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The long term evolution of Cataclysmic Variables

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The state of the theory of long term behavior of Cataclysmic Variables is reviewed and the basic assumptions are specified. Next, despite the fact that the nova phenomenon is treated as a periodic one, secular changes caused by the changes in the masses of the binary system must be taken into account as well as other secular changes in the system parameters. In most reported calculations in the literature this extremely important changes are ignored. Preliminary results showing the effects of these changes on the evolution are presented.

The Golden Age of Cataclysmic Variables and Related Objects IV
11-16 September, 2017
Palermo, Italy

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[†]Supported in part by ISF grant 428-2014.

1. Introduction

Cataclysmic Variables (CV) are binary systems in which the primary is a star that completed its evolution and became a White Dwarf while the secondary is still on the Main Sequence or on its way to the tip of the Red Giant. The fundamental problem is how the WD could evolve without interacting with the secondary long before reaching the CV state?

The most favorable idea for the formation of Cataclysmic Variables is that these systems are formed from wider binaries composed of two main sequence stars [Paczynski, 1976], Meyer and Meyer-Hofmeister [1979], Taam and Ricker [2010], Webbink [2008], De Marco et al. [2011] and Izzard et al. [2012]. When the more massive star at the beginning becomes a giant and expands quickly it pours prohibitively large amounts of matter on the secondary, so large as to prevent it from "swallowing" the entire mass transferred and creates a large envelop and engulfs the secondary star so as to have two stellar nuclei moving inside a common envelope. The timing should be such that the initially massive star had time to evolve and become a WD before the mass transfer starts while the secondary is still on the Main Sequence or on its way to the tip of the Red Giant branch. As the two stars orbit within the common envelope, their separation decreases and the orbital period decreases from days to hours. Various dissipation mechanisms are at work and generate energy which is absorbed by the common envelop and increase its energy (and decrease its binding energy) and cause the gradual dissipation of the envelop. We may identify this stage as a planetary system with a binary system inside.

Once the common envelope dissipates, the resulting 'white dwarf-envelope eroded MS' binary system evolves for a while without mass transfer, continually losing angular momentum through a braking wind from the secondary and decreases its orbital period until the secondary fills its Roche lobe and begins to transfer mass to the white dwarf. This time the mass transfer is assumed to take place at moderate rates of $10^{-10} - 10^{-6} M_{\odot}/yrs$. Thus at first mass was transferred from the massive star to form a CE system and once the system ejects the envelope the role changes and the now the lower in mass MS star transfers mass back to the WD. At this point, it appears to us as a CV.

As the evolution causes the expansion of the companion (the now lower in mass component) it reaches the point where it fills the Roche lobe and mass transfer from the stripped MS star to the WD resumes but in the opposite direction. The accumulated mass on the WD cools, becomes degenerate and gives rise to a thermonuclear run away which eventually removes most, if not all, the accumulated mass. After a period of relaxation, sometime called hibernation, the chain of events repeats itself. The result is that most of the accreted mass is ejected, the masses of the WD and the MS stars change and together with other processes bring the pair of stars closer.

If on the other hand, the accreted mass has no time to cool it stays on the WD and burns in a shell, creating a Red Giant. The Red Giant has a core of C/O and a H burning shell which advances slowly outwards thus increasing the mass on the underlying WD.

Once the mass of the WD increased above $1M_{\odot}$ many possibilities come to play. A single WD with mass $\leq 1M_{\odot}$ does not ignite carbon. But as the mass of the WD increases it contracts and heats and can ignite carbon explosively. The core cools via neutrino losses and heats through compression. The outcome depends on the time scale of these processes. It depends on how fast the mass of the WD grows relative to the time scale for heat propagation in the star. A simple alternative is to reach the Chandrasekhar mass and implode. We do not know at the moment which way it goes and to what extent it depends on the layer of He which accumulates on the WD.

As the period of the binary system continues to shrink to 3 hours, the secondary star structure changes, becoming completely convective, and at a period near 2 hours gravitational waves emission become the source of angular momentum loss (resulting in low mass transfer rates) until a period minimum near 80 minutes is reached. After this point, the structure of the secondary changes again (becoming degenerate) and the orbital period increases and the system will not show anymore the eruptive events mentioned above.

The plan of this review is as follows: We start with the initial conditions as common envelope state (CE) and continue with the problem of how the CE state is left to become the initial CV state. We review the attempts to calculate the sequence of nuclear flashes and spell out the difficulties involved. We then discuss briefly the possible fates of such systems and end with conclusions.

Before we leave this section we should mention that the CE is not the only possible outcome of massive mass transfer. Beer et al. [2007] investigated the evolution of interacting binaries where the donor star is a low-mass giant yet more massive than its companion. It is usual to assume that such systems undergo common envelope (CE) evolution, where the orbital energy is used to eject the donor envelope, thus producing a closer binary or a merger. Beer et al. suggest instead that because mass transfer is super- Eddington even for non-compact companions, a wide range of systems avoid this type of CE phase. The accretion energy released in the rapid mass-transfer phase unbinds a significant fraction of the giants envelope, reducing the tendency to dynamical instability and merging. Beer et al. show that this physical picture accounts for the success of empirical parametrizations of the outcomes of assumed CE phases.

2. Modelling a Common Envelope (CE)

Our story starts with the evolution of a progenitor binary system till the onset of the common-envelope phase, which usually takes place near the tip of the giant branch or asymptotic giant branch.

There is no real simulation of the CE state. The problem is so far too complicated for a reliable numerical simulations. Hence what you find is a description by means of a number of system parameters and the hope is that the space of parameters covers the actual state.

We define three major parameters to describe the CE. These parameters are crucial for the evolution of the CE and mass ejection. The parameters are: the energy of the envelop E_{env}, the rotational energy ΔE_{orb} and the efficiency of envelope ejection η_{CE}. (Try to think about the description of a single star only by means of such three parameters and how poor it is.) The parameter λ is defined by converting the expression on the right hand side into the energy of the envelope:

$$E_{env} = -\frac{GM_{donor}M_{env}}{\lambda a_i r_L}, \tag{2.1}$$

where M_{donor} is the mass of the donor star at the onset of the CE phase, M_{env} - the mass of the H-rich envelop of the donor, a_i the orbital separation at the start of the CE state, a_f the orbital separation at the end of the CE state, $r_L = R_L/a_i$ where R_L is the Roche lobe radius ($R_{Roche} \sim R_{donor}$). λ is the

PoS(GOLDEN 2017)036

a numerical factor hopefully of order unity, that depends on the density distribution. de Kool de Kool [1990] finds, by comparison with detailed stellar models, that $\lambda \approx 1/2$.

The next parameter is the orbital energy ΔE_{orb} given by:

$$\Delta E_{orb} = -\left[\frac{GM_{core}M_2}{2a_f} + \frac{GM_{donor}M_2}{2a_i}\right] \tag{2.2}$$

Here we define $M_{core} = M_{donor} - M_{env}$ and note that this expression assumes that the energies are additive, while they are not.

Finally we define η_{CE}, the efficiency of envelop ejection by

$$\frac{GM_{donor}M_{env}}{\lambda a_i r_L} = \eta_{CE}\left[\frac{GM_{core}M_2}{2a_f} + \frac{GM_{donor}M_2}{2a_i}\right]. \tag{2.3}$$

Han et al (1995) added an additional parameter, namely

$$E_{env} = -\int_{M_{core}}^{M_{donor}} \frac{GM(r)}{r} sm + \alpha_{th}\int_{M_{core}}^{M_{donor}} U dm, \tag{2.4}$$

where U is the internal energy and α_{th} is its parameter. The last parameter depends on the details of the mass ejection. The authors show that there are solutions to CE becoming CV in the range where all parameters obey $0 < p < 1$, namely have acceptable values.

We have now the degenerate core of the red giant and the relatively dense MS star moving inside the giant's extended envelope. To proceed and eliminate the thin common envelope a dissipation process must be called. The role of the dissipation is to transfer angular momentum and energy from the orbit of the cores to the envelope. Thus, as the cores will consequently spiral-in, the envelope would be ejected. Depending on how much of the released orbital energy goes into driving away the envelope the result will be either a wide MS plus a WD binary, a pre-cataclysmic variable or a coalesced object that appears like a rapidly rotating red giant. The α_{CE} parameter controls the fraction of the released orbital energy that goes into pushing the envelope out of the system. We note that it is plausible that the system at this state would resemble a planetary nebula with a binary pair as a central star.

The amount of envelope mass lost in the mass ejection is very sensitive to the definition and the exact location in the star where the core ends and the envelope starts. This also depends on the detailed structure of the stars, in particular how much hydrogen was consumed.

We assume here that the systems pass the CE phase and the phase of envelop ejection and we have a young CV. It is conceivable that the WD is covered with a (thick? thin?) layer of hydrogen and helium and the mass loss stops before the C/O or Ma/Mg layers are exposed. We also know that a too massive H/He envelop will not proceed directly towards the CV state. A CV can form only if $M_{envelope} < M_1$ but we do not know what the value of M_1 is and whether the mass ejection stops before or after the mass envelop reaches this mass.

Recently Dewi and Tauris [2000] investigated the structure of evolved giant stars with masses in the range $3 - 10M_{\odot}$ in order to evaluate the binding energy of the envelope on the core prior to mass transfer in close binary systems. They discussed the λ-parameter and the efficiency of envelope ejection in the CE-phase, and showed that λ depends strongly on the evolutionary stage (i.e. stellar radius) of the donor star at the onset of the mass transfer. The existence of this relation

PoS(GOLDEN 2017)036

enables them to introduce a new approach for solving the energy equation. For a given observed binary system they derived a solution for the original mass and age of the donor star, as well as the pre-CE orbital period. They found that λ is typically between 0.2 and 0.8. But in some cases, particularly on the asymptotic giant branch of lower-mass stars, it is possible that $\lambda > 5$.

For further discussion of the potential values of the parameter see the extensive review of CE systems by Ivanova et al. [2013]

Few more comments. Soker [2013] found that energy formalism, the CE α-prescription, is inadequate to predict the final orbital separation of the CE system in massive envelopes. Soker founds that when the orbital separation decreases to ~ 10 times the final predicted orbital separation the companion does not have enough mass in its vicinity to carry away its angular momentum. The proposed solution is that the core-secondary binary system must get rid of its angular momentum by interacting with mass present further out.

3. The start of the accretion phase or From a Common Envelope to Pre-Cataclysmic Variables

We assume now that due to angular momentum loss by magnetic braking followed by gravitational radiation, the red dwarf component fills its Roche lobe and a cataclysmic variable is formed.

The basic idea now is that accretion of essentially H-rich matter or He pure matter, causes matter to accumulate on the WD. We note that the emerging WD from the CE state contains an unspecified layer of H rich stuff. We do not know the size of this layer and assume it to be well below the M_1, the mass needed to burn steadily. Note that if the accreted matter contains hydrogen it is the hydrogen layer that is expected to determine the outcome and the He layer is passive. The temperatures are below the burning temperatures of helium if the amount of hydrogen in appreciable.

Thermo-nuclear-run-aways calculations yield that the critical mass of a hydrogen rich layer to undergo a TNR is about $10^{-4}M_{\odot}$ and the question now is whether the left over mass M_1 is more or less than this amount. Also, the cold WD must be very degenerate. So the accreted mass becomes degenerate and ignites the hydrogen violently and ejects practically the entire envelope but 'a small left over'. The cardinal question in the evolution of CVs is how the 'left over' mass depend on the mass of the WD and its central temperature.

The properties of the outcome of a nova eruption depend on few parameters: T_c the core temperature of the WD (which is equivalent to its age), the accretion rate $\dot{m}$, the erosion of the donor, illumination of the donor, rotation and the composition of the accreted matter and of course the mass of the WD. If the retention of the accreted matter is α, τ_{hyber} the time of nova hibernation, $\dot{m}$ the accretion rate and m_{nuc} the mass that gives rise to a single eruption, then the cycle time between two successive eruptions is given by:

$$\tau_{nova} = \frac{m_{nuc}}{\dot{m}} + \tau_{hyber} \tag{3.1}$$

and the mass accreted per flash is $\tau_{nova}\dot{m}$. We assume that just a fraction α of this mass is retained by the WD after the flash. The calculation is far from trivial because the accreted matter mixes with the pristine matter of the WD and you do not get "clean layers" of accreted and WD original layers.

Let us provide a numerical example: Assume an accretion rate of $10^{-8}M_{\odot}/yr$. The minimal mass for a flash is $\sim 10^{-4}M_{\odot}$. Hence the time to reach a flash is $10^{-4}/10yrs^{-8} = 10^{4}yrs$. (We assume mass gain but there are cases of erosion (core mass mixes with the accreted matter) so the result does not apply for all cases.)

Assume that only a fraction α of the accreted mass is retained by the WD, hence the gained mass is $\alpha 10^{-4}M_{\odot}$ per 10^4 years.

Assuming that $\alpha \approx 0.01$ which is a very generous assumption, we can calculated when the accreted mass will reach a significant fraction of $1M_{\odot}$. If only a fraction $\alpha = 0.01$ remains per flash, we need only 100 flashes which would take $10^{6}yrs$ for a vanishing hibernation time case. In reality α is smaller and the times significantly longer.

Suppose you start with a $1M_{\odot}$ donor, then before you reach the critical mass your donor disappears or has changed its state significantly. The rate of mass transfer would change with the gradual change of the total mass. We find that the margin is very narrow, a too small a donor or a too small a WD will disappear before the mass of the WD reaches the Chandrasekhar mass. Note that we assumed a favorable example namely, the scene does not change upon mass transfer despite the mass transferred being of the order of the masses themselves. We conclude that: if you expect the condition for mass transfer to remain unchanged during this massive mass transfer something unique has to take place. Also, not all CVs grow in mass to posses massive Chandrasekhar mass. This unknown fraction of WD which grow in mass should enter the rate estimates derived form population synthesis.

4. What happens in extensive calculations?

The simplest model is to assume a mass accretion boundary condition and keep this boundary condition fixed through out the sequence of flashes and see what happens. The problem is that all such calculations assume that the conditions which bring the two stars together so that mass transfer takes place, do not change. Thus, the donor does not change its mass despite mass transfer and being exposed to wind from the accretor, the donor is not polluted by the flashes, the change in the relative masses does not change the rate of accretion and the period etc. In short, the system remains frozen as well as the rate of accretion. Salazar et al. [2017] compared the orbits before and after the eruption of the classical nova V1017 Sgr and demonstrated how real this effect is.

There are several such calculations and we bring here only few examples. Shara et al. [1993], Epelstain et al. [2007], Starrfield et al. [2013], Ruiter et al. [2014] Hillman et al. [2016] Starrfield [2015] Neunteufel et al. [2016]. Hillman et al. pose the question: Can a WD, accreting He-rich matter from a non-degenerate companion star, ever exceed the Chandrasekhar mass and explode as a SN Ia?

Hillman et al. [2016] approach the problem by repeating the same calculation assuming fixed accretion rate as well as constant masses and parameters. The calculation itself starts with a quite massive WD composed of C/O and it is not clear how the WD reached this mass. The result found is that He accumulates and the system has a C/O WD with a steady burning He shell. The core temperatures never reach C burning. This determines the effective He mass accretion rate for long-term, self-consistent evolutionary runs with He flashes.

PoS(GOLDEN 2017)036

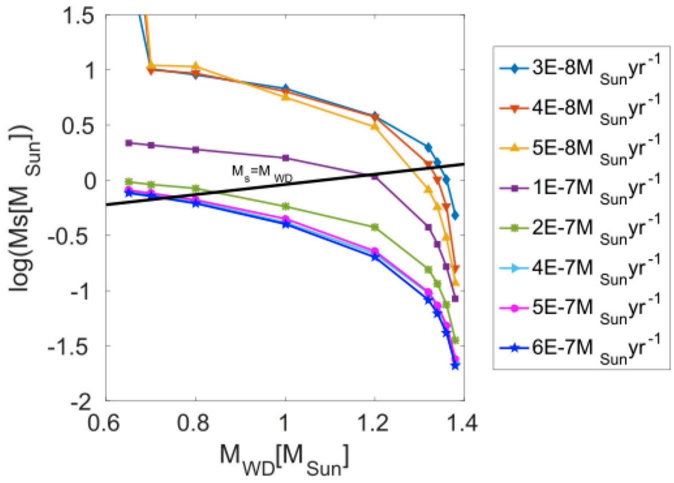

Figure 1: Lower limit on the donor mass (M_s) required to grow a WD companion to the Chandrasekhar mass vs. the WD mass (M_{WD}), for different rates of accretion (mass transfer) of hydrogen-rich matter ($\dot{M}$), as marked. The black line corresponds to $M_{WD} = M_s$, which defines the upper limit for stable mass transfer, assuming Roche-lobe overflow. This limit does not apply for wind accretion in a symbiotic binary. Taken from Hillman et al. [2016]

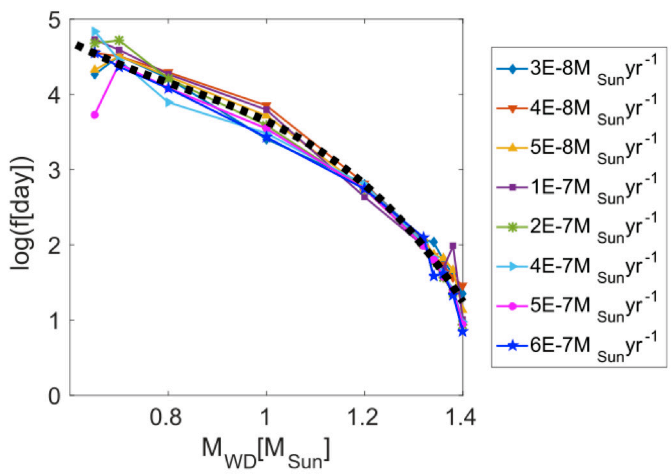

Figure 2: Hydrogen flash duration (f) vs. WD mass (M_{WD}) for different rates of accretion (mass transfer) of hydrogen-rich matter ($\dot{M}$), as shown. Note the very weak dependence on accretion rate, which results in a $f(M_{WD})$ relation represented by the dotted line. Taken from Hillman et al. [2015],Hillman et al. [2016].

The authors find that a net mass accumulation always occurs despite He flashes which eject most of the accreted matter. Although the amount of mass lost during the first few He flashes is a significant fraction of that accumulated prior to the flash, that fraction decreases with repeated He shell flashes. Eventually no mass is ejected at all during subsequent flashes. Just the system settles onto a steady state of burning He at the bottom of the envelope and mass accreted at the top and the rate of mass accretion is set to be equal to the rate of mass burnt.

This unexpected result occurs because of continuous heating of the WD interior by the He

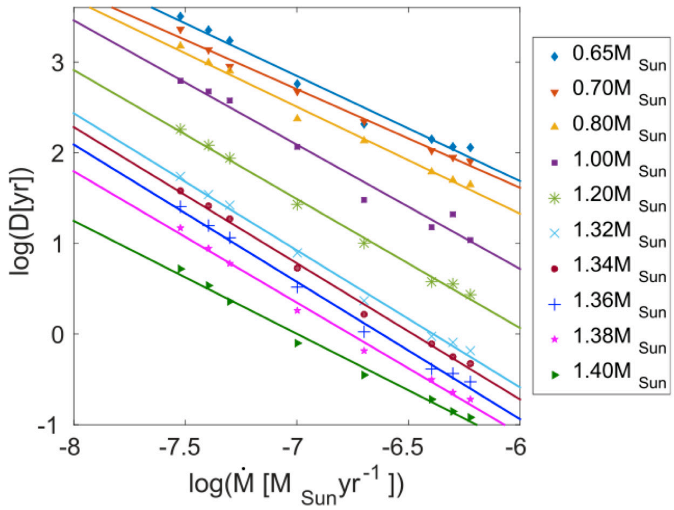

Figure 3: Cycle duration D in years (the time between successive hydrogen flashes) vs. accretion rate $\dot{M}$ in $M_\odot/yrs$ on a double logarithmic scale, for different WD masses, with linear fits. Taken from Hillman et al. [2016]

flashes near its surface. The effect of heating is to decrease electron degeneracy throughout the WD, especially in the outer layers. For this to be the case the WD should be sufficiently hot, namely relatively young.

This key result yields eventually He burning that is quasi- steady and in this way C/O accumulates behind the burning shell.

Moreover, a remarkably large parameter space within which long-term, self- consistent simulations show that a WD can grow, is found. Eventually the total mass can reach the Chandrasekhar limit, despite its He flashes.

The numbers are interesting. The initial mass is $(0.65 - 1.4)M_\odot$ and the constant accretion rate is $\dot{m} = 10^{-7}M_\odot/yr$. Several cases were run and we note that the accretion rate increases with the mass of the WD. There should be a significant fraction of WDs which are massive but has a small accretion rate and hence no mass gained. The effective mass gained by the WD is:

$$\dot{m}_{eff} = \frac{m_{acc} - m_{eject}}{M_{WD}} \quad with \quad M_{WD} \sim 1M_\odot. \tag{4.1}$$

The WD has to cool to a central temperature below $T_{central} < 6 \times 10^7 K$. This means that the two stars must approach each other and start mass transfer only after the WD had time to sufficiently cool and possess a degenerate outer layers. Cooling to $T_{central} \leq 10^7 K$ takes about 10^9 years.

How many cycles are needed to reach the Chandrasekhar mass (ignoring the phase of steady He burning)? we have

$$Mean\ value = \frac{(mass\ gained\ 0.4)(Time\ between\ cycles\ 10^2 yrs)}{accretion\ rate\ (10^{-7}M_\odot yr)} \approx 4 \times 10^8 yrs. \tag{4.2}$$

This is quite a long time. Does the binary system stay unchanged when its mass changes by many per cents?

The life-time on the main sequence is given by

$$\tau_{MS} = 10^{10}\left(\frac{M_\odot}{M}\right)^{2.5}, \tag{4.3}$$

hence we find that

$$M_{donor} < 3.6 M_\odot. \tag{4.4}$$

If on the MS the star has a mass of $M > 2M_\odot$ no degenerate core is formed. Consequently two possible scenarios rates and mass loss rate are possible. This star has a He core and a hydrogen rich envelop.

Finally, how do we know that the helium star transfers mass at a rate of $10^{-7} M_\odot/yr$? We need to know the change in the radius with time, $R(t)$ for different masses to see where a given accretion takes place and what its value is.

In summary, we have to know how the binary system responds to (a) Mass loss (ejecta) and (b) Mass transfer between the binary to asses the evolution over many flashes. For example, the donor should start transferring mass to the WD when $M_{WD} > M_{Ch} - M_{WD} + M_0$ where M_0 is the initial mass. These are of course the most favorable moment but it is not necessarily what take place in reality.

We recall that if the mass transfer is stable: $R(t)$ shrinks so the mass transfer stops for a while (hibernation?) and will it provide the same accretion higher or lower when accretion resumes? If the mass transfer is unstable then $R(t)$ expands so will it provide a higher accretion rate or even an avalanche when the situation repeats and shorten the time to reach the Chandrasekhar mass.

Idan et al. [2013] Shaviv et al. [2014] investigated the case of a high accretion of H-rich matter onto a WD. The assumptions were of frozen binary system so that the accretion rate was constant despite thousands of nuclear eruptions. The authors found that after 4153 flashes the entire He layer exploded and removed from the star. The system returned to the initial state. Thus even constant conditions of accretion have surprises.

5. New Physics

Are the models complete from a physical point of view? Do they contain all the required physics? Recently, Shaviv [2000] came out with a new theory of the super Eddington luminosity. According to this theory at αL_{Edd} where $\alpha = 0.6 - 0.8$ the matter becomes unstable and disintegrates into two phases: a dense one and a dilute one with two distinct microscopic properties (viscosity etc). The two phases have distinct hydrodynamic bulk properties (speed etc). A steady state of mass outflow appears and the total luminosity remain constant and above the Eddington luminosity, for a long time, much longer than the dynamic time of the system. Thermonuclear calculations assuming the new theory are now underway (Idan, Shaviv & Shaviv in preparation). One typical characteristic is the splitting of the matter to a dense and a thin states mixed together. Consequently the conditions for a wind mass loss change completely.

Several authors assume that the Eddington wind starts when $L > L_{Edd}$. We find that the wind starts at a much smaller luminosities and not always at the same L/L_{Edd}.

Wang et al. [2015] had the idea to follow the observed mass - radius relationship of their donor star. They applied the MESA code to obtain a 'correct' locations for the minimum period and the upper edge of the period gap. The observed spectral types of CV donors were compatible with both standard and revised models. They simulated the He accretion process onto C/O WDs for WDs with masses of $(0.6-1.35)M_{\odot}$ and various accretion rates of $10^{-8}-10^{-5}M_{\odot}yr^{-1}$. However, they calculated just a single thermonuclear runaway and hence it is impossible to draw conclusions about long term evolution.

They find that if the contribution of the total luminosity is included when determining the Eddington accretion rate, then a super-Eddington wind could be triggered at relatively lower accretion rates than those of previous studies based on steady-state models.

The super-Eddington wind can prevent the WDs with high accretion rates from evolving into red-giant-like He stars. The contributions from thermal energy of the WD are non-negligible, even though the nuclear burning energy is the dominating source of luminosity.

Finally, they provide a limit on the steady He-burning regime in which the WDs do not lose any accreted matter and increase their mass steadily. They calculate the mass retention efficiency during He layer flashes for various WD masses and accretion rates.

Shaviv [2018] developed a code for evolution of a binary system. All the physics of the binary is included i.e. the effect of mass transfer and mass loss on the orbit. The calculation starts after the CE phase with an assumed guessed binary system.

The authors calculated the evolution of a special classical nova system composed of a $1.25M_{\odot}$ MS and a $1.0M_{\odot}$ C/O WD. The system begins as a well separated non-interacting binary system. Initially, the two stars evolve independently of each other. However, Roche lobe overflow begins as the MS star expands on its way to become a Red Giant. Once the stars touch each other accretion from the expanding MS star onto the WD starts and the ensuing nuclear runaways is followed for several thousand flashes.

The result is that the mass transfer is modulated by oscillations in the envelope of MS star, with a period that is somewhat shorter than the thermal time scale of the star. This oscillation modulates the rate of thermonuclear flashes on the WD so that the WD cools and heats periodically cf. Williams [2013], Sion and Sparks [2014].

The system is further complicated by the secular drift in the secondary modulation. Such secondary modulation could explain systems like T Pyxidis. Last, it is found that the overall process of mass gain by the WD has an efficiency of just $\sim 9\%$, thus requiring a donor with an initial MS mass of $5M_{\odot}$ for an initial $1M_{\odot}$ WD, if the WD is to reach the Chandrasekhar mass.

Piersanti et al. [2014] investigated He accreting WD's and their results are shown in 7. We stress that the conditions of the mass transfer and the binary system remained fixed during the calculation.

6. Summary

You cannot obtain the evolution of a CV system extending over many nuclear flashes by simply repeating accretion, flashes and mass loss and ignore the secular changes in the parameters of the binary system.

The number of successive flushes in an actual case is excessive. If the single WD scenario is to be valid as SN progenitor, we should expect a unique phenomenon on the long way of successive flashes. Awaiting are disk instabilities, different behavior of high and low mass donors and you must repeat the calculations with the new physics.

The margin appears very small. The set of parameters which possible leads to a massive WD is narrow.

7. Acknwledgement

This research has been partly supported by the Israel Science Foundation, grant 428/14. (Technion number 2021346)

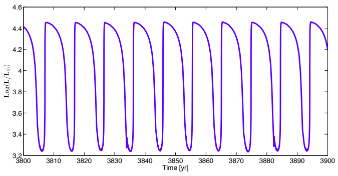

Figure 4a. The secular sequence of flashes.

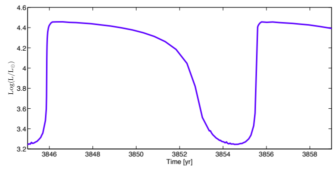

Figure 4b. A flash cycle in more detail.

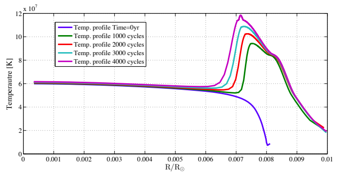

Figure 4c. Temperature profiles.

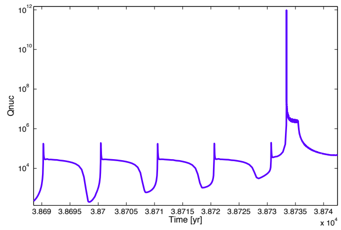

Figure 4d. The approach to the giant flash which ejected 1/3 of the accreted envelope.

Figure 4: Fig-4a describes the almost but not quite perfect sequence of flashes. Fig-4b shows the detail of a typical flash. Fig-4c shows the temperature wave produced near the surface and eventually moves inward. Fig-4d shows the sequence of flashes just before the large flash which ejected the entire envelope. Taken from Idan et al. [2013].

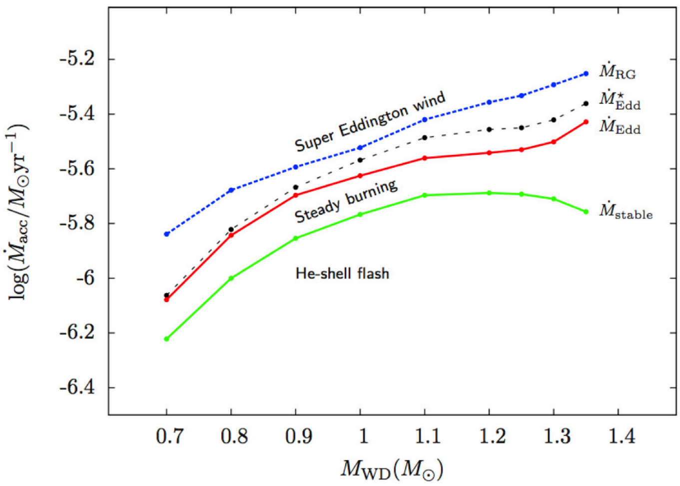

Figure 5: The modified Nomoto diagram based on standard treatment of the super Eddington luminosity. Taken from Wang et al. [2015].

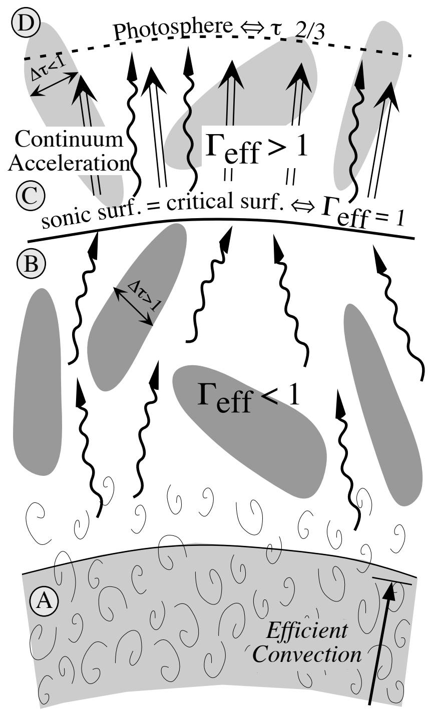

Figure 6: A schematic view of the structure of an envelope with super Eddington luminosity. The shape of the fragmentation depends on the optical depth. Taken from Shaviv [2000].

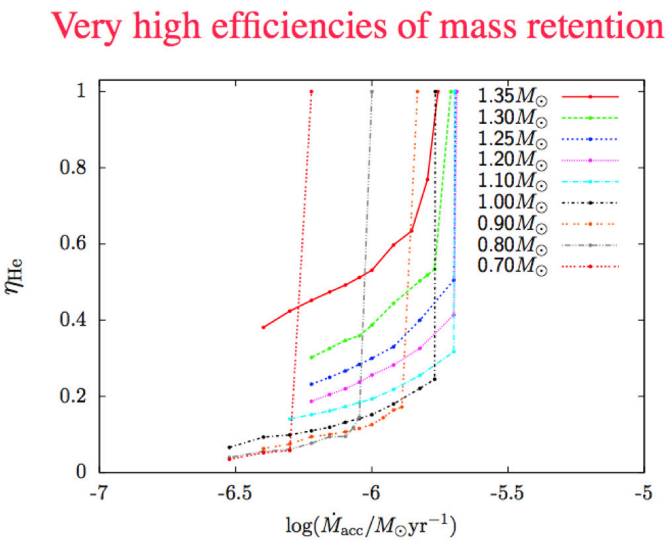

Figure 7: The predicted retention mass assuming standard super Eddington luminosity theory. Taken from Piersanti et al. [2014]

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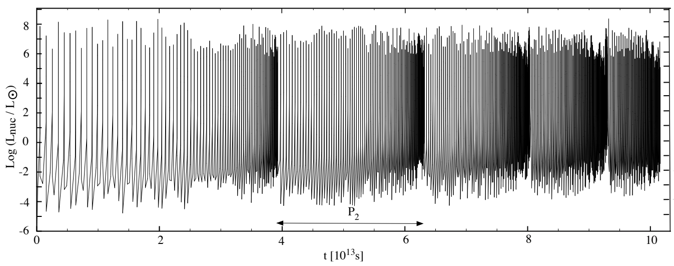

Figure 8: The sequence of flashes taking into account the response of the secondary and the mass transfer but not the change in the masses. Taken from Shaviv et al. [2014]

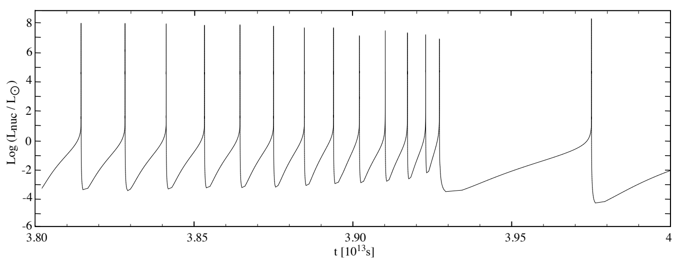

Figure 9: The sequence of flashes showing the variability in the flashes. Taken from Shaviv et al. [2014]

References

M. E. Beer, L. M. Dray, A. R. King, and G. A. Wynn. An alternative to common envelope evolution. *MNRAS*, 375:1000–1008, 2007. doi: 10.1111/j.1365-2966.2006.11386.x.

M. de Kool. Common envelope evolution and double cores of planetary nebulae. *ApJ*, 358:189–195, July 1990. doi: 10.1086/168974.

O. De Marco, J.-C. Passy, M. Moe, F. Herwig, M.-M. Mac Low, and B. Paxton. On the α formalism for the common envelope interaction. *MNRAS*, 411:2277–2292, March 2011. doi: 10.1111/j.1365-2966.2010.17891.x.

J. D. M. Dewi and T. M. Tauris. On the energy equation and efficiency parameter of the common envelope evolution. *A&A*, 360:1043–1051, August 2000.

N. Epelstain, O. Yaron, A. Kovetz, and D. Prialnik. A thousand and one nova outbursts. *MNRAS*, 374:1449–1456, February 2007. doi: 10.1111/j.1365-2966.2006.11254.x.

Y. Hillman, D. Prialnik, A. Kovetz, and M. M. Shara. Observational signatures of SNIa progenitors, as predicted by models. *MNRAS*, 446:1924–1930, January 2015. doi: 10.1093/mnras/stu2235.

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*, 819:168, March 2016. doi: 10.3847/0004-637X/819/2/168.

I. Idan, N. J. Shaviv, and G. Shaviv. The fate of a WD accreting H-rich material at high accretion rates. *MNRAS*, 433:2884–2892, August 2013. doi: 10.1093/mnras/stt908.

N. Ivanova, S. Justham, X. Chen, O. De Marco, C. L. Fryer, E. Gaburov, H. Ge, E. Glebbeek, Z. Han, X.-D. Li, G. Lu, T. Marsh, P. Podsiadlowski, A. Potter, N. Soker, R. Taam, T. M. Tauris, E. P. J. van den Heuvel, and R. F. Webbink. Common envelope evolution: where we stand and how we can move forward. *Ast.Astrophys Review*, 21:59, February 2013. doi: 10.1007/s00159-013-0059-2.

R. G. Izzard, P. D. Hall, T. M. Tauris, and C. A. Tout. Common envelope evolution. In *IAU Symposium*, volume 283 of *IAU Symposium*, pages 95–102, August 2012. doi: 10.1017/S1743921312010769.

F. Meyer and E. Meyer-Hofmeister. Formation of cataclysmic binaries through common envelope evolution. *A&A*, 78:167–176, September 1979.

P. Neunteufel, S.-C. Yoon, and N. Langer. Models for the evolution of close binaries with He-star and white dwarf components towards Type Ia supernova explosions. *A&A*, 589:A43, May 2016. doi: 10.1051/0004-6361/201527845.

B. Paczynski. Common Envelope Binaries. In P. Eggleton, S. Mitton, and J. Whelan, editors, *Structure and Evolution of Close Binary Systems*, volume 73 of *IAU Symposium*, page 75, 1976.

L. Piersanti, A. Tornambé, and L. R. Yungelson. He-accreting white dwarfs: accretion regimes and final outcomes. *MNRAS*, 445:3239–3262, December 2014. doi: 10.1093/mnras/stu1885.

A. J. Ruiter, K. Belczynski, S. A. Sim, I. R. Seitenzahl, and D. Kwiatkowski. The effect of helium accretion efficiency on rates of Type Ia supernovae: double detonations in accreting binaries. *MNRAS*, 440:L101–L105, May 2014. doi: 10.1093/mnrasl/slu030.

I. V. Salazar, A. LeBleu, B. E. Schaefer, A. U. Landolt, and S. Dvorak. Accurate pre- and post-eruption orbital periods for the dwarf/classical nova V1017 Sgr. *MNRAS*, 469:4116–4132, August 2017. doi: 10.1093/mnras/stx1161.

M. M. Shara, D. Prialnik, and A. Kovetz. Multiple hydrogen flashes on accreting low-mass white dwarfs - Novae and DAO stars. *ApJ*, 406:220–228, March 1993. doi: 10.1086/172433.

G. Shaviv. Merger by migration at the final phase of common envelope evolution. *In prep.*, 2018.

G. Shaviv, I. Idan, and N. J. Shaviv. Long term evolution of an interacting binary system. *ArXiv e-prints*, November 2014.

N. J. Shaviv. The Porous Atmosphere of η Carinae. *ApJL*, 532:L137–L140, April 2000. doi: 10.1086/312585.

E. M. Sion and W. Sparks. On the Effect of Explosive Thermonuclear Burning on the Accreted Envelopes of White Dwarfs in Cataclysmic Variables. *ApJL*, 796:L10, November 2014. doi: 10.1088/2041-8205/796/1/L10.

N. Soker. Merger by migration at the final phase of common envelope evolution. *New Ast.*, 18: 18–22, January 2013. doi: 10.1016/j.newast.2012.05.001.

S. Starrfield. The Accretion of Solar Material onto White Dwarfs: No Mixing with Core Material Implies that the Mass of the White Dwarf is Increasing. *ArXiv e-prints*, February 2015.

S. Starrfield, F. X. Timmes, W. R. Hix, C. Iliadis, W. D. Arnett, C. Meakin, and W. M. Sparks. Hydrodynamic Studies of the Evolution of Recurrent Novae to Supernova Ia Explosions. In R. Di Stefano, M. Orio, and M. Moe, editors, *Binary Paths to Type Ia Supernovae Explosions*, volume 281 of *IAU Symposium*, pages 166–171, January 2013. doi: 10.1017/S1743921312014937.

R. E. Taam and P. M. Ricker. Common envelope evolution. *New Ast*, 54:65–71, March 2010.

B. Wang, Y. Li, X. Ma, D.-D. Liu, X. Cui, and Z. Han. Super-Eddington wind scenario for the progenitors of type Ia supernovae: Accreting He-rich matter onto white dwarfs. *A&A*, 584:A37, December 2015.

R. F. Webbink. Common Envelope Evolution Redux. In E. F. Milone, D. A. Leahy, and D. W. Hobill, editors, *Astrophysics and Space Science Library*, volume 352 of *Astrophysics and Space Science Library*, page 233, 2008. doi: 10.1007/978-1-4020-6544-6-13.

R. Williams. Episodic Mass Transfer: A Trigger for Nova Outbursts? In R. Di Stefano, M. Orio, and M. Moe, editors, *Binary Paths to Type Ia Supernovae Explosions*, volume 281 of *IAU Symposium*, pages 88–95, January 2013. doi: 10.1017/S1743921312014755.