Mem. S.A.It. Vol. 83, 505

Memorie della

Formation and evolution of cataclysmic variables

H. Ritter

Max–Planck–Institut für Astrophysik, Karl–Schwarzschild–Str. 1, D–85741 Garching, Germany, e-mail: hsr@mpa-garching.mpg.de

Abstract. This review summarizes the basic facts and ideas concerning the formation and evolution of cataclysmic variables (CVs). It is shown that the formation of CVs must involve initially very wide binaries and subsequently huge losses of mass and orbital angular momentum, very likely via a common envelope (CE) evolution, i.e. a process which is still poorly understood. The main uncertainties regarding the evolution of detached post-CE binaries into CVs are the largely unknown rate of loss of orbital angular momentum and the stability of mass transfer when the semi-detached state is reached. A brief discussion of the basic aspects of CV evolution follows. It is shown that here the main uncertainties derive fron the a priori unknwon state of nuclear evolution of the donor star and, again, from the largely unknown rate of loss of orbital angular momentum.

Key words. Stars: evolution – Stars: binaries: close – Stars: novae, cataclysmic variable

1. Introduction

The formation and evolution of cataclysmic variables (CVs) is a vast subject to deal with. Given the limited space available, this review will, therefore, necessarily be somewhat sketchy. In the following I shall concentrate on four main aspects of the topic to be reviewed, namely 1.) on the progenitors of CVs, 2.) on common envelope (CE) evolution, 3.) on the evolution of detached post-CE binaries to CVs, and 4.) on the evolution of CVs themselves. For a more detailed review of the subject the reader is referred to Ritter (2010).

Now is not only *the golden age of cataclysmic variables*. 2012 is also the year of *the golden anniversary of CVs* as an independent topic of research. It was in 1962 when the first (Kraft 1962) of a series of 12 papers on *Binary Stars Among Cataclysmic Variables* by Kraft and co-workers appeared in print. By the time the last paper in this series (Mumford 1971) was published, it was already clear that all CVs are close binary stars in which a white dwarf (WD) accretes matter from a (low-mass) companion star. Interestingly, among the 12 papers by Kraft and co-workers which mostly dealt with observations of individual objects there were two which addressed more general aspects of CVs, aspects which are still of relevance today. Kraft, Mathews & Greenstein (1962) were the first to propose that the loss of orbital angular momentum via gravitational waves is a viable mechanism for driving mass transfer in short-period binary systems. And in 1965 Kraft (1965) argued, based on the similarities of W UMa contact binaries and CVs with respect to total mass, orbital angular momentum, kinematics and space distribution, that W UMa systems might be the progenitors of CVs. With hindsight this proposition seems

Send offprint requests to: H. Ritter

almost ridiculous. But one must not forget that it was made before knowledge of stellar structure and evolution could have been applied to the evolution of either type of binary system and, moreover, before theoreticians were able to explain the formation of WDs. Therefore, we have no reason to critizise Kraft for his proposition even though it later turned out that the progenitors of CVs are binaries with quite different properties (Ritter 1976a,b).

2. The progenitors of CVs

It was not before 1967 that the formation of a (low-mass) WD in a binary system could be explained in the framework of stellar evolution by means of numerical computations (Kippenhahn, Kohl & Weigert 1967). In their computation which was conservative with respect to total mass and angular momentum a binary system consisting of two main sequence stars of initial masses $M_{1,i} = 2M_\odot$ and $M_{2,i} = 1M_\odot$ and an initial orbital period of $P_i = 1.135^d$ transformed into a binary system consisting of a low-mass WD of mass $M_{WD} = 0.264M_\odot$, an unevolved companion with a mass $M_{2,f} = 2.736M_\odot$ and a final orbital period $P_f = 24.09^d$. Though not quite a CV the final system does share some of the key properties of CVs, namely being a binary system conststing of a WD and an unevolved companion.

Later, systematic studies of binary evolution (e.g. Refsdal & Weigert 1971) showed that in this type of binary evolution the final orbital period and the mass of the resulting WD are strongly correlated. This is a direct consequence of the relation $\mathcal{R}(M_c)$ between the mass of the degenrate core M_c and the total radius R of giants and AGB stars (see e.g. Paczyński 1970; Kippenhahn 1981; Joss, Rappaport & Lewis 1987).

From basic properties of stellar structure and evolution one can derive a few simple rules according to which WDs (single or in binaries) are formed: 1.) WDs are predominantly formed from the degenerate core of either giants (He-WDs, $M_{He-WD} \lesssim 0.45M_\odot$), AGB stars (CO-WDs, $0.5M_\odot \lesssim M_{CO-WD} \lesssim 1.1M_\odot$), or of super AGB stars (ONeMg-WDs, $1.1M_\odot \lesssim M_{ONeMg-WD} \lesssim 1.38M_\odot$. 2.) There is an almost unique relation $\mathcal{R}(M_c)$ between the mass of the degenrate core M_c and the total radius $\mathcal{R}$, and 3.) $\mathcal{R}$ is a steeply rising function of M_c. The consequence of all this is that the formation of WDs requires space, a lot of space indeed. Whereas in single stars the available space is virtually unlimited this not the case in close binary stars. There the radius up to which either of the components can grow is constrained by the Roche limit, i.e. by the Roche radius $R_{i,R}$, $i = 1, 2$. Since it is the initially more massive component (hereafter the primary) which evolves faster and thus will become a giant/AGB-star/super AGB-star first the Roche radius of relevance here is $R_{1,R} = a f_1(q)$, where a is the orbital separation and f_1 a well-known function of the mass ratio q (either defined as M_1/M_2 or the inverse). As a consequence the formation of a WD of mass M_{WD} requires an initial orbital separation of the binary system of

$$a_i = \mathcal{R}(M_{WD})/f_1(q_i). \tag{1}$$

For the initial mass M_i of the primary we can derive a lower limit as follws: For single stars of intermediate mass, i.e. with $1M_\odot \lesssim M \lesssim 8M_\odot$, there is a one to one relation between the initial mass M_i and the final mass M_f, i.e. the mass of the WD produced. This relation is known as the *initial mass-final mass relation* (see e.g. Salaris et al. (2009) and references therein). Therefore, $M_{WD} = M_f(M_i)$.

In binary evolution things are a bit different: because mass transfer sets a premature end to the donor's nuclear evolution the mass of the resulting WD is smaller than what a single star evolution would yield, i.e. $M_{WD} < M_f(M_i)$. Turning the argument around this implies that for the formation of a WD of mass M_{WD} the primary's initial mass must be larger that what is required in a single star evolution, i.e. $M_i > M_f^{-1}(M_{WD})$.

Finally, for reasons given below, we may assume that the secondary's pre-CE mass $M_{2,i}$ and its post-CE mass $M_{2,f}$ are very nearly the same, i.e. that $M_{2,i} \approx M_{2,f} = M_2$.

Furthermore we require mass transfer in the future CV to be stable (for a discussion of this point see e.g. Sect. 4 or Ritter 2010) which translates into the condition $M_2 \lesssim M_{\rm WD}$.

From the core mass-radius relation, i.e. from Eq. (1), it follows directly that compared to W UMa-stars the progenitors of CVs containing a WD of typical mass $0.5 M_\odot \lesssim M_{\rm WD} \lesssim 1 M_\odot$ must be very wide binaries. In addition, the total mass of viable progenitors must also be significantly larger than that of the CVs to be formed. This is because the initial mass-final mass relation $M_{\rm f}(M_{\rm i})$ is a rather flat function (see e.g. Salaris et al. 2009), as a consequence of which one typically finds that $M_{\rm i}/M_{\rm f} \approx 2 \ldots 7$. Therefore, the total mass of a CV progenitor system must be larger by a factor of order $2 \ldots 5$ and its orbital angular momentum by a factor of typically $\sim 10^2$ than that of the resulting CV. In other words: the formation of a CV invokes a binary evolution in which the progenitor system has to lose $\sim 50\% - 80\%$ of its initial mass and up to $\sim 99\%$ of its initial orbital angular momentum (Ritter 1976a,b), and this after the onset of the first mass transfer.

3. The common envelope phase

The answer to the question as to how a CV progenitor could shed such prodigious amounts of mass and angular momentum has been given by Paczyński (1976). His proposition was what we now know as common envelope evolution. By this term we denote the process which arises as a consequence of dynamical time scale mass transfer. As a result, a detached short-period binary is formed in which one of its components is the core of the former primary (in our case a pre-WD). Because of its importance for the formation of all sorts of compact binaries the subject has generated a vast literature. For lack of space I am unable to give a detailed review here. Rather I shall concentrate on sketching a few key aspects of this process and for more details refer the reader to recent reviews by Taam & Sandquist (2000), Webbink (2008), and Ivanova (2011).

3.1. Formation of the common envelope

Let's first address the formation of a CE. The situation of a CV progenitor at the onset of mass transfer can be characterized as follows: because mass transfer occurs from the more massive star, the orbital separation a as well as the critical Roche radii $R_{1,\rm R}$ and $R_{2,\rm R}$ shrink. At the same time, the mass losing donor star, having a deep outer convective envelope, has the tendency to expand upon mass loss (see e.g. Hjellming & Webbink 1987). But forced by dynamical constraints to essentially follow $R_{1,\rm R}$ the donor must lose mass at rates approaching $\sim\ M_\odot {\rm yr}^{-1}$. And the secondary, in turn, exposed to such enormous accretion rates, reacts by rapid expansion (Kippenhahn & Meyer-Hofmeister 1977; Neo et al. 1977). The consequence of all this is that within a very short time after the onset of mass transfer the system evolves into deep contact, and the immediate result of this evolution can then be roughly characterized as follows: A binary system consisting of the primary's core (the future WD) of mass $M_{\rm c}$ and the original secondary of mass $M_{2,\rm i}$ finds itself deeply immersed in a CE of mass $M_{\rm CE} = M_{1,\rm i} - M_{\rm c}$ and a size which must be of order of or even larger than the radius given by the core mass-radius relation, i.e. $R_{\rm CE} \gtrsim \mathcal{R}(M_{\rm c})$.

3.2. Common envelope evolution

The basic notion of CE evolution is that because of its huge moment of inertia $I_{\rm CE}$ the rotation of the CE is subsychronous with respect to the immersed binary. As a consequence, due to dynamical friction, the binary loses orbital angular momentum which it transfers to the CE. By this the CE is spun up. But if $I_{\rm CE} > I_{**}/3$, where I_{**} is the binary's orbital moment of inertia, i.e. under circumstances that are easily met by such binaries, the CE cannot be synchronized (Darwin 1879) and the binary must spiral in. In order for the binary to survive, the CE needs to be ejected the latest when the binary approaches the semi-detached state.

Despite decades of heroic efforts to model CE evolution, for reviews see e.g. Taam & Sandquist (2000) or Ivanova (2011), to this day it has not yet been possible to follow such an evolution from its beginning to its end with really adequate numerical computations. Therefore, it is still not possible for a given set of initial parameters to reliably predict the outcome of CE evolution. The expectation is that in many, but not necessarily all, cases the frictional energy release will unbind the CE and leave a close binary consisting of the former primary's degenerate core and the secondary.

Clearly the ejection of the CE requires the envelope's binding energy to be released in a sufficiently short time. This means that the time scale of the spiral-in must be short. However, there are limits to how short the spiral-in can be. Meyer & Meyer-Hofmeister (1979) have found that there is a negative feedback between the frictional energy release and the resulting radiation pressure. An estimate of the duration of the spiral-in is obtained from the argument that because of this feedback the frictional luminosity can not exceed the Eddington luminosity by much. From this argument one can estimate the duration of the spiral-in phase $\tau_{\rm CE}$ which is found to be of order of $10^2 - 10^3$yr. Thus $\tau_{\rm CE}$ is very short, so short indeed that the secondary star has no time to accrete a significant amount of mass during the CE phase (Hjellming & Taam 1991). This is the a posteriori justification for our assumption in Sect. 2 that $M_{2,\rm i} = M_{2,\rm f}$.

3.3. Webbink's approach

CE evolution, if it ends with the ejection of the CE, transforms a binary with initial parameters $(M_{1,\rm i}, M_{2,\rm i}, a_{\rm i})$ to one with final parameters $(M_{1,\rm f}, M_{2,\rm f}, a_{\rm f})$. With current theory it is not possible to precisely link these two sets of parameters. Therefore, in evolutionary studies and population synthesis calculations of compact binaries CE evolution is usually dealt with by means of a simple estimate introduced by Webbink (1984). It derives from the assumption that a fraction $\alpha_{\rm CE} \lesssim 1$ of the binary's binding energy $\Delta E_{\rm B,**}$ which is released in the spiraling-in process is used to unbind the CE.

Using $M_{1,\rm f} = M_{\rm c,i} = M_{\rm c}$, $M_{2,\rm f} = M_{2,\rm i} = M_2$ we have

$$\Delta E_{\rm B,**} = \frac{G\, M_{\rm c}\, M_2}{2} \left(\frac{1}{a_{\rm i}} - \frac{1}{a_{\rm f}} \right) . \tag{2}$$

On the other hand, the binding energy of the CE can be written as

$$E_{\rm B,CE} = -\frac{G\, M_{1,\rm i}\, M_{\rm CE}}{\lambda\, R_{1,\rm i}} , \tag{3}$$

where $M_{\rm CE} = M_{1,\rm i} - M_{\rm c}$ is the mass and $R_{1,\rm i} = a_{\rm i}\, f_1(q_{\rm i})$ the radius of the CE, and λ a dimensionless factor which can be determined from stellar structure calculations provided one knows exactly where the mass cut between core and envelope is. Unfortunately it turns out that λ depends rather sensitively on this (Tauris & Dewi 2001). The CE criterion, namely that

$$E_{\rm B,CE} = \alpha_{\rm CE}\, \Delta E_{\rm B,**} \tag{4}$$

is then equvalent to

$$a_{\rm f} = a_{\rm i} \left\{ \frac{2\, M_{1,\rm i}\, M_{\rm CE}}{\alpha_{\rm CE}\, \lambda\, M_{\rm c}\, M_2\, f_1(q_{\rm i})} - \frac{M_{1,\rm i}}{M_{\rm c}} \right\}^{-1} . \tag{5}$$

Eq. (5) provides the formal link between the pre-CE and the post-CE binary parameters, and shows that when dealing with CE evolution in this way one introduces essentially one free parameter, namely $\alpha_{\rm CE}\, \lambda$ (per CE phase). Since so far we do not have any a priori knowledge about $\alpha_{\rm CE}$ and since also λ is not really well known, the degree of uncertainty introduced via $\alpha_{\rm CE}\, \lambda$ is quite considerable.

Several recent investgations of binary evolution involving CE evolution have come to the conclusion that the energy criterion (4) is not always adequate and that in addition to the orbital binding energy possibly also other sources of energy such as the ionization energy may have to be taken into account. For a comprehensive discussion of this point see e.g. Webbink (2008), or Ivanova (2011).

4. Evolution of post-common envelope binaries

The ejection of the CE leaves a detached short-period binary inside a planetary nebula which is excited by the hot pre-WD component. Currently about 50 of those objects are known (Ritter & Kolb 2003). Once the planetary nebula disappears what remains is a binary consisting of a WD and an essentially unevolved companion. Because the lifetime of a typical planetary nebula of $\sim 10^4$ yr is much shorter than the lifetime of a typical post-CE binary in the detached phase, the intrinsic number of detached post-CE systems lacking a visible planetary nebula must be vastly larger than that of post-CE systems with a planetary nebula. Although such systems are intrinsically rather faint, about ~ 200 of them are currently known (see e.g. Ritter & Kolb (2003) for a compilation). They are collectively refrerred to as *precataclysmic binaries*, hereafter pre-CVs.

In the following, we need to discuss two questions: 1.) how does a detached pre-CV become semi-detached, i.e. a CV, and 2.) whether with the onset of mass transfer all pre-CVs really become CVs or perhaps follow a totally different evolutionary path.

Since in a detached system the future donor star underfills its Roche lobe, mass transfer can only be initiated if either the donor star grows (as a consequence of nuclear evolution) or if the orbital separation shrinks as a consequence of orbital angular momentum loss (AML). Which of the two possibilities is relevant for a particular binary system depends on the ratio of the nuclear time scale

$$\tau_{\rm nuc,2} = (\partial t/\partial \ln R_2)_{\rm nuc} \quad (6)$$

on which the star grows to the AML time scale

$$\tau_{\rm J} = -(\partial t/\partial \ln J_{\rm orb}) = -2\,(\partial t/\partial \ln a) \quad (7)$$

on which the orbital separation a shrinks.

If $\tau_{\rm J} < 2\,\tau_{\rm nuc,2}$ mass transfer is initiated by AML, otherwise by nuclear evolution. The typical future donor star of a CV is a low-mass MS star. Thus $\tau_{\rm nuc,2} > 10^9$ yr. AML in such binaries results either from the emission of gravitational waves (Kraft, Mathews & Greenstein 1962) or from *magnetic braking*. In typical pre-CV systems AML is probably dominated by magnetic braking. Unfortunately, for this mechanism there is as yet no theory which would allow a reliable computation of $\dot{J}_{\rm orb}$ from first principles. Instead, simple semi-empirical estimates (e.g. Verbunt & Zwaan 1981) or simplified theoretical approaches (e.g. Mestel & Spruit 1987) must do. For the typical pre-CV with a low-mass MS companion, these estimates yield $\tau_{\rm J} \sim 10^8$ yr. Thus, for such systems mass transfer is typically initiated via AML (see e.g. Ritter 1986; Schreiber & Gänsicke 2003). But the simple fact that we do observe a number of long-period CVs with a giant donor shows that mass transfer can also be initiated by nuclear evolution of the future donor star. However, the fraction of pre-CV systems ending up with a giant donor appears to be small and, unfortunately, is strongly model-dependent (de Kool 1992).

When the secondary reaches its Roche limit and mass transfer sets in stability of mass transfer becomes an issue. Whether mass transfer is stable or not depends on the change of the secondary's radius R_2 relative to the critical Roche radius $R_{2,\rm R}$ upon mass loss. Hereby one must distinguish between the secondary's reaction to very fast mass loss (dynamical or adiabatic mass loss) and very slow mass loss (mass loss near thermal equilibrium). Mass loss is adiabatically (thermally) stable if as a consequence of mass loss R_2 shrinks with respect to $R_{2,\rm R}$. Otherwise it is unstable. If mass transfer is adiabatically unstable the resulting mass transfer rates can become very large, i.e. $-\dot{M}_2 \rightarrow M_2/P_{\rm orb}$ and the corresponding evolutionary time scale very short. If, on the other hand, mass transfer is adiabatically stable but thermally unstable, mass transfer proceeds on the donor's thermal time scale, i.e. $-\dot{M}_2 \approx M_2/\tau_{\rm th}$. For a more comprehensive discussion of the stability of mass transfer see e.g. Ritter (1988).

Why is this important? Observations and theoretical arguments show that in the vast majority of CVs mass transfer is thermally and adiabatically stable. In other words: only those pre-CVs for which mass transfer is stable can directly become CVs. What happens to the rest? That depends mainly on the evolutionary status of the donor and the binary's mass ratio. If we distinguish for simplicity MS stars and giants as possible donor stars, then the following cases can arise:

1. MS donor, mass transfer thermally and adiabatically stable → short-period CV ($P_{\rm orb} \lesssim 0.5$ d) with an unevolved donor.
2. MS donor, mass transfer adiabatically stable but thermally unstable → thermal time scale mass transfer, WD with (stationary) hydrogen burning, system appears as a supersoft X-ray source (see e.g. van den Heuvel et al. 1992; Schenker et al. 2002) → CV with an artificially evolved MS donor.
3. MS donor, mass transfer adiabatically unstable → very high mass transfer rates, second common envelope?, coalescence?
4. giant donor, mass transfer thermally and adiabatically stable → long-period CV ($P_{\rm orb} \gtrsim 1$ d).
5. giant donor, mass transfer either thermally or adiabatically unstable → very high mass transfer rates, second common envelope?, formation of an ultrashort-period detached WD+WD binary?

5. CV evolution

CV evolution is a complex subject. Here I can present only a brief outline of this topic. For a more comprehensive treatment see e.g. the reviews by King (1988), Ritter (1996), or the recent paper by Knigge, Baraffe, & Patterson (2011), hereafter KBP.

5.1. Computing the evolution of a cataclysmic binary

If mass transfer in a binary is thermally and adiabatically stable, as in the majority of CVs, no mass transfer occurs unless some external force drives it. And in CVs the driving agents are the same as in pre-CVs (cf. Sect. 4), i.e. AML and nuclear evolution of the donor. Furthermore, if mass transfer is stable and the strength of the driving changes only on long time scales, mass transfer will be essentially stationary. In that case the donor's radius R_2 and its Roche radius $R_{2,\rm R}$ are equal to within very few of the secondary's atmospheric scale height $H \sim 10^{-4} R_2$ (Ritter 1988). Thus, to a very good accuracy we must have $R_2 = R_{2,\rm R}$ and $\dot{R}_2 = \dot{R}_{2,\rm R}$. This is the additional boundary condition by which the computation of a semi-detached binary differs from that of a single star.

For a realistic simulation of the evolution of a CV the full stellar structure problem must be solved. Because stellar evolution is an initial value problem, for setting up a simulation one has first to decide at which moment of the evolution to start the calculation and to specify at least the masses of the components and their internal structure, i.e. the evolutionary status of the donor star, but as the case may be also the structure of the accreting WD. Furthermore, one has to specify, i.e. parametrize, the loss of orbital angular momentum resulting from mass loss from the system, and finally to decide what to do about systemic AML (i.e. AML not being a consequence of mass transfer), in particular about magnetic braking, i.e. which of the various prescriptions available in the literature (e.g. Verbunt & Zwaan 1981; Mestel & Spruit 1987) to use. When everything is set up calculating the evolution is in the simplest case just a single star evolution for the donor star with variable mass where the mass loss rate is an eigenvalue of the problem and is determined by the additional outer boundary condition , e.g. by $R_2 \leqslant R_{2,\rm R}$.

5.2. A sketch of CV evolution

The orbital period $P_{\rm orb}$ is the only physical quantity which is known with some precision for a large number of CVs, currently for over 900 objects (Ritter & Kolb 2003). Reliable masses, on the other hand, are known, if at all, only for a very small minority of CVs. Therefore, much of the work on CV evolution in the past 30 years has concentrated on understanding the observed period distribution of CVs. Broadly speaking, this distribution is bimodal with $\sim$ 40% of the objects having periods in the range $3^{\rm h} \lesssim P_{\rm orb} \lesssim 16^{\rm h}$, another $\sim$ 50% with 80 min $\lesssim P_{\rm orb} \lesssim 2^{\rm h}$, and the remaining $\sim$ 10% with $2^{\rm h} \lesssim P_{\rm orb} \lesssim 3^{\rm h}$. The dearth of objects in the period interval $2^{\rm h} \lesssim P_{\rm orb} \lesssim 3^{\rm h}$ is known in the literature as the *period gap*.

The maximum period of $\sim 16^{\rm h}$ is easily understood as a consequence of the facts that 1.) the donor is a MS star, 2.) the mass of the WD is $M_{\rm WD} < M_{\rm CH} \approx 1.4 M_\odot$, where $M_{\rm CH}$ is the Chandrasekhar mass, and 3.) mass transfer must be stable.

The minimum period of $\sim$ 80 min, in turn, is at least qualitatively understood as a consequence of mass transfer from a hydrogen-rich donor which is mainly driven by gravitational radiation (Paczyński & Sienkiewicz 1981, 1983; Rappaport, Joss & Webbink 1982). Because of mass loss, of the order of $10^{-10} M_\odot \mathrm{yr}^{-1}$, the donor star becomes more and more degenerate when $M_2 \lesssim 0.1 M_\odot$ and its structure changes from that of a low-mass MS star to that of a brown dwarf. Thereby its effective mass radius exponent $\zeta_{\mathrm{eff},2} = d\ln R_2/d\ln M_2$ changes from ~ 0.8 on the MS to $-1/3$. P_{orb} is minimal when $\zeta_{\mathrm{eff},2} = +1/3$. Whether mass transfer near the period minimum is really driven by gravitational radiation only is currently under dispute because of the mismatch between the corresponding theoretical prediction for the minimum period of $\sim$ 70 min and the observed value of $\sim$ 80 min (see e.g. Renvoizé et al. (2002), Gänsicke et al. (2009), or KBP for a discussion).

The period gap is more difficult to account for. Over the years a number of different hypotheses has been put forward to explain it. For lack of space I cannot review them all here. Rather I shall concentrate on the one hypothesis (Spruit & Ritter 1983; Rappaport, Verbunt & Joss 1983) which, in my view, still provides the most plausible explanation for what we see, and which is known in the literature as the *disrupted (magnetic) braking hypothesis*. It postulates that as long as the donor star has a radiative core "magnetic braking" is effective and CV evolution is driven by a high AML rate due to "magnetic braking" and gravitational radiation, but that, as soon as the donor star becomes fully convective, "magnetic braking" becomes ineffective and the evolution is mainly driven by AML from gravitational radiation. As a consequence of the rather sudden and significant drop of the AML rate the system detaches.

In a recent study KBP have shown by "reverse engineering" CV evolution that the disrupted magnetic braking hypothesis is a viable model of CV evolution and that by adjusting the AML rate it works also quantitatively if the following conditions are met: AML above the gap must drive mass transfer at a level of $-\dot{M}_2 \sim 10^{-9} M_\odot \mathrm{yr}^{-1}$. As a result, the donor becomes fully convective when $M_2 \sim 0.2 M_\odot$ and $P_{\mathrm{orb}} \sim 3^{\mathrm{h}}$. At that moment, as a consequence of previous high mass loss, the stellar radius is larger by about 30% than in thermal equilibrium. With a significant reduction of AML from "magnetic braking" the AML loss rate drops by a factor of $\sim 10 - 20$. After the detached phase which lasts for a few 10^8 yr mass transfer resumes with $M_2 \sim 0.2 M_\odot$, $R_2 = R_{2,\mathrm{e}} \sim 0.2 R_\odot$ and $P_{\mathrm{orb}} \sim 2^{\mathrm{h}}$ at a level of $-\dot{M}_2 \sim 10^{-10} M_\odot \mathrm{yr}^{-1}$. In order to get a minimum period of $P_{\mathrm{min}} \sim$ 80 min the AML rate below the gap must be larger than $\dot{J}_{\mathrm{GR}}$, the rate due to gravitational radiation alone, namely $\dot{J}_{\mathrm{orb}}(P \lesssim 2\,\mathrm{h}) \approx 2.5\, \dot{J}_{\mathrm{GR}}$.

Explaining the gap as a collective phenomenon of CV evolution requires furthermore that the majority of the donor stars are of the same type, i.e. MS stars, and that AML via "magnetic braking" yields similar mass transfer rates in different systems at the same orbital period. Only this guarantees the coherence of the phenomenon.

The fact that the period range of the gap is not empty already indicates that not all CVs follow the above-described evolution strictly. There are several reasons for why there may be CVs in the gap. The most important ones are: 1.) a donor mass such that at the end of the pre-CV evolution the orbital period is $2^{\mathrm{h}} \lesssim P_{\mathrm{orb}} \lesssim 3^{\mathrm{h}}$ (e.g. Kolb 1993; Davis et al. 2008); 2.) a donor star which initially was close to the terminal age MS (see e.g. Ritter 1994), or which is the artificially evolved remnant of earlier thermal time scale mass transfer (Schenker & King 2002); 3.) reduced "magnetic braking" because of the presence of a strongly magnetized WD (for details see e.g. Li, Wu & Wickramasinghe 1994). At the end of CV evolution the donor star is a very faint brown dwarf. The WD, in turn, with an effective temperature of typically $< 10^4$K is also very faint. And because the mass transfer rate is very small as well, i.e. $-\dot{M}_2 \lesssim 10^{-11} M_\odot \mathrm{yr}^{-1}$, so is the resulting accretion luminosity. Thus, such CVs are very inconspicuous objects, and correspondingly difficult to detect. And though intrinsically the vast majority of all CVs is in this late phase (Kolb 1993) so far only one convincing candidate beyond and far from the period minimum is known (Littlefair et al. 2006). The CV graveyard, as this evolutionary branch is sometimes referred to, is thus largely hidden from our view.

References

Darwin, G.H. 1879, Proc. Roy. Soc. London, 29, 168
Davis, P.J., Kolb, U., Willems, B., & Gänsicke, B.T. 2008, MNRAS, 389, 1563
de Kool, M. 1992, A&A, 261, 188
Gänsicke, B.T., et al. 2009, MNRAS, 397, 2170
Hjellming, M.S., & Webbink, R.F. 1987, ApJ, 318, 794
Hjellming, M.S., & Taam, R.E. 1991, ApJ, 370, 709
Ivanova, N. 2011, ASP Conf. Ser. Vol. 447, p. 91
Joss, P.C., Rappaport, S., & Lewis, W. 1987, ApJ, 319, 180
King, A.R. 1988, QJRAS, 29, 1
Kippenhahn, R. 1981, A&A, 102, 293
Kippenhahn, R., Kohl, K., & Weigert, A. 1967, ZAp, 66, 58
Kippenhahn, R., & Meyer-Hofmeister, E. 1977, A&A, 54, 539
Knigge, C., Baraffe, I., & Patterson, J. 2011, ApJS, 194, 28
Kolb, U. 1998, A&A, 271, 149
Kraft, R.P. 1962, ApJ, 135, 408
Kraft, R.P., Mathews, J., & Greenstein, J.L. 1962, ApJ, 136, 312
Kraft, R.P. 1965, ApJ, 142, 1588
Li, J., Wu, K., & Wickramasinghe, D.T. 1994, MNRAS, 268, 61
Littlefair, S.P., et al., 2006, Science, 314, 1578
Mestel, L., & Spruit, H.C. 1987, MNRAS, 226, 57
Meyer, F., & Meyer-Hofmeister, E. 1979, A&A, 78, 167
Mumford, G.S. 1971, ApJ, 165, 369
Neo, S., Miyaji, S., Nomoto, K., & Sugimoto, D. 1977, PASJ, 29, 249
Paczyński, B. 1970, AA, 20, 47
Paczyński, B. 1971, ARA&A, 9, 183
Paczyński, B. 1976, IAU Symp. No. 73, p. 75
Paczyński, B., & Sienkiewicz, R. 1981, ApJ, 248, L27
Paczyński, B., & Sienkiewicz, R. 1983, ApJ, 268, 825
Refsdal, S, & Weigert, A. 1971, A&A, 13, 367
Rappaport, S., Joss, P.C., & Webbink, R.F. 1982, ApJ, 254, 616
Rappaport, S., Verbunt, F., & Joss, P.C. 1983, ApJ, 275, 713
Renvoizé, V., Baraffe, I., Kolb, U., & Ritter, H. 2002, A&A, 389, 485
Ritter, H. 1976a, IAU Symp. No. 73, p. 205
Ritter, H. 1976b, MNRAS, 175, 279
Ritter, H. 1986, A&A, 169, 129
Ritter, H. 1988, A&A, 202, 93
Ritter, H. 1994, MmSAI, 65, 173
Ritter, H. 1996, NATO ASI Ser. C, Vol. 477, Kluwer, Dordrecht, p. 223
Ritter, H. 2010, MmSAI, 81, 849
Ritter H., & Kolb, U. 2003, A&A, 404, 301 (update RKcat7.16)
Salaris, M., Serenelli, A., Weiss, A., & Miller Bertolami, M. 2009, ApJ, 692, 1013
Schenker, K., et al., 2002, MNRAS, 337, 1105
Schenker, K., & King, A.R. 2002, ASP Conf. Ser. Vol. 261, 242
Schreiber, M.R., & Gänsicke, B.T. 2003, A&A, 406, 305
Spruit, H.C., & Ritter, H. 1983, A&A, 124, 267
Taam, R.E., & Sandquist, E.L. 2000, ARA&A, 38, 113
Tauris, T.M., & Dewi, J.D.M. 2001, A&A, 369, 170
van den Heuvel, E.P.J., Bhattacharya, D., Nomoto, K., & Rappaport, S.A. 1992, A&A, 262, 97
Verbunt, F., & Zwaan, C. 1981, A&A, 100, L7
Webbink, R.F. 1984, ApJ, 277, 355
Webbink, R.F. 2008, in: Short Period Binary Stars, ed. M.F. Milone, D.A. Leahy, & D.W. Hobill, Springer Verlag, p. 208