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The period gap – revisited

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For a few decades now it has been commonly believed that the near-lack of nova eruptions in cataclysmic variable (CV) systems with orbital periods in the range $2-3$ hours may be explained by the donor red dwarf (RD) being eroded down to below roughly $\sim 0.35M_{\odot}$, for which the star becomes fully convective, deeming magnetic braking as an inefficient angular momentum sink. Thus, the donor radius shrinks and Roche-lobe overflow (RLOF) resumes only after the orbital period emerges at the bottom of the period gap. However, this theory does not explain the existence of the occasional nova (or dwarf nova, or nova-like) detected within the period gap. The mechanism proposed here explains both the existence of the gap and of eruptions within the gap by using a self-consistent evolution code that accounts for both stellar components and their binary separation simultaneously. The method reveals that mass transfer resumes well before the orbital period shrinks below the gap, thus explaining the observed eruptions within the gap as well as exhibiting an orbital period distribution remarkably similar to that observed.

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1. Introduction

A cataclysmic variable (CV) is a class of binary systems that comprises a primary white dwarf (WD) and a companion red dwarf (RD). As implied by its name, these celestial objects exhibit powerful sudden variability, i.e., eruptions that culminate as sharp, temporary brightenings. Be that as it may, the wealth of even the basic features exhibited by CVs has led to convenient sub-categorizing. The CV family comprises of novae (classical novae (CN) and recurrent novae (RN)), dwarf novae (DN), and nova-likes (NL), while CVs may also be detached, in which case will not exhibit any form of eruption. Since the physical processes that are responsible for each eruption type are entirely different [1–4], it became allegedly clear that there should be certain system parameters that are affiliated with each type, yet these were never defined, and for good reason.

Nova simulations show that the rate that mass is accreted onto the WD, along with the mass of the WD, are the two primary ingredients that are responsible for the nature of the outcome of the nova eruption [5–7], however, these models use a constant, external, arbitrary accretion rate. Recently, While accounting for the major physical processes at work (e.g., angular momentum removal, mass lost from the system, irradiation of the companion during the nova eruption etc.), long-term self-consistent numerical simulations of CVs undergoing tens of thousands of consecutive nova eruptions, have demonstrated that the rate that mass is transferred from the donor to the WD is not at all constant but rather experiences considerable changes throughout the system's lifetime, both increasing and decreasing. The changes were found to be vast, both secularly and on a cyclic timescale, and to have immense repercussions on the outcoming eruption [8, 9]. While in symbiotic systems there are semi-chaotic factors that affect the mass transfer rate, e.g., the companion producing wind which can vary over relatively short periods of time, and a radius that can endure extensive fluctuations (especially if it is in the AGB and experiencing thermal pulses) [10, 11], in CVs the mass accretion rate changes slowly and steadily [8, 9]. More importantly, the accretion rate in CVs can be followed via models based on the stellar masses and their orbital period ($P_{\rm orb}$). Understanding the connection between the basic CV system parameters —– the stellar components' masses, and the accretion rate —– are the key to understanding CVs.

2. The period gap

One of the important findings of the long-term self-consistent simulations is the deficiency of systems within a regime of orbital periods that is very similar to the well known *period gap* derived from observations. This well known observed period gap was derived by the simple process of dividing the range of orbital periods of observed eruptions in CVs (including novae, DNe, and NLs), into random equal bins, and summing the number of systems observed for each bin [12, 13]. This reveals a regime, roughly between two and three hours, for which it seems like there is a lack of CVs. The conventional explanation for this is that as the companion loses mass, the orbital period decreases. When the mass becomes below roughly 0.35$M_\odot$, the star becomes fully convective, resulting in the magnetic braking (MB) becoming inefficient in removing angular momentum from the system. This leaves gravitational radiation (GR) as the primary angular momentum sink, which is much weaker than MB, thus, the separation shrinkage slows, delaying the increase of the mass transfer rate, allowing the companion radius to relax and shrink back to its natural radius (undisturbed thermally by mass loss). Finally, the system becomes detached. The common reasoning for the period gap follows from this by assuming that the system will only resume mass transfer after emerging on the other side of the gap [12, 13].

3. Eruptions in the period gap — the challenge

If the theory described above were complete, it would mean that CVs in the period gap, since assumed to be detached, would experience negligible to no mass transfer from the companion to the WD, hence there would be no eruption of any type — no novae, no DNe and no NLs — because they all require a non-negligible mass transfer rate. However, the observational distribution clearly shows some detections within the gap. Such as, the CN V Per with $P_{\rm orb}$ = 2.57 hr or the NL V348 Pup with $P_{\rm orb}$ = 2.44 hr [14–16] strongly implying that the above theory is imprecise. There *should not be any eruptions* within the period gap if the CV is presumably detached the entire time.

4. The missing puzzle piece — methods and solution

The self-consistent binary evolution code settles this discrepancy [8, 9]. The code follows the evolution of a the binary system from initial contact, i.e., Roch-lobe overflow (RLOF), through long accretion epochs and nova eruptions, calculating the accretion rate ($\dot{M}$) at each time step adopting [8, 9, 17]:

$$\dot{M} \propto \dot{M}_0 \times e^{\frac{R_{\rm RD}-R_{\rm RL}}{H_P}} \tag{1}$$

where H_P is the pressure scale height and $\dot{M}_0$ is the mass transfer rate for the case in which the donor exactly fills its Roche-lobe (RL), i.e., the RD's radius ($R_{\rm RD}$) equals its RL radius ($R_{\rm RL}$), and depends on several system's parameters, i.e., the donors' effective temperature, mass, RL radius and surface density, as well as the WD's mass. The accretion rate is calculated following Eq.1 at every time step during accretion, while updating these system's parameters at each time step to account for angular momentum loss (AML) due to two major mechanisms — magnetic braking (MB) and gravitational radiation (GR) following [8, 9, 18]:

$$\dot{J}_{\rm MB} \propto M_{\rm RD} R_{\rm RD}^4 P_{\rm orb}^{-3} \tag{2}$$

$$\dot{J}_{\rm GR} \propto \frac{(M_{\rm RD} M_{\rm WD})^2}{P_{\rm orb}^{\frac{7}{3}} (M_{\rm RD} + M_{\rm WD})^{\frac{2}{3}}} \tag{3}$$

where $\dot{J}_{\rm MB}$ and $\dot{J}_{\rm GR}$ are the (negative) change in angular momentum as a result of MB and GR respectively. The AML due to these mechanisms cause the binary separation (a) to shrink [8, eq.4], decreasing the RL radius [19], which increases the mass overflow, i.e., the accretion rate.

The mass that is ejected during a nova eruption may be considered to occur momentarily (relative to the accretion time scale) and this mass is considered to be lost from the system taking with it angular momentum. This is applied after the cessation of ejection, before resuming accretion, following:

$$\frac{\Delta a}{a} = 2\left(\frac{m_{\rm ej} - m_{\rm acc}}{M_{\rm WD}} + \frac{m_{\rm acc}}{M_{\rm RD}}\right) \tag{4}$$

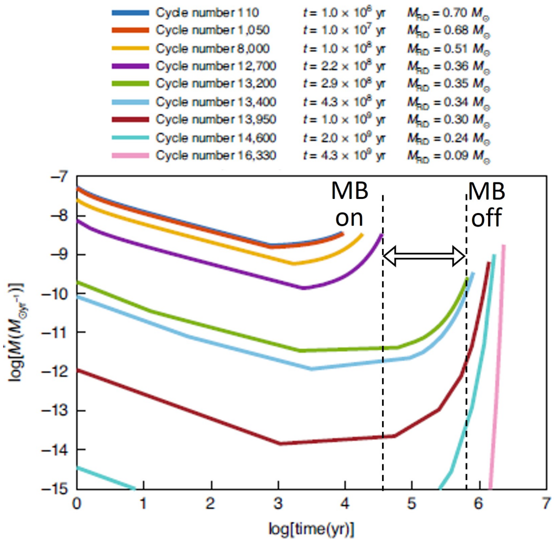

Figure 1: Example simulation for initial $M_{\rm WD} = 1.0 M_\odot$ and $M_{\rm RD} = 0.7 M_\odot$ showing the accretion rate vs. time from the beginning of accretion for each sample cycle. Adapted from [8].

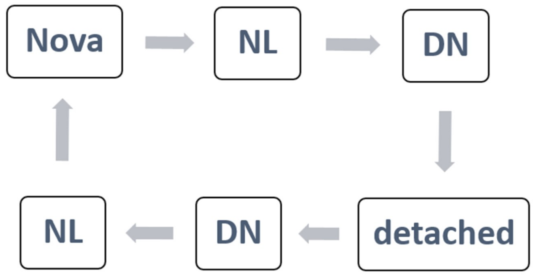

Figure 2: Illustration of the phases that a CV may go through following one curve from Figure 1.

where $m_{\rm acc}$ and $m_{\rm ej}$ are the accreted and ejected masses of the previous nova cycle respectively. This separation change is positive for all but extreme rare cases.

Additionally accounted for is the heat blast that the RD endures during the nova eruption, causing its envelope to temporarily expand in order to regain thermal equilibrium, and then retract. This causes the mass transfer rate to be enhanced for a short time (of order 10^2 years) after each eruption [8, eq.8-11]. These mechanisms explain how $\dot{M}$ varies throughout evolution. In fact, it was found [8, 9] that for a certain regime of stellar masses, $\dot{M}$ becomes so low — a negligible mass transfer rate — that the system is essentially detached for long epochs of tens or hundreds of thousands of years, while $\dot{M}$ slowly increases back to a non-negligible rate towards the next nova eruption. This is demonstrated in Figure 1 where the $\dot{M}$ changes are clear over a single cycle's accretion phase as well as secularly changing as the evolution progresses.

Figure 2 illustrates the evolution of a cycle: After a nova eruption ($t = 0$) the accretion rate is high, of order $10^{-8} - 10^{-9} M_\odot {\rm yr}^{-1}$. This is because it is enhanced due to irradiation of the RD from the nova eruption. During this time the CV will exhibit nova-like (NL) features. As the RD radius relaxes the accretion rate declines, becoming of order $10^{-10} - 10^{-11} M_\odot {\rm yr}^{-1}$ which is suitable for producing instabilities in the accretion disk that culminate as dwarf novae (DN). The accretion rate will then continue to decline and may eventually become negligible, i.e., the system will become detached. Eventually, AML will pull the stars closer together, slowly increasing the accretion rate back up to the DN regime, and then the NL regime, until a critical amount of mass is accumulated, triggering the next nova eruption. As shown in Figure 1, not every cycle will pass through all the stages. In fact, only systems for which the RD mass is low enough for the MB to have become inefficient (to the right of "`MB off`" in Figure 1) will endure DNe and become detached while more massive RDs lose angular momentum faster due to MB thus the accretion rate remains high.

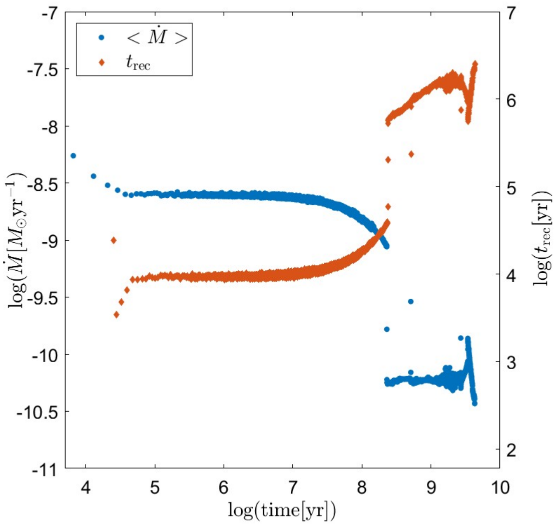

Figure 3: Average $\dot{M}$ per cycle and $t_{\rm rec}$ vs. evolutionary time. Simulation input stellar masses are as described in Figure 1. Adapted from [8].

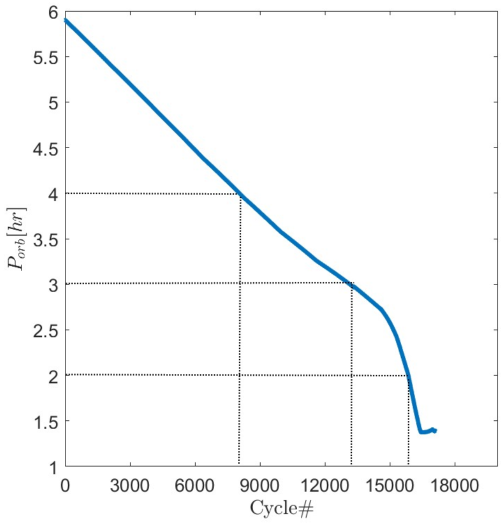

Figure 4: $P_{\rm orb}$ vs. cycle number. Simulation input stellar masses are as described in Figure 1. Adapted from [8].

These simulations support *almost* all the stages of the theory behind the period gap — while *neglecting one **crucial** finding*. The common explanation stated earlier is that the radius shrinkage caused by "turning off" the MB (for $M_{\rm WD} \lesssim 0.35 M_\odot$ which is correlated with $P_{\rm orb} \approx 3$ hr) will lead to the system becoming detached, and remaining that way until the separation shrinks enough to yield an orbital period of ≈ 2 hr. The results of these simulation [9] have demonstrated for a range of seven models that indeed when the MB becomes inefficient in removing angular momentum the separation shrinkage slows down substantially, and GR is the main AML sink that remains, but has roughly only a few percent the efficiency of MB in removing angular momentum. The results of these simulations show that this causes a delay in the increase of the accretion rate by the order of a tenth to one hundredth of the previous timescale, leading to recurrence times of order ten to one hundred times longer, meaning that it takes that much longer to accrete the required triggering mass. This may be seen clearly in Figure 3 as the stark decrease (increase) in $\dot{M}$ ($t_{\rm rec}$) at $\sim 3 \times 10^8$ yr which is correlated with the RD mass being eroded below $\sim 0.35 M_\odot$ rendering the MB an inefficient AML sink. *However, this process occurs much before the orbital period shrinks down to* ~ 2 *hours*. Figure 4 demonstrates, for two regimes, the number of eruption that occur while the system's orbital period shrinks one hour. The first regime is from 4 to 3 hours, i.e., while MB is still "on", and the second regime is from 3 to 2 hours, — the period gap — i.e., after the MB is "turned off". The first regime exhibits a total of approximately 5×10^3 nova eruptions (cycles) while the second regime exhibits only about half this amount of novae. The implication of this finding is that there *should be* nova (and DN) eruptions within the "period gap", just substantially less than the number that occur outside the gap. Figure 5 shows the orbital period distribution for one complete simulation, exhibiting a remarkable similarity with the observed period gap [12, 13], meaning that the presence of some novae in the gap is supported by modeling.

Not only do the results of the simulations explain the period gap, but by showing that the

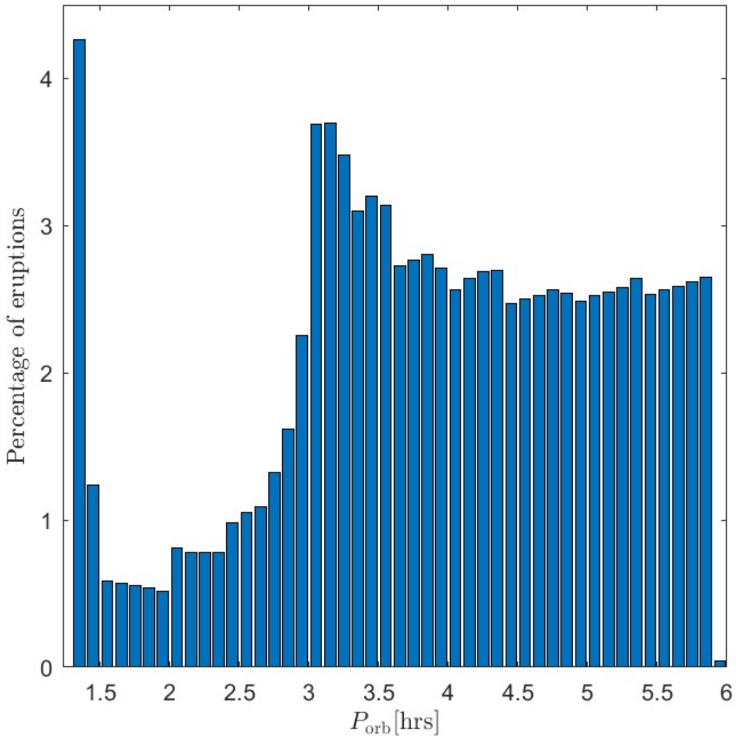

Figure 5: Distribution of percentage of eruptions per $P_{\rm orb}$ bin. Simulation input stellar masses are as described in Figure 1. Adapted from [9].

accretion rate evolves, they validate the long since theorized *hibernation theory* that states that systems that exhibit nova, DN and NL eruptions are not each a different class of systems, but rather one class at different evolutionary epochs [20].

5. Orbital period of symbiotic novae

Turning to nova that occur in symbiotic systems reveals an entirely different behavior. While the accretion rate in CVs is governed by RLOF culminating as slow secular changes, in wide symbiotic systems, the accretion is from wind that is expelled from the donor red giant (RGB). This means that the accretion rate depends strongly on the wind rate [e.g., 10, eq. 7-8] which can vary considerably. If the donor is on the asymptotic giant branch (AGB) then it may experience thermal flashes that radically change the wind rate on a relatively short, and somewhat chaotic timescale. Long-term simulations of symbiotic binaries that produce nova eruptions have demonstrated the evolution of $P_{\rm orb}$ for an AGB donor mass ($M_{\rm AGB}$) of $1.0M_\odot$ with a range of WD masses and binary separations [10, 11]. The code used for these simulations is an adaption of the long-term code used for CVs. It calculates the accretion rate via the Bond-Hoyle-Lyttleton (BHL) prescription [21–23] and accounts for mass lost from the system constantly due the wind from the donor as well as for AML due to drag being inflicted on the WD from this cloud of wind [10, eq. 4-9].

Figures 6 and 7 demonstrate the relationships between the separation, orbital period and donor mass for the evolution of a CV and a symbiotic system respectively. Clearly, for the CV example these three parameters are closely bound to each other, i.e., all three behave in a similar manner. The RD loses mass, thus the orbital period and separation decrease. This may be understood from the following three equations. The first, Kepler's third law of motion which gives:

$$P_{\rm orb}^2 \propto \frac{a^3}{M_{\rm RD} + M_{\rm WD}}, \tag{5}$$

the second which is deduced from Roche geometry:

$$P_{\rm orb} \propto \left(\frac{R_{\rm RD}^3}{M_{\rm RD}}\right)^{0.5} \tag{6}$$

and the third stems from stellar evolution of a main sequence star:

$$R_{\rm RD} \propto M_{\rm RD}^{\alpha} \tag{7}$$

where $\alpha \sim 1$. Combining Equations 5 through 7 yields:

$$P_{\rm orb} \propto M_{\rm RD} \propto a \tag{8}$$

which explains the strong correlation between these three parameters in figure 6. On the other hand, glancing at Figure 7 firmly conveys that this correlation does not hold for symbiotic stars. This is because Equation 6 is not relevant for BHL accretion since the separation is large and there is no RLOF. Equation 7 is also irrelevant since it does not apply to a RGB or AGB star. This leaves Equation 5 alone to determine the behavior. Now since in CVs mass is only lost from the system during nova eruptions, the decrease in separation (a) due to AML will always entail a decrease in $P_{\rm orb}$. However, simulations show that in symbiotic systems mass is rapidly lost from the system at a rate comparable to the separation decrease [10, 11]. Moreover, as mentioned above, the mass loss (wind) rate can radically change. This results in a competing process in which at some epochs separation decreases faster while at other epochs the total mass decreases faster. When the former ensues, the orbital period decreases as well, however when the latter has the upper hand, the orbital period will increase even though both the total mass and the separation decrease. This explains the peculiar behavior exhibited in Figure 7.

6. Summary and conclusions

The common assumption that a CV system is detached in the period gap *forbids the existence of any type of eruption within the gap*, yet, there is evidence of novae, DNe and NLs well within the gap, casting serious doubt on this theory. A detached system should not produce ANY novae, DNe or NLs at all.

The results presented here approach the problem from am unbiased point of view, allowing the CV to evolve self-consistently from initial RLOF. The findings introduce a critical refinement to the earlier simplistic approach by realizing that indeed the accretion rate increases at a much slower pace within the period gap and the system may experience detached epochs, however, AML allows

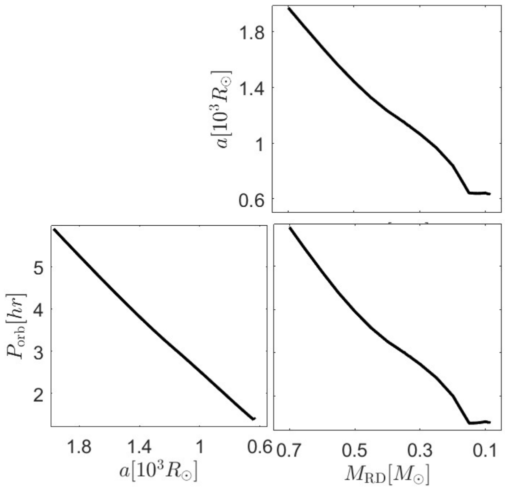

Figure 6: $a(M_{\rm RD})$,$P_{\rm orb}(a)$ and $P_{\rm orb}(M_{\rm RD})$ for a CV long-term simulation with input stellar masses are as described in Figure 1.

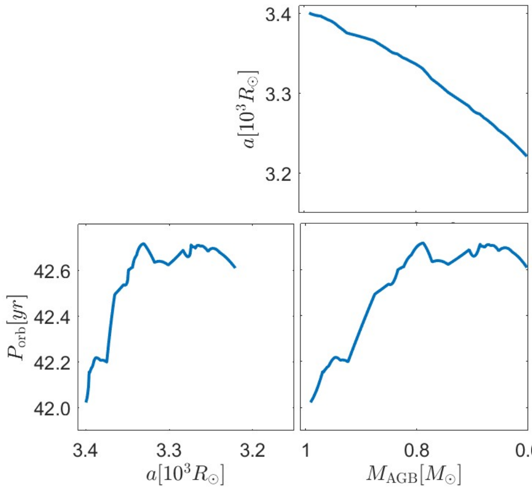

Figure 7: $a(M_{\rm AGB})$, $P_{\rm orb}(a)$ and $P_{\rm orb}(M_{\rm AGB})$ for a symbiotic system hosting a WD and AGB with masses of $M_{\rm WD} = 1.25M_\odot$ and $M_{\rm AGB} = 1.0M_\odot$ respectively.

the RLOF to resume and the accretion rate to become non-negligible on a time scale of order ~ 10 times shorter than that above the gap, leading to recurrence times of order $10^5 - 10^6$ years. Within this recurrence time, the orbital period shrinks only a fraction of an hour (of order a few hundred ppm), thus leading to less eruptions within the gap. Comparing the percentage of eruption within the gap that occur in the models, with the observed distribution yields a remarkable compatibility.

This lends support to the decades old *hibernation theory* by showing for the first time via a "hands off" numerical simulation, that novae, DNe and NLs are not different system types, but rather one type of system at different evolutionary epochs.

In addition, the timescales derived from the binary simulations emphasizes that the observed period gap is highly influenced by observational bias. In fact —- there should exist about X100 more CVs in the gap than above it. This is revealed by normalizing the number of nova eruptions (i.e., system detections) by the time between two consecutive eruptions.

Finally, it is noted that the $P_{\rm orb} - a$ relation, which is highly correlated in CVs, is entirely chaotic for novae in symbiotic systems for which $P_{\rm orb}$ can decrease OR increase while the separation (a) monotonically decreases. Whether $P_{\rm orb}$ will decrease or increase depends on the rate that mass is lost from system, and can rapidly change during evolution on relatively short timescales [10, 11].

References

[1] Y. Osaki, *An Accretion Model for the Outbursts of U Geminorum Stars*, *Publications of the ASJ* **26** (1974) 429.

[2] G. Dubus, M. Otulakowska-Hypka and J.-P. Lasota, *Testing the disk instability model of cataclysmic variables*, *A&A* **617** (2018) A26 [1805.02110].

[3] J.-P. Lasota, *The disc instability model of dwarf novae and low-mass X-ray binary transients*, *New Astronomy Review* **45** (2001) 449 [astro-ph/0102072].

[4] M. M. Shara, K. M. Lanzetta, J. T. Garland, S. Gromoll, D. Valls-Gabaud, F. M. Walter et al., *Introducing the Condor Array Telescope: III. The expansion and age of the shell of the dwarf nova Z Camelopardalis, and detection of a second, larger shell*, *arXiv e-prints* (2023) arXiv:2310.00123 [2310.00123].

[5] D. Prialnik and A. Kovetz, *An Extended Grid of Multicycle Nova Evolution Models*, *ApJ* **445** (1995) 789.

[6] O. Yaron, D. Prialnik, M. M. Shara and A. Kovetz, *An Extended Grid of Nova Models. II. The Parameter Space of Nova Outbursts*, *ApJ* **623** (2005) 398 [astro-ph/0503143].

[7] Y. Hillman, D. Prialnik, A. Kovetz and M. M. Shara, *Growing White Dwarfs to the Chandrasekhar Limit: The Parameter Space of the Single Degenerate SNIa Channel*, *ApJ* **819** (2016) 168 [1508.03141].

[8] Y. Hillman, M. M. Shara, D. Prialnik and A. Kovetz, *A unified theory of cataclysmic variable evolution from feedback-dominated numerical simulations*, *Nat. Astron.* **4** (2020) 886 [2001.05025].

[9] Y. Hillman, *In-depth analysis of evolving binary systems that produce nova eruptions*, *MNRAS* **505** (2021) 3260 [2106.13006].

[10] Y. Hillman and A. Kashi, *Simulations of multiple nova eruptions induced by wind accretion in symbiotic systems*, *MNRAS* **501** (2021) 201 [2010.05869].

[11] I. B. Vathachira, Y. Hillman and A. Kashi, *Eruptive novae in symbiotic systems*, *MNRAS* **527** (2024) 4806 [2311.08334].

[12] C. Knigge, *The donor stars of cataclysmic variables*, *MNRAS* **373** (2006) 484 [astro-ph/0609671].

[13] C. Knigge, I. Baraffe and J. Patterson, *The Evolution of Cataclysmic Variables as Revealed by Their Donor Stars*, *ApJS* **194** (2011) 28.

[14] A. W. Shafter and T. M. C. Abbott, *V Persei: Bridging the Period Gap*, *ApJL* **339** (1989) L75.

[15] A. W. Shafter, K. A. Misselt, P. Szkody and M. Politano, *QU Vulpeculae: an Eclipsing Neon Nova in the Period Gap*, *ApJL* **448** (1995) L33.

[16] N. A. Katysheva, E. P. Pavlenko and S. Y. Shugarov, *Nova V Persei - a classical nova in the "period gap"*, in *Classical Nova Explosions* (M. Hernanz and J. José, eds.), vol. 637 of *AIP Conf. Proc.*, pp. 543–547, Nov., 2002, DOI.

[17] H. Ritter, *Turning on and off mass transfer in cataclysmic binaries*, *A&A* **202** (1988) 93.

[18] B. Paxton, P. Marchant, J. Schwab, E. Bauer, L. Bildsten, M. Cantiello et al., *Modules for Experiments in Stellar Astrophysics (MESA): Binaries, Pulsations, and Explosions*, *Astrophysical Journal Supplement* **220** (2015) .

[19] P. Eggleton, *Approximations to the Radii of Roche lobes*, *ApJ* **268** (1983) 368.

[20] M. M. Shara, M. Livio, A. F. J. Moffat and M. Orio, *Do Novae Hibernate During Most of the Millennia Between Eruptions? Links Between Dwarf and Classical Novae, and Implications for the Space Densities and Evolution of Cataclysmic Binaries.*, *ApJ* **311** (1986) 163.

[21] F. Hoyle and R. A. Lyttleton, *The effect of interstellar matter on climatic variation*, *Proceedings of the Cambridge Philosophical Society* **35** (1939) 405.

[22] H. Bondi and F. Hoyle, *On the mechanism of accretion by stars*, *MNRAS* **104** (1944) 273.

[23] H. Bondi, *On spherically symmetrical accretion*, *MNRAS* **112** (1952) 195.