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A New Evolutionary Picture for CVs and LMXBs II. The Impact of Thermal-Timescale Mass Transfer

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Abstract. Depending on the outcome of pre-CV formation, mass transfer may set in under thermally unstable conditions in a significant number of systems. Full computations have shown that such an early phase of thermal-timescale mass transfer usually leads to ordinary looking CVs, but these do also show some unusual properties (e.g. chemical anomalies in later stages).

Rather than investigating the common envelope evolution leading to pre-CVs, we study the properties of multiple evolutionary tracks starting with a phase of thermal-timescale mass transfer. Apart from fitting unusual CVs (like AE Aqr), global properties of the CV population as a whole give indications that this is indeed the channel where many CVs come from.

1. Introduction

The standard picture of cataclysmic variable (CV) evolution has in spite of its many benefits serious problems, some of which have been discussed in the previous contribution. If we adopt the new picture sketched therein, it is worth to investigate in detail whether some of these problems have indeed disappeared (without generating an equal number of new ones :-).

As an additional starting point, we take a closer look at some of the individual, strange objects among known CVs. First of all there is AE Aqr, a rapidly spinning intermediate polar at $P_{\rm orb} \simeq 10\,\rm hr$, which apparently has no accretion disk at all. Another puzzling system is V1309 Ori, a polar at $P_{\rm orb} \simeq 8\,\rm hr$. Finally we would like to mention V485 Cen, a system that harbours a probably He-rich donor (Augustijn et al. 1996) at $P_{\rm orb} \simeq 1\,\rm hr$ and may be considered as an example of a binary in-between CVs and AM CVn systems. We will see that all of these can be understood as part of the group of non-standard CVs emerging from higher mass donors, which can be much more evolved (but still on the main sequence) when mass transfer commences.

The important question asked in this contribution would therefore be: How do more massive donor stars (progenitors) in a CV evolve in the light of less effective common envelope (CE) evolution? Can we make at least some of all these loose ends in CV evolution come together?

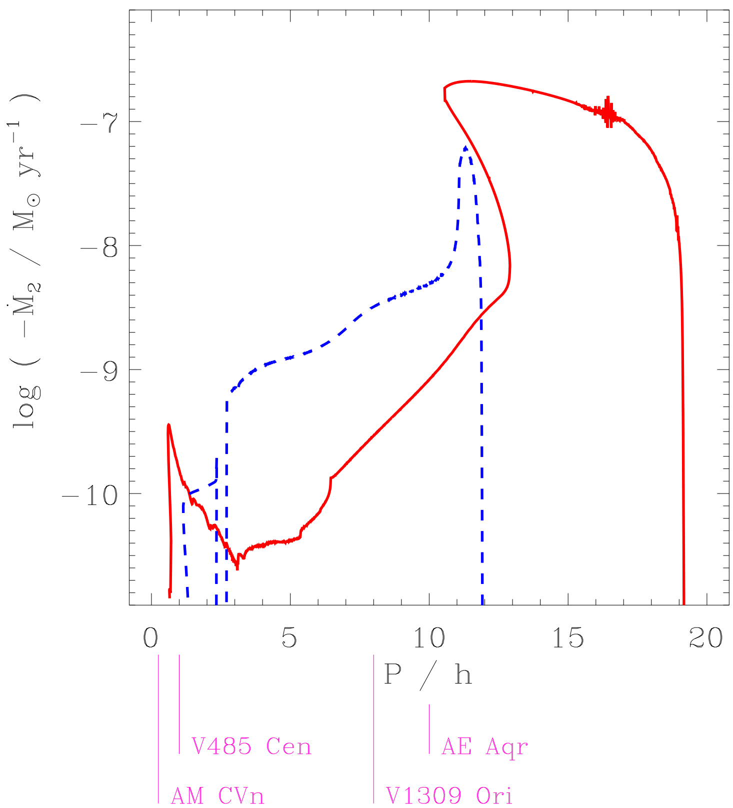

Figure 1. Evolution of mass transfer rate over orbital period for two different cases of thermal-timescale mass transfer: Track 1 (broken line) for a weak case shows an almost normal behaviour after an initial phase, while the extreme case track 2 (full line, with lower primary mass and a much more evolved donor of the same mass) shows a typical S-shaped curve during the TTMT, and no period gap but a lower mass transfer rate all the way down to an orbital period minimum below 1 hr. Additional labels mark the orbital period of various interesting systems discussed in the text.

2. Features of Thermal-Timescale Mass Transfer Evolution

Of fundamental importance is the question of thermal stability. When applying standard concepts and assumptions (cf. Ritter 1996) this there is an upper limit $q_{\rm crit}$ on the mass ratio M_2/M_1 for main sequence (MS) donors, above which mass is transferred on roughly M_2's thermal timescale, i.e. leads to Thermal-Timescale Mass Transfer (TTMT). Such phases of TTMT can be computed with a stellar evolution code (Cyg X-2 (Kolb et al. 2000), SN Ia study (Langer et al. 2000), and LMXBs (Podsiadlowski et al. 2001).

An additional second upper limit is due to delayed dynamical instability (DDI, Webbink 1977), thus systems with $q_{\rm crit} < q < q_{\rm DDI}$ would undergo TTMT

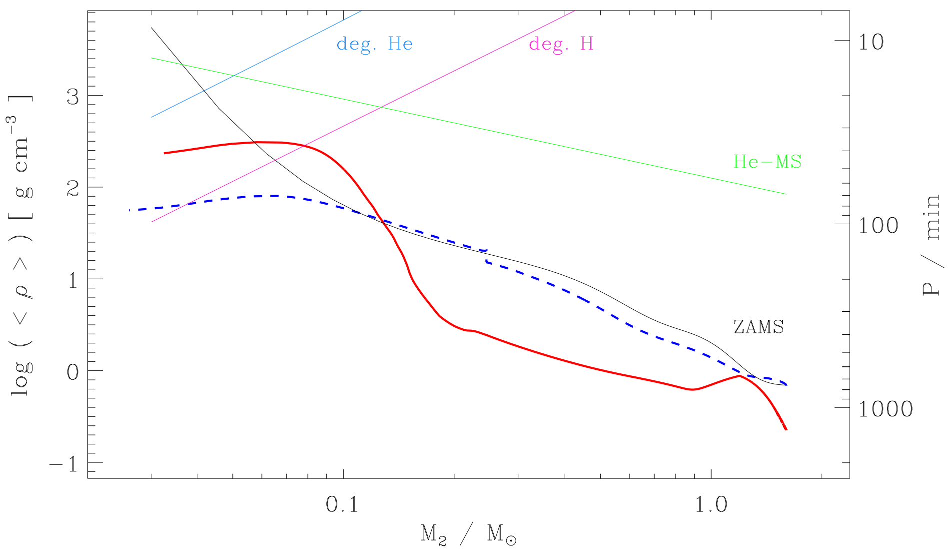

Figure 2. Mean density (and orbital period) of the same two tracks as in Fig. 1 are shown in comparison with various theoretical lines as labelled. Note that while track 1 (broken line) is reasonably well represented by a ZAMS donor until the very late phase around the bounce period, track 2 (full line) is extremely different: It appears to be much more evolved (lower mean density), until the He-core gets exposed, leading to a more compact star filling its Roche lobe down to ultra-short orbital periods.

and may become ordinary CVs afterwards (or *extraordinary* ones, like AE Aqr and similar cases).[1]

This leaves a range of initial donor star masses where instead of the normal, stable CV evolution we get a more complex one including an initial, thermally unstable phase of mass transfer. In general, both the sensitivity of such a phase on details of the mass loss, and the wider range of possible nuclear evolution (due to the shorter MS life-time for more massive stars) lead to a much more complex individual mass transfer history. Let us take a closer look with the help of two very different examples.

2.1. Two exemplary evolution tracks

The dashed curve in Fig. 1 shows a case of 'weak' TTMT. The initial donor star mass $M_{2,i} = 1.6\,\mathrm{M}_\odot$, filling its Roche lobe in a 12 hr binary with a $1.4\,\mathrm{M}_\odot$ primary star (the sequence actually shows a low-mass X-ray binary with a neutron star accretor). The relatively short orbital period indicates the low age of the donor, which still has around 56% hydrogen left in the core at this moment. In

[1] Our current unability to follow the dynamical evolution in any reliable way forces us to exclude all cases of dynamically unstable mass transfer, although their actual role and importance in close binary evolution is far from being settled.

contrast, the thick full curve gives the other end of the possible scale of TTMT evolution, showing a secondary of the same mass ($1.6\,\mathrm{M}_\odot$), but much further evolved: here the central hydrogen is down to $\sim 5\%$, which explains the much larger radius and hence the initial orbital period of 19 hr. This binary has a $0.7\,\mathrm{M}_\odot$ white dwarf primary, so the initial mass ratio is quite large leading to a very violent initial phase of TTMT, whereas the other example merely shown an initial 'hump' of enhanced $\dot{M}_2$, hardly modifying the subsequent evolution when compared to say a similar track starting with a $1.3\,\mathrm{M}_\odot$ donor.

One of the common assumptions regarding CVs is, that the donors are essentially unevolved main sequence stars, i.e. their mass-radius relation should be close to theoretical ZAMS models. Figure 2 illustrates how different our second track behaves in this respect, showing the mean density $\langle\rho\rangle$ evolution over donor mass for the two examples. Other lines in the plot show the ZAMS, a fit curve for the location of the He-MS, plus two lines derived from the assumption of completely degenerate stars consisting of either solar (H-rich) material or pure He. A common expression

$$\langle\rho\rangle \simeq 115\, P_{\mathrm{hr}}^{-2}\,\mathrm{gcm}^{-3}\,, \tag{1}$$

which is based on Paczyński's approximation for the Roche radius, allows to translate $\langle\rho\rangle$ into orbital period (e.g. King 1988).

It is quite obvious from these lines, that while the dashed curve of track 1 nicely follows the ZAMS line, a similar assumption for the radii – say using M_2-P_{orb} relation – of the other sequence would give completely wrong results. From high to low masses, the donor is very oversized (because it was near the end of its MS life), forced to shrink by the initially fast mass transfer (TTMT), then relaxing back towards its larger equilibrium radius. Around $0.2\,\mathrm{M}_\odot$ the old core becomes exposed, and the star is rapidly becoming more compact than a normal MS mass of similar mass (heading from below the ZAMS towards the He-MS, roughly), until degeneracy becomes important and the star turns towards the degenerate He line (at a much shorter orbital period than the corresponding H-rich star, which turns towards the degenerate H-line).

2.2. Pre-CV evolution

The diagrams shown in Figs. 3 & 4 of the previous contribution (King & Schenker 2002) are illustrating a scenario when there are two kinds of systems emerging from the common envelope evolution forming the WD in a future CV. In the first 'normal' group of systems, some form of magnetic braking is operating on relatively low-mass secondaries to bring them into contact by angular momentum losses. These will become ordinary CVs, hosting effectively unevolved donor stars (due to their low masses and the short timescale associated with a sufficiently effective braking). The other group contains more massive secondaries, that may have no additional braking mechanism at all, but start filling their Roche lobe simply due to expansion *on the main sequence.* Detailed properties of such a bimodal population depend severely on binary formation, CE evolution, and magnetic braking (or any other angular momentum loss that might be operating). As long as huge uncertainties in the combination of these effects persist, we should try and reverse the problem by trying to make predictions from observed features of the pre-CV and CV population for the required initial states when mass transfer began in each of the systems.

In addition to the discussion in King & Schenker (2002), we would like to make the point here why our track 2 is to be expected to occur assuming a post-CE situation vaguely similar to the simplistic assumption going into the pre-CV plot shown before: A post-CE orbital period of around 20..30 hr allows main sequence donors of 1..2 $M_\odot$ to fill their Roche lobes still on the MS (cf. Fig. 1 in Podsiadlowski et al. 2001). A range of masses framed by the critical interval for TTMT will therefore in many cases include the lowest mass where such a period is still reached on the MS, i.e. lead to an extremely evolved donor with hardly any hydrogen left in its core. In this simplified picture, we thus obtain automatically two very different groups of CVs: Normal one, showing a period gap, a bounce period, and a frontline at the current period minimum, and in addition a very evolved looking group derived from more massive secondary stars via a TTMT phase, many of which have been reduced to the He-rich donors in AM CVn systems.

We do not consider the assumption for such a post-CE configuration to be very special. In fact, even at $P_{\rm post-CE} = 8\,{\rm hr}$ system would not have been born below the gap in the age of the galaxy. Given the current status of known pre-CVs, no system but MT Ser (whose orbital period in still debated, cf. Bruch 2002) would indicate such a short birth period after the CE.

It should however also be made clear that the whole issue of TTMT is independent the way systems come into contact. The examples shown allow for a mixture of the two groups, e.g. TTMT in systems driven by magnetic braking. The important effect of TTMT is to allow more massive, and possibly evolved systems to finally evolve towards shorter orbital periods and thus to become CVs, even if no angular momentum loss was operating (or strong enough) at their initial mass.

3. Answers to various CV and LMXB problems

Before addressing various problems and how the TTMT population in particular can help to overcome these, we should take a careful look to understand what CVs we do actually observe.

3.1. What do we actually see when looking at CV data

Usually distributions of different subclasses and types of CVs are compared over orbital period, so the issue of phase space density needs to be addressed. Low $\dot{M}$ – or more accurately low $\dot{P}$ – enhances the occurrence of certain objects. Thus it may seem plausible that above the period gap TTMT systems (i.e. evolved donor stars) may dominate the whole population, whereas below the gap (almost) normal looking CVs are the rule. Therefore such a bimodality does not automatically lead to a contradiction with an observational agreement of the standard model.

When it comes to the vicinity of the period gap, one possibly useful way of overcoming the dreaded selection effects could be to specifically analyse the subclass of AM Her magnetic systems. Finally we have to bear in mind that the CV distribution is not a static one, but rather influenced by various temporal evolution effects (generating the observed $P_{\min}$, modifying the current masses of systems undergoing a TTMT, ...).

3.2. Generic properties of TTMT tracks

White dwarf masses Let us assume for simplicity that all WDs in pre-CVs have initially $\sim 0.6\,M_{\odot}$. Those who pass through a TTMT can at least during their super-soft phase grow by $\sim$ few $0.1\,M_{\odot}$. An example of a systems just having left TTMT is AE Aqr (Schenker et al. 2002), whose WD has a claimed mass of $0.89\,\mathrm{M}_{\odot}$. Under special circumstances some may even grow further and become SN Ia (cf. Langer 2002).

We might therefore expect (or rather, predict) that post-TTMT CVs would have larger M_1 on average. A larger number of weak cases of TTMT (like the one shown in track 1) might actually smear out such an effect, making it more difficult to establish such a relation (as would a wide initial WD mass distribution).

One of the immediate implications of this would be regarding nova outbursts in the two groups: More massive WDs are supposed to ignite earlier and more frequent, thus possibly leading to a preferential detection of classical novae in post-TTMT systems.

Similarly NSs may grow beyond their limiting mass and collapse into a BH, or at least appear to be significantly more massive than a single NS. Various cases (e.g. XTE J2123-0547) show hints of such an overmassive primary.

Chemical abundances, in particular the C/N ratio The surface abundances of the donors star (or equivalently the accreted matter of disk or stream) can contain a clear signature of CNO processed material. We interpret such observations as clear indications of initially massive, evolved stars.

We have to caution however that there is also the possibility of contamination by the WD (e.g. via novae) that needs to be excluded, in particular when analysing the WD spectrum alone.

A crucial point is, that only very evolved stars on the MS which lose their envelopes rapidly before becoming fully convective can reach extreme C/N ratios (similar to CNO equil.). In less extreme cases some mixture with solar envelope material will take place, leading to dilution and a value of the C/N ratio between solar and the CNO equilibrium value. The required large M_2 (with a large mass fraction having approached CNO equilibrium abundances of C and N) and a strong TTMT are both natural consequences of the pre-CV scenario described above. This picture is confirmed in AE Aqr (with the largest apparent C/N ratio among CVs), where these requirements come also from its current properties like mass, spin, etc.

Although not quite accurate, we feel confident to infer abundance ratios from the line ratios of C IV and N V in the UV. Mauche, Lee & Kallman (1997) have analysed IUE data of a large number of CVs. Besides some objects showing a very weak C line, many CVs only have a slight increase in the C/N ratio, which might still carry information about their nuclear past.

An important question (or challenge) to observers will therefore lie in the answer to the question, how many CV show C/N anomalies similar to AE Aqr

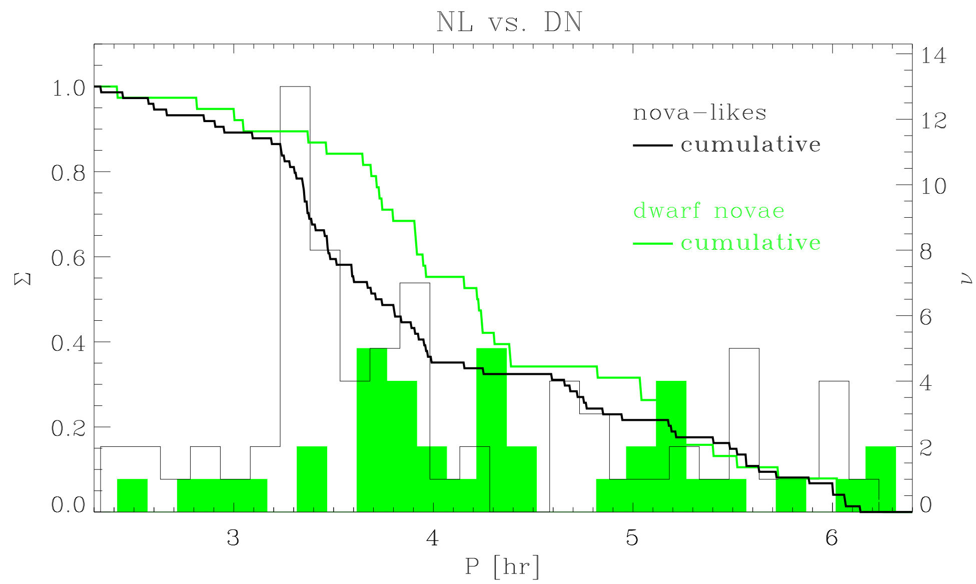

Figure 3. Distribution of dwarf novae (DN) and nova likes (NL) above the period gap, with data taken from Ritter & Kolb (1998). Histograms show the number of systems per orbital period bin ν, whereas the lines represent the relative cumulative distribution with the scale on the right vertical axis. Note the lack of DNs shortwards of 3.5 hr.

and V1309 Ori (cf. King et al. 2001), and whether we will be able to reach a stage of quantitative comparison between theory and observations.

3.3. A peak at the list of problems

Many problems in the standard model are instantly solved assuming the scenario sketched in this and the previous contribution. At the very least, many of the issues look very different now, and can possibly be overcome easily.

To name but a few, several puzzles in connection with the observed period minimum disappear when interpreted as an age effect (as discussed in King & Schenker 2002). Evolved donors naturally appear above the period gap, and individual systems like AE Aqr or V485 Cen, as well as a whole class of AM CVn binaries find their proper place among the family of CVs and related objects.

Let us now take a closer look at one particular, tricky example.

The DN-NL problem just above the period gap Figure 3 seems to suggest an apparent lack of dwarf novae (DNe) in the period range of 3..3.5 hr, shown by comparing the distributions of DNe and nova-likes (NL) both binned and cumulative. In a way this may also be described as a slightly different upper edge of the period gap for DNe (as opposed to NL or the all CV subclasses combined). This is very confusing mostly because in the region immediately above the gap the critical mass transfer rate separating stable from unstable disks is believed to be larger than the one required to form the observed period gap in the interrupted magnetic braking picture. In other words: theoretically

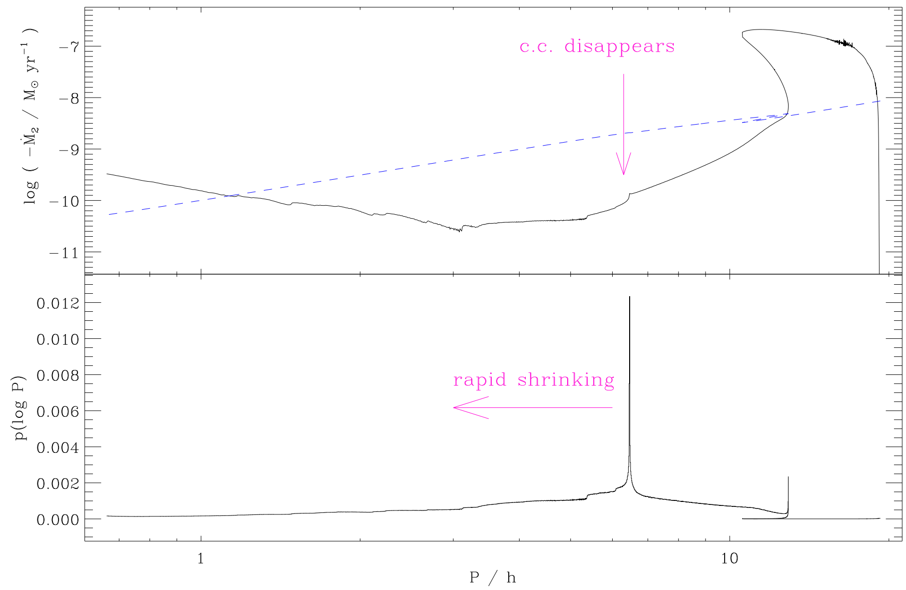

Figure 4. Evolution of track 2 in Fig. 1 shown together with the systems intrinsic observational probability in the panel below. The additional dashed line marks the boundary for disk instability (see text). The hump around the spike in the lower panel (which is associated with the disappearance of the convective core of the donor) reflects the enhanced chance of seeing a system at period longer than 3..4 hr.

we would expect to find only DNe just above the gap, i.e. almost the opposite to what is observed.

This fairly long-standing problem still lacks any compelling explanation (Shafter 1992). Our contribution towards a possible solution of this paradoxon is based on the phase space density argument introduced above. In fact the observational probability of finding a system in a certain period range in inversely proportional to

$$\frac{\mathrm{d}\ln P}{\mathrm{d}t} \sim \frac{1}{2}\,(3\,\zeta_2 - 1)\,\frac{\mathrm{d}\ln M_2}{\mathrm{d}t}\,, \tag{2}$$

i.e. besides $\dot{M}_2$ it also depends heavily on the donor stars mass–radius exponent ζ_2. A close look at track 2 in Fig. 4 together with its critical stability line for the disk shows, that the system appears as a DN over almost the entire CV period range between 1..10 hr. Thus this 'extreme' TTMT provides a huge spike in observational probability (bottom panel of Fig. 4) between 6..7 hr when the convective core of the donor disappears and the orbital period stalls (cf. Fig. 2). Shortly afterwards the star shrinks rapidly, rushing through period space and thus is less likely to be observed as the DN which the system still would be. A suitable superposition of systems of this sort could provide enough DNe to explain the set of low $\dot{M}_2$, long period systems that 'vanish' and apparently do not follow the paradigm required for the gap formation at all.

Obviously this has not solved the whole of the problem: 'normal' systems would still be expected to become DNe as they approach the upper edge of the period gap. As these are the high $\dot{M}_2$ fraction of systems in our picture, the stability criterion would have to be modified accordingly to stabilise all disks in these systems. Clearly we still have a way to go before fully understanding this phenomenon.

Some of the not-so-well-hidden new problems A cautionary note should be made to some of the assumptions made in arriving at the above solutions. The post-CE period is most likely not constant in pre-CVs. This may be derived from observational data (Ritter & Kolb 1998), indicating longer periods for more massive systems, however sparse the actual pre-CV data may be. This is also supported by theoretical models, e.g. de Kool & Ritter (1993). Various *ad hoc* slopes and shifts could modify Fig. 4 significantly and lead to *very* different proportions and properties of the two groups.

Another possible point of concern is the clump of unusual looking systems around $P_{\rm orb} \simeq 80\,$min, claimed to be post-bounce period systems. Apart from the fact that (as discussed in King & Schenker 2002) this interpretations has a number of problems as well, only a more accurate determination of masses, spectral types, and composition of these systems can unravel the remaining mystery about them. Being at the frontline of the 'normal' population group may imply some special properties (e.g. with respect to metallicity) which lead to some unexpected features.

Most seriously, however, we do not understand magnetic braking, even more so after the presentation given at this meeting. Thus we are effectively left without a properly working model for the period gap. Clearly the approach taken herein, i.e. to simply assume a sufficiently strong angular momentum loss mechanism of unknown origin and (nowadays) relatively unmotivated specification (Verbunt & Zwaan) is no longer satisfactory.

4. Conclusion

The concept of allowing and even integrating thermal timescale mass transfer into the general evolution of CVs has proven very successful. It allows us to explain many individually *strange systems* (AE Aqr, V1309 Ori, . . . , AM CVn!?) that would otherwise break the coherent picture of the standard model.

Closely related is the realization of a second formation channel for CVs, namely forming the CV by nuclear evolution followed by the fast TTMT, that allows angular momentum loss to take over driving the evolution only after this initial phase. The bimodality of CVs formed in both ways thus naturally provides an evolved population and a spread in $\dot{M}_2$ above the period gap *without necessarily destroying the gap and the population below the gap.*

We consider it an important strength of this scenario, that a large number of things appear to fall into place now. In particular, the period minimum can be understood as an age effect, CVs below the gap are generally not born there (but at rather higher masses), and ultra-short period binaries (AM CVn for WD primaries, as well as the corresponding LMXBs) derive from fairly evolved & massive donor stars after passing through a CV-like phase. The overall differences between CVs and LMXBs appear diminished and due to well understood differences between the two primary types. It is reassuring that CVs and LMXBs do follow the same fundamental evolutionary principles after all.

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