physicists at the time went through a few wrong theories before landing on the current one. Originally, no distinction could be made between geometrically variable (eclipsing) and intrinsically variable stars. Moreover, there was a certain reluctance to accept stars as having larger degrees of physical variability. As such, the first attempts at explaining cataclysmic variables, dwarf novae included, were made on the idea that they were geometrically variable (La Dous 1994). With this in mind, several observations were analyzed using light-curve analysis methods in an attempt to provide a physics explanation of cataclysmic variables. This idea, unfortunately, had many problems. First, at the time, the observations of cataclysmic variables were done using time resolutions that didn't allow the detection of the binary nature of stars. Second, since observed phenomena linked to dwarf novae were an increase in brightness and not a decrease, and since the phenomena were not strictly periodic, they could not be attributed to eclipses (La Dous 1994).

Due to the high variability of the characteristics of dwarf novae preventing the recognition of an easy solution, all attempts at explanations failed until around 1930. The development of powerful spectrographs with sufficiently high spectral resolutions enabled some crucial breakthroughs. By looking at the changes in spectral energy distribution in connection with brightness, they were able to determine whether the changes were due to geometrical origins or changes in temperature (La Dous 1994). In 1932, the origin was determined to be geometric due to the small variation in the colour indices on SS Cyg and U Gem. However, in 1948, Hinderer obtained spectra at very good resolution and was able to determine that the changes were due to temperature changes.

The model of the dwarf novae that Hinderer depicted was that of a G-type star surrounded by a shell of thin gas that emitted the emission line seen during the quiescent state. According to Hinderer, the outburst was due to the liberation of large quantities of the star's internal energy, causing an increase in temperature (La Dous 1994).

An important piece of the puzzle was eventually found with the study of the star UX UMa. UX UMa had been known as an eclipsing binary with one of the shortest orbital periods for a while. The application of conventional methods of analysis kept failing due to a slight brightness increase ("hump"). Spectroscopic investigations of sufficient quality for radial velocities eventually led to the new scenario of UX UMa being a primary star of stellar type O surrounded by a gaseous cloud with a hot "head" and a cool "tail". Eventually, similarities between the spectra of UX UMa and the old nova DQ Her were found. With the idea of accretion disks not being new, going from an O-type star with a gas cloud and a hot "head" to an accretion disk with a hot spot was a small step – leading to the creation of the Standard Model for cataclysmic variables. Shortly after the hypothesis published by Crawford and Kraft in 1956, Kraft published a paper in which he applied the Standard Model for cataclysmic variables to dwarf novae (1962), showing that they are caused by accretion disks (La Dous 1994). An artist's depiction of the accretion disk model of dwarf novae can be seen in Figure 3, with an in-depth explanation of the physics associated with that model given in Section 3.

3. CURRENT THEORY: DISK INSTABILITY AND ACCRETION PROCESSES

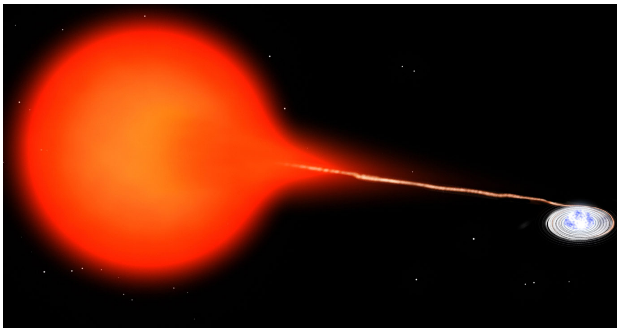

Figure 3. Artist's depiction of the SS Cygni double-star system according to the Standard Model of CVs. White-dwarf star (right) accretes material from red-dwarf star (left), forming an accretion disk and 'hot spot.' Credit: Bill Saxton, NRAO/AUI/NSF (NRAO).

The recurring outbursts in dwarf novae are understood through two types of models. The first suggests that the outbursts result from instability in the accretion disk surrounding the white dwarf, where matter from the donor star builds up over time (Lasota 2001). The second proposes instead that the mass transfer from the donor star to the disk is unstable, leading to a burst in mass transfer. Then, the large amount of added material in the disk is efficiently accreted onto the white dwarf, which explains the burst in luminosity (Schlindwein & Baptista 2024). Thus, after presenting the understanding of Dwarf Novae formation, some time will be spent presenting the first model – Disk Instability Model (DIM) – and the second – the Mass Transfer Burst model (MTB). Finally, before concluding, an overview of the link to observables will be given, as well as the limitations of the model.

3.1. *Formation of Dwarf Novae*

First, the two stars form in proximity in the giant molecular clouds of the interstellar medium. Due to their different masses, they evolve differently. Namely, the more massive one evolves faster. Thus, by the time the less massive one, the *donor*, reaches the Main Sequence, the other has already shed its outer layers to become a white dwarf. Throughout this evolution, the separation of the binary can decrease due to loss of angular momentum to surrounding dust, through gravitational wave emission, or to a third interacting massive body such as a star. Regardless, as the donor evolves into a giant, if the two stars are close enough, mass will be lost through Roche lobe overflow. Recall that the Roche lobe is the region around a star in a binary system where matter stays gravitationally bound to the star. Thus, mass is not lost to the vacuum but enters the main star's Roche lobe, creating an accretion disk. To this day, two competing models present differing perspectives. Modern treatments incorporate both models. The first is the Mass Outburst Model, where the luminosity outbursts are thought to be due to instability in the mass-transfer rate. The second is the Disk Instability Model, which postulates that thermal-viscous instabilities, and more recently tidal instabilities, within the accretion disk onset the luminosity peak (Hameury 2020).

3.2. *The Disk Instability Model (DIM)*

The disk instability model, in its simplest form, assumes constant mass transfer from the donor to the disk. Other assumptions used are that the disk is geometrically thin and radially symmetric, allowing one-dimensional analysis and reducing computational complexity (Hameury 2020). In its *quiescent*, or cool state, the disk's accretion efficiency slowly varies but is always less efficient than the mass transfer to it. Thus matter accumulates, and due to the gravitational dynamics and velocity profile within the disk, this leads to heating of the disk, rather than simply growth in size (Hameury 2020). The disk stays in this stable state of temperature build-up until temperatures comparable to the ionization temperature of hydrogen are reached. The ionization of hydrogen is crucial since the separation of a neutral fluid into two charged fluids introduces coulomb interactions as well as interactions with the magnetic field, ubiquitous to stars. These effects drastically change the viscosity of the system for a number of reasons. Before getting into the specifics, it's important to recall the role of viscosity in such a system. Recall, the equation for the *shear* τ, between two fluid layers, equivalent to a force per area with a normal vector perpendicular to the force[1],

$$\tau = \mu \frac{\partial \omega}{\partial r}, \tag{1}$$

where μ is the viscosity, ω is the angular velocity, and r is the radial parameterization of the disk. This is key since it illustrates that with a greater viscosity, the force between the layers will be greater, implying that there is more transfer of angular momentum in the outward direction. This more efficient loss of momentum from the inner layers allows for a more efficient in-fall of material, leading to more photon emission. Now let's delve into the specifics of why this viscosity changes.

It's important to mention the temperature dependence of viscosity. Spitzer-Härm theory predicts $\mu \propto T^{5/2}$ (Hameury 2020). However, for the purposes of computational efficiency, in most cases, a simpler parameterization is used instead of explicitly incorporating this dependence since the effect of this profile is negligible in terms of observed luminosity. The details of this will be explained in Section 4. Additionally, the temperature gradient in the disk itself compensates for this variation, making the approximation even better than one would naively expect.

In a neutral fluid, viscosity comes from the short-range collisions between the molecules. However, in a charged fluid, the long-range nature of Coulomb interactions allows interactions over long ranges in the same conditions, increasing the viscosity. Essentially, the distance between communicating layers increases, allowing momentum transfer over longer distances making the process more efficient. This can be seen equivalently through the lens of larger mean free paths in the ionized case.

Further, the presence of magnetic fields introduces non-negligible effects (Hameury 2020). The motion of charged particles generates[2] a magnetic field, which then interacts with the moving charges in other layers, increasing once again the viscosity. This effect could be modelled independently, but modelling this through viscosity enhancement is much simpler, and the results are equivalent. The underlying magnetic field due to the white dwarf also generates viscous instability, leading to chaotic behaviour in the disk, which is another component of the more significant accretion (Hameury 2020).

Viscous instability in the ionized disk is thought to originate from magneto-rotational instabilities (MRI). Since the fluid is charged and its angular velocity decreases as the distance from the white dwarf increases, the Lorentz force felt by the magnetic field decreases. The force is in the radial direction because the magnetic field is typically perpendicular to the disk, which rotates in the same plane as the star. Recall that the magnetic field of the star, relying on the dynamo process, has its most significant component perpendicular to the rotation plane of the star. This leads to the mixing of the fluid layers, creating instability. As the viscosity of the fluid is intimately related to temperature, through its role as a heating mechanism but also due to its dependence on it, this instability is usually referred to as *thermal-viscous instability* (Hameury 2020).

This period of luminosity outburst, in which the disk is depleted faster than it is supplied, is short-lived. Once the disk is sufficiently depleted, when the temperature is much smaller than the ionization temperature, the fluid is fully recombined. The disk has returned to the quiescent phase, aligning with the cyclic nature of the outbursts.

This way of modelling the outbursts was missing a key component of luminosity outburst light curves, the so-called "superhumps" or "superoutbursts". An example is shown in Fig. 4. They are five to ten times longer than normal outbursts, are less frequent and are around between half a magnitude and a full magnitude brighter in general. This issue was resolved by implementing tidal instabilities in the DIM. To distinguish between the old DIM, without tidal

[1] As opposed to the area having a normal vector parallel to the force in the case of pressure.

[2] Rather, it enhances the magnetic field since, despite ionization, there wouldn't be net charge flow in the disk without an initial field; the currents would be net neutral.

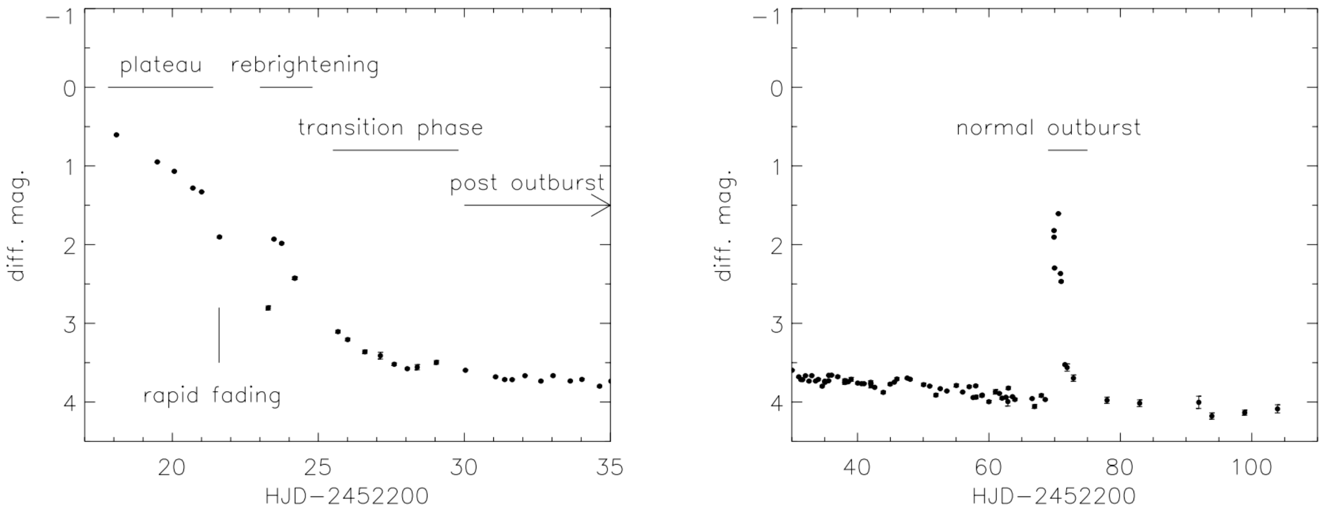

Figure 4. Light curves of the dwarf nova 1RXS J232953.9 + 062814 in 2001 November. The left panel shows the second half of a superoutburst and the right panel shows a normal outburst. This illustrates the differences in their duration and magnitude (Uemura et al. 2002).

considerations, and the modern one, some use the name Thermal-Tidal Instability model (TTI). Nevertheless, all modern models of disk instability incorporate tidal effects (Hameury 2020).

The tidal instabilities are thought to originate from resonances between the disk and the orbital motion of the binary system. The donor star can excite orbital resonances within the disk through gravitational interactions. The most efficient of these excitations happens when the orbital period of the disk material is three times smaller than the binary's orbital period. This is called 3:1 resonance, and it is the most important when the mass of the donor is a fourth of the mass of the white dwarf. Furthermore, tidal forces lead to the deformation of the disk. It shears the disk into an ellipse rather than a perfect circle allowing more efficient mass and angular momentum transfer. With this added eccentricity, along with additional tidal forces, spiral density shocks can travel through the disk, dissipating energy and momentum. These spirals can be observed, and explaining these patterns was a significant theoretical feat. Finally, the additional dynamics induced by the tidal interactions between the disk and the donor star allow for a new heating channel which can lead to the critical temperature being reached. If you closely look at the left panel of Fig. 4, we can see the re-brightening of the disk, which is explained by this tidally induced heating. These instabilities also explain the different nature of the two bursts in Fig. 4 since these instabilities operate on larger time scales and are a relatively rare form of coupling (Uemura et al. 2002).

3.3. *Mass Transfer Burst Model*

Another model that lost traction in the 1990s due to the success of the DIM and its more modern iteration is the Mass-Transfer Burst model (MTB). Nevertheless, it's been recently used to very accurately model the light curve of the EX Draconis dwarf nova, illustrating that it can do better than the DIM in certain contexts (Schlindwein & Baptista 2024). In this model, it's believed that the mass transfer from the donor to the disk is the process regulating the luminosity of the system; the material would accrete from the disk to the white dwarf as fast as the mass transfer allows. Further, it's believed that Roche lobe overflow can lead to instabilities in the donor star's envelope. The instability can be due to timescales of dynamics or thermal processes (Schlindwein & Baptista 2024). The dynamical timescale instability originates from the convection in the envelope leading to a strong reaction to mass loss. This, in turn, overfills the lobe more dramatically, leading to a runaway process. The thermal timescale instability is due to the envelope's inability to thermally adjust to the mass loss. In simple terms, the mass is lost too quickly for the temperature to be stable. This leads to a loss of pressure support, allowing the star to puff up, and the radius increases, leading to even more mass loss. In both cases, the net effect is a burst in the mass transfer, after which the disk becomes unstable and efficiently accretes material onto the dwarf, leading to increased luminosity. The details of the disk instability aren't modelled here and simply result in efficient accretion (Schlindwein & Baptista 2024).

Another incorporated effect is the interaction between the binary orbit and the mass transfer. The flow of material leads to a change in angular momentum, so the separation between the stars must change to compensate and conserve angular momentum globally. If the conditions are right for the proximity of the stars to increase in this way, the Roche lobe shrinks, increasing the overflow and leading to a positive feedback loop (Schlindwein & Baptista 2024).

Another mass burst mechanism is magnetic activity. The magnetization of the envelope leads to different rates of mass transfer depending on which region of the star is overflowing. Since the region facing the white dwarf changes as a function of time, this incurs variable mass transfer. Namely, the burst would happen when the magnetic field or lack thereof encourages easier lobe overflow (Schlindwein & Baptista 2024).

Finally, tidal considerations are incorporated into this model as well. In binary systems, the rotation of the stars plays a role. Tidal interactions changing the orbit can make the rotation of the donor star asynchronous with the orbit. This leads to an oscillating Roche lobe size, leading to episodic outbursts. The main feature lacking in the MTB is a mechanism leading to superoutbursts. However, it explains the variety in outburst periods better than the DIM (Schlindwein & Baptista 2024).

To conclude, the Disk Instability Model has established itself as a fundamental framework for understanding the recurrent outbursts of dwarf novae. While the DIM provides a robust explanation based on thermal-viscous instability and was improved with incorporation of tidal instability, factors that are less understood still require further research. Some examples include magnetohydrodynamic instabilities and a better understanding of MRI (Hameury 2020). The MRI fails to be well implemented since many details about the magnetic fields in stars and accretion disks remain to be precisely quantified. The modern standard in the field is to use the DIM, since observational evidence suggests mass transfer from the donor isn't burst like in general and even if it is, it wouldn't be the primary mechanism regulating luminosity.

4. OBSERVATIONS

As stated in Section 1, dwarf novae systems can be categorized by their orbital period into two groups: those below and those above the period gap which ranges from 2 h to 3.12 h (Garraffo et al. 2018). The period gap can be translated to a mass ratio gap given by (Inight et al. 2023)

$$q = \frac{M_{\rm donor}}{M_{\rm WD}} \approx 0.3. \tag{2}$$

The group below this gap is called the SU Ursae Majoris (SU UMa) group and exhibits both normal outbursts and superoutbursts. As explained in Section 3, normal outbursts are brief and lower in magnitude than superoutbursts, which are brighter and have a much longer duration. Additionally, superoutbursts often feature smaller periodic variations called superhumps. Systems above the period gap rarely show these superoutbursts or superhumps, highlighting a distinctive observational difference between these populations. These specific characteristics and the differences in behaviours of these groups allow us to classify dwarf novae and their dynamics.

4.1. *Detection of Dwarf Novae*

Dwarf novae are primarily detected by analyzing light curves constructed from photometric data, which monitor the brightness of the system over time. These light curves show the characteristic outburst patterns of dwarf novae, with sharp increases in brightness followed by gradual declines, making them a key tool for identification. This can be complemented with spectroscopic data, which can be used to analyze the physical and dynamic behaviour of their accretion disk. It is then possible to study the interactions between the white dwarf, the companion star, and the disk and get a more comprehensive understanding of the binary system.

Hubble Space Telescope (HST) STIS (Space Telescope Imaging Spectrograph) data has been used to observe and classify dwarf novae based on quantities like orbital period, mass, temperature, and measured flux (i.e. brightness). This was done using FUV spectroscopy of five dwarf novae, where every snapshot (with integration times smaller than 35 minutes) was converted to a single time-averaged spectrum of each dwarf nova (Sion et al. 2008). FUV flux distribution and absorption lines were then modelled in order to perform spectral fitting and recover information about each system, such as disk inclination, mass accretion rate, the temperature of the second component in the binary, and the white dwarf's mass, surface temperature, gravity, and projected rotational velocity.

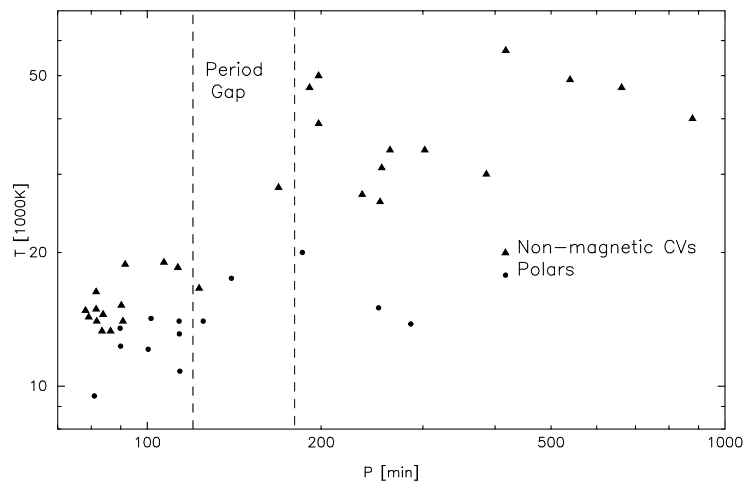

Figure 5. White dwarf temperature as a function of orbital period for nonmagnetic CVs (triangles) and magnetic CVs (circles) (Sion et al. 2008). The period gap is located between the dashed lines.

Figure 5 illustrates the temperatures of white dwarfs in both nonmagnetic and magnetic CVs; these two qualities are based on the white dwarf's magnetic field strength, which influences the accretion process. The plot demonstrates possible clustering of white dwarf temperatures for orbital periods around 300 min, and a second grouping for periods around 600 min where the temperature remains around 40 000 K. Sion et al. (2008) concluded that it was difficult to attribute any physical significance to these groupings. It can also be seen that there is greater dispersion in temperatures for white dwarfs above the period gap, while the dispersion below the gap is much narrower, specifically around 15 000 K. Analyzing this data enables us to explore potential theories to explain our observations and narrow down the possible mechanisms responsible for them. This kind of research enhances the understanding of dwarf novae's quiescent phases and helps bridge knowledge gaps in white dwarf characteristics above and below the period gap.

Other telescope measurements have been used to either confirm or detect new dwarf novae candidates. For example, Modiano et al. (2020) does this using archival data from the Ultraviolet/Optical Telescope (UVOT) on board the Neil Gehrels Swift Observatory, where near-ultraviolet observations of four candidate dwarf novae in the globular cluster 47 Tucanae are considered. Some analysis is performed on the data to constrain the characteristics and, thus, the nature of each transient source. This included constructing light curves by getting the magnitude and the flux of each source. To obtain these accurately, the underlying sky background must be subtracted from the measurements. This is done by selecting a region close to the target source with no apparent bright sources. Removing the background flux is, however, challenging since globular clusters have very high stellar densities, which introduces source confusion and blurring effects. Modiano et al. (2020) corrected for the effect of both the sky and the cluster background, and source outburst amplitudes were estimated using the maximum observed fluxes with respect to the cluster background flux (referred to as flux from non-detections). Using these techniques, five transient sources were detected due to their significant UV variability, one of which is the RR Lyrae star (Modiano et al. 2020). These sources were found to exhibit outburst characteristics typical of dwarf novae, increasing the known number of such systems in globular clusters.

Figure 6 shows the light cure for one of the found dwarf novae candidates, where the black data represents the non-detection background flux and the red points show data for detections. We can, therefore, see four outburst peaks within a period of roughly 2000 days for this given source. Studying these light curves allows us to study the properties of the binary, like orbital periods, and outburst properties, like duration, brightness, and temperature. With these, it is possible to constrain the parameters that describe dwarf novae and have a better understanding of their mechanisms. This also allows us to constrain proposed models as they need to fit trends seen in observed data.

4.2. *Modeling Accretion Disks*

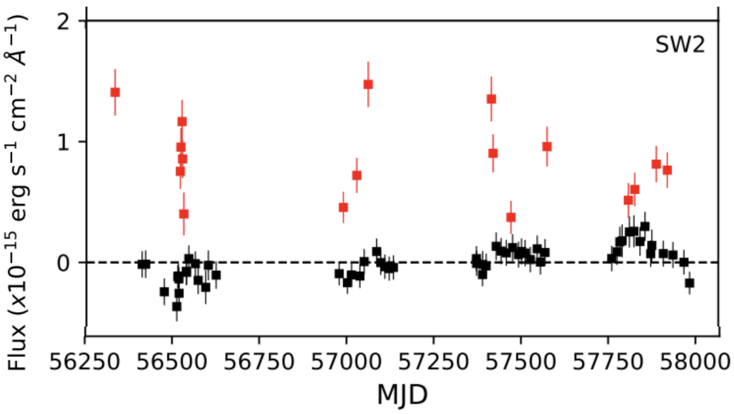

Figure 6. Light curve for the SWIFT J002402-720541 UV transient. The red points denote detected outbursts, and the black ones denote non-detections. All data points are corrected for cluster background by subtracting the mean cluster flux at the source position when the sources are not detected (Modiano et al. 2020).

An important step to learning about dwarf novae and their mechanism is through modelling of their accretion disks and their outburst processes. By comparing these models to observed data as described in Section 4.1, we can constrain parameters that describe dwarf novae and thus refine our models and theories on accretion disks.

In SU UMa systems, the mechanisms given by the TTI model trigger superoutbursts when the disk expands to a critical size, allowing tidal forces to elongate the disk. This increased tidal interaction extends the outburst duration and creates superhumps (Jordan et al. 2024). The TTI model uses the parameter α to describe the viscosity within the accretion disk, with $\alpha_{\rm cold}$ and $\alpha_{\rm hot}$ associated with the quiescent and the outburst states respectively. Specifically, $\alpha_{\rm cold}$ is used to describe the viscosity parameter when the disk temperature is low, resulting in incomplete ionization of hydrogen in that region. This lower ionization leads to reduced angular momentum transport, resulting in a weaker viscosity and slower mass accretion. Consequently, the system enters an inactive or quiescent state, where accretion is minimal, and the disk remains relatively stable. On the other hand, $\alpha_{\rm hot}$ describes the viscosity when the disk temperature is high, which leads to the complete ionization of the hydrogen and makes the disk more turbulent. In other words, the angular momentum transport is enhanced, and the system enters its active outburst phase where the viscosity is stronger and the mass accretion rate is higher (Mineshige & Osaki 1983).

By modelling the accretion disk according to the TTI model, it was found that varying the disk viscosity between $\alpha_{\rm cold} = 0.01$ and $\alpha_{\rm hot} = 0.1$ was needed to explain the outburst cycles observed in data (Mineshige & Osaki 1983). These values of α were confirmed through 3D MHD simulations (Oyang et al. 2021) and can be explained by magneto-rotational instabilities (MRI) in the accretion disk, specifically convection-enhanced MRI for high α values. These instabilities arise when weak magnetic fields interact with the rotation of the disk, enabling the outward transport of angular momentum and facilitating inward mass accretion. With 1D simulations, Coleman et al. (2016) were successful in simulating outburst cycles, however, additional features were seen during simulated outbursts that were not observed in real data.

In Jordan et al. (2024), two-dimensional hydrodynamical simulations were performed in order to study unknown parameters of the DIM and analyze their influence on the outburst cycles of CVs. Early tests found that using constant $\alpha_{\rm cold}$ values often produced outbursts that propagate outward, while outside-in outbursts were only seen in simulations with high mass transfer rates. The model used includes a new equation of state that accounts for hydrogen ionization and dissociation. Unlike previous studies where the isothermal equation of state only allows for the study of the quiescent or outburst states individually, this approach successfully replicates both normal and superoutburst cycles while capturing disk eccentricity and gravitational torques, key elements missing from 1D simulations. The simulation used in Jordan et al. (2024) reveals how variations in disk viscosity ($\alpha_{\rm cold}$ and $\alpha_{\rm hot}$), mass transfer rates, and binary mass ratios influence outburst mechanisms. Figure 7 shows a comparison between a model from Ichikawa & Osaki

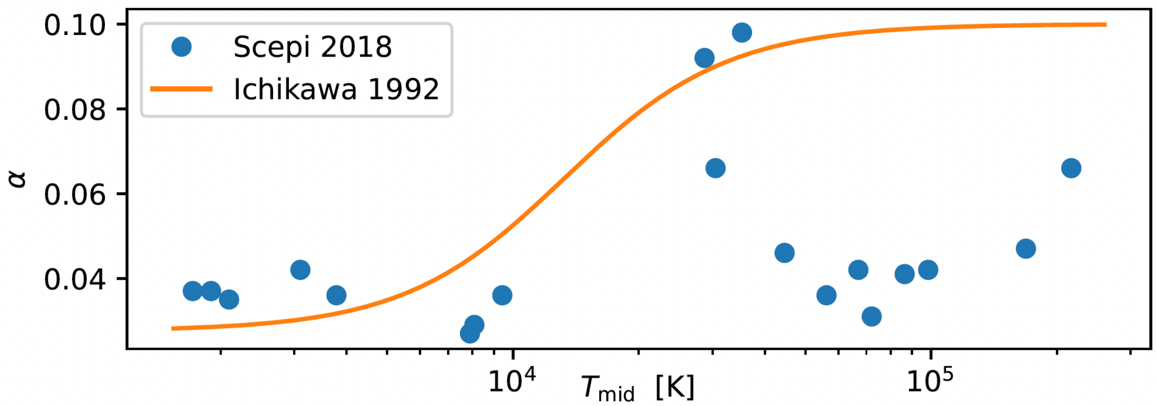

Figure 7. Figure taken from Jordan et al. (2024) showing values obtained for the α parameter in Scepi et al. (2018) and the interpolation function from (Ichikawa & Osaki 1992) as a function of the mid-plane temperature.

(1992) for parameters used in Jordan et al. (2024) and values from MRI simulations (Scepi et al. 2018). Although the two are in agreement for low α values and during the transition to α_{hot}, the high α values were found to disagree with the model from Ichikawa & Osaki (1992), indicating that further disk effects need to be taken into account. The main problem encountered with the simulation presented by Jordan et al. (2024) is that the superhumps amplitudes for higher mass ratios q were found to be higher than observations, where higher amplitudes are seen for lower mass ratios. This further validates that several mechanisms and effects like eccentricity or tilt in the accretion disk require 3D simulations in order to be modelled accurately.

Simulations are thus a powerful tool for testing and refining models of outbursts in dwarf novae, offering deeper insights into the mechanisms behind these phenomena. While two-dimensional simulations yield valuable information, fully three-dimensional models are essential for accurately capturing disk eccentricity and superhump formation. These factors are crucial for understanding the long-term evolution and precession of the accretion disk in dwarf novae.

Observations of dwarf novae have largely validated the DIM's predictions. For instance, the variability in temperature and luminosity observed in light curves and spectral data of dwarf novae aligns with the DIM's explanation of transitions between hot and cool states. Telescopic data showing temperature fluctuations in the outer regions of the disk support the model's assertion that material accumulation and temperature variations drive outbursts (King & Ritter 1995). Additionally, the spectral features seen during quiescent and outburst phases match predictions of hydrogen ionization and increased mass flow rates within the disk.

5. CONCLUSION

In conclusion, Dwarf Novae allow a better understanding of the physics of accretion disks through the study of their recurring outbursts. After the discovery of UGem in 1855, multiple theories on DN were developed before landing on accretion disks in 1962. While the MTB model has recently been used successfully (Schlindwein & Baptista 2024), the standard in the field is the DIM model, which now includes both thermal-viscous and tidal instabilities. By comparing simulations of theoretical models and observational data, it is possible to refine our understanding and develop better models. Nonetheless, some important questions remain in our understanding of dwarf novae (Smak 2000). Why do light curve models for the disk luminosity during quiescence show a significant increase that is not present in observed light curves? Can the issues with the TTI model be solved by combining it with the irradiation-enhanced mass-transfer model? Further observations in the X-ray and UV range could be useful in better understanding the quiescent state (Nabizadeh & Balman 2020) (Modiano et al. 2020), and with a better understanding and more research, some dwarf novae could also be used as standard candles. (Kato 2015)

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