A New Evolutionary Picture for CVs and LMXBs

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Abstract. We consider an alternative to the standard picture of CV and LMXB evolution, namely the idea that most CVs (and by extension LMXBs) may not yet have had time to evolve to their theoretical minimum orbital periods. We call this the Binary Age Postulate (BAP). The observed short–period cutoff in the CV histogram emerges naturally as the shortest period yet reached in the age of the Galaxy, while the post–minimum–period space density problem is removed. The idea has similar desirable consequences for LMXBs. In both cases systems with nuclear–evolved secondary stars form a prominent part of the short–period distributions. Properties such as the existence and nature of ultrashort–period systems, and the spread in mass transfer rates at a given orbital period, are naturally reproduced.

1. Introduction

The current picture of CV evolution (see e.g. King, 1988 for a review) has remained essentially unchanged for more than two decades. Its main elements are the propositions that

1. Formation: Common–envelope (CE) evolution produces pre–CVs close to contact at all periods P such that $1.5 \lesssim P \lesssim 12$ hr

2. Secular evolution: angular momentum loss brings pre–CVs rapidly into contact after the CE phase and also drives their subsequent evolution as CVs, accounting for the main features of the observed CV period histogram. The loss mechanism is gravitational radiation (GR) and some rather stronger agency, perhaps magnetic braking (MB) at periods $P \gtrsim 3$ hr

3. Youth 1: CVs are significantly younger than the Galaxy, so many generations of CVs have passed through the observed CV period range

4. Youth 2: CV secondaries are not nuclear–evolved

The great difficulty inherent in theoretical studies of CE evolution via numerical simulations has meant that elements 1, 3 and 4 have remained largely unexamined. Until recently, most researchers have concentrated on tying down the details of 2. above.

The evolution of low–mass X–ray binaries (LMXBs) is more complex than that of CVs because of the need to form a neutron star or black hole through a supernova explosion, with a resulting potential for disruption of the binary. In particular proposition 1. is no longer obvious. Nevertheless the similarity of *short–period* LMXBs to CVs has encouraged tacit adoption of at least 2. and 4.
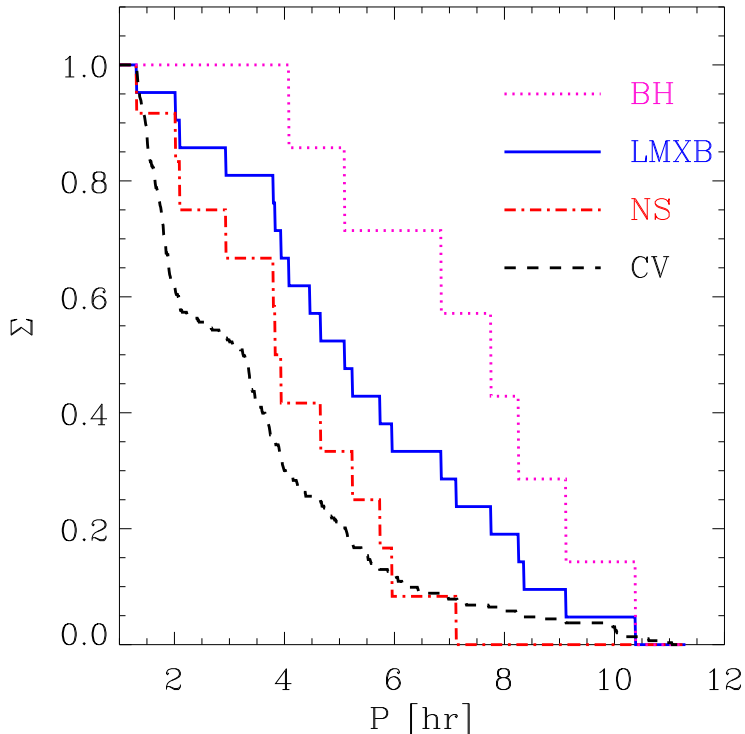
Figure 1.   Comparison of the LMXB period distribution (cumulative only) with that of CVs (dashed) over a typical range of orbital periods. Data are taken from Ritter & Kolb (1998, with updates). Additional curves are shown for LMXBs with established NS (dotted) and BH accretors (dash-dotted). Note the systematic trend between different primaries.

for them also. Significant differences (cf Fig. 1) in the period histograms of the two types of binary (first pointed out by White & Mason, 1985) have received relatively little attention.

Here we suggest that for CVs there are real reasons to question the three linked propositions 1.–3.–4., and even some of the apparent successes of 2. We suggest a way out of these difficulties which appears promising for both CVs and LMXBs.

2.   The CV period minimum as an age effect

The observed CV period histogram (Fig. 2) cuts off sharply at an orbital period of $P = P_0 \simeq 76$ min. There are respectively 0 and 12 systems in the period ranges $P_0 \pm 5$ min. The idea that P_0 represents a global period minimum ($\dot{P} = 0$ for $P_{\min}$) for CVs has been widely accepted for the last two decades. It is clear that such a global minimum can exist (Paczyński & Sienkiewicz, 1981; Paczyński, 1981; Rappaport, Joss & Webbink, 1982). As the mass M_2 of an unevolved secondary star in a CV is reduced by mass transfer, the binary period P decreases also. However for very small $M_2 \lesssim 0.1\,\mathrm{M_\odot}$, the secondary's Kelvin–
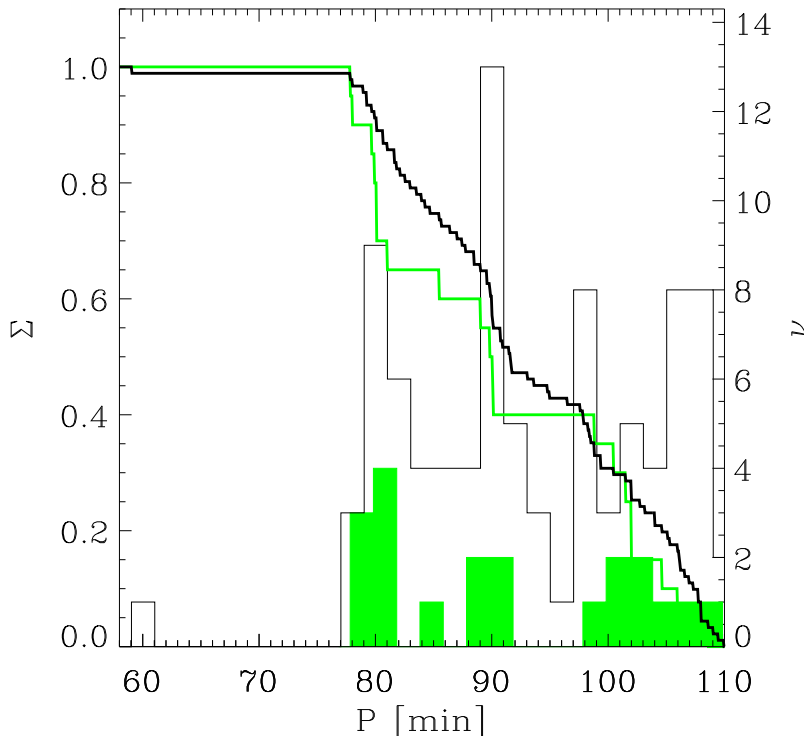
Figure 2. Observed CV period distribution (binned and cumulative) at periods around P_0. Data are taken from Ritter & Kolb (1998). Over-plotted in grey is the subclass of AM Her systems showing essentially identical behaviour. The single system at $P \simeq 60$ min is V485 Cen.

Helmholtz time t_{KH} begins to exceed the timescale $t_{\mathrm{M}} = -M_2/\dot{M}_2$ for mass loss driven by angular momentum loss, e.g. by gravitational radiation. At this point the star will expand adiabatically, causing the binary period to increase rather than decrease.

Detailed calculations always predict a value $P_{\min}$ very close to, if slightly shorter than, the observed P_0. The discrepancy $P_{\min} < P_0$ is persistent, but may reflect uncertain or over–simple input physics (cf Kolb & Baraffe, 1999). However there is a much more serious problem with this interpretation of the observed cutoff at P_0. This concerns the discovery probability

$$p(P) \propto \frac{(-\dot{M}_2)^\alpha}{|\dot{P}|}. \tag{1}$$

Here α is some (presumably positive) power describing observational selection effects (e.g. $\alpha = 3/2$ for a bolometric flux–limited sample). Since $\dot{P} = 0$ at $P = P_{\min}$, $p(P)$ must clearly have a significant maximum there unless $-\dot{M}_2$ declines very sharply near this period. In other words, the observed CV period histogram should show a sharp rise near a global minimum $P_{\min}$ unless the mass transfer rate drops there. However all evolutionary calculations show that $-\dot{M}_2$ changes very little as $P_{\min}$ is approached. We conclude that there should be a

large 'spike' in the CV period histogram near a global minimum $P_{\min}$ (cf Kolb & Baraffe, 1999).

The lack of such a spike in the observed period histogram (Fig. 2) has prompted numerous theoretical investigations. Many of these propose ways in which CVs might become difficult to discover near $P_{\min}$. A basic problem for this type of argument is that, as we have seen, there is nothing at all unusual about the system parameters (mass transfer rate, separation etc) at this period. Further, attempts to use accretion disc properties as a way of making systems hard to discover founder on the fact that the AM Herculis systems, which have no accretion discs, have precisely the same observed short–period cutoff $P_0 \simeq$ 80 min, and no spike either (cf Fig. 2).

The identification of the observed cutoff P_0 with the global minimum period $P_{\min}$ creates a second problem, particularly emphasized by Patterson (see the review in this volume, and references therein). Namely, if many generations of CVs have completed their evolution and passed the minimum period in the history of the Galaxy, the predicted space density of post–minimum CVs becomes uncomfortably high. The nearest systems should be close enough to be detectable even as bare white dwarfs; and the problem gets worse when one realises that mass transfer decreases only very slowly (timescales $\sim 10^{10}$ yr) after passing $P_{\min}$, so that they are definitely brighter than the bare white dwarfs. Since the orbital period also changes very little, the result should be a very large number of nearby CVs with brightness and periods very close to those at P_0, which are not observed.

In view of these and other difficulties, it seems reasonable to consider dropping the assumed identification of the observed cutoff P_0 with the global minimum $P_{\min}$. Thus, from now on we will instead investigate the idea that $P_{\min}$ might be genuinely shorter than P_0, or more succinctly, *that even the oldest CVs have not yet reached $P_{\min}$*.

The timescale t_{evol} for the secular evolution of CVs down to $P_{\min}$ is considerably shorter than the age of the Galaxy, even from the longest commonly observed periods $\sim 8 - 10$ hr (assuming that magnetic braking is not drastically reduced as has been recently proposed – see the article by Pinsonneault in this volume). Thus to maintain the idea that $P_{\min} < P_0$, we must require that most CVs came into contact only a time $< t_{\text{evol}}$ ago. In the conventional picture where CE evolution produces pre–CVs close to contact at all orbital periods, this would mean that CVs emerged from CE evolution relatively recently in the age of the Galaxy, presumably as the result of a starburst. This seems unlikely, so we assume instead that for most systems *the time $t_{contact}$ to shrink the binary enough to initiate mass transfer is at least comparable to the Galactic age t_{Gal}* (more precisely $t_{contact} \gtrsim t_{\text{Gal}} - t_{\text{evol}}$).

We call this idea the Binary Age Postulate (BAP). In the usual language, it amounts to requiring *either* that CE evolution is more efficient in removing the envelope of the white dwarf progenitor, thus leaving wider systems than usually assumed, *or* that with conventional CE evolution, orbital decay into contact by angular momentum loss is much slower than usually assumed. The second possibility would fit with the idea of drastically reduced magnetic braking (see the article by Pinsonneault in this volume). However, unless the usual value of the magnetic braking torque is restored once the system reaches contact there

are obvious problems in explaining the brighter (novalike) CVs and the period gap itself. Hence while the reduced braking idea is worth bearing in mind, for the expository purposes of this paper we shall assume the first possibility, i.e. that BAP is satisfied because CE evolution is more efficient than usually assumed. Thus most CVs with secondaries massive enough to have magnetic braking would emerge from CE evolution with periods of order 12 hr or more. CVs with lower–mass secondaries could emerge with shorter orbital periods, but such that relatively few reached contact (evolving via gravitational radiation) within t_{Gal}. We note that this type of distribution is not in conflict with the observed pre–CV distribution (Ritter & Kolb, 1998).

Armed with these assumptions we can give two immediate consequences for CVs, and two for LMXBs.

(i) *The period distribution near P_0.* The characteristic square shape of this distribution is naturally reproduced, provided only that CVs at longer periods decrease their periods more quickly than those at short periods, e.g. $-\dot{P} = G(P)$ with $\mathrm{d}G/\mathrm{d}P > 0$. This is of course true for the usually assumed forms of magnetic braking. Hence the observed distribution appears naturally if CVs generally come into contact with secondary masses M_2 large enough ($M_2 \gtrsim 0.3\,\mathrm{M_\odot}$) for their pre–contact evolution to have been driven by this mechanism. This is of course precisely the content of the BAP idea.

(ii) *The space density problem.* This is removed, since there is no presumption that many generations of CVs have passed the observed cutoff P_0, and thus no presumed rate at which CVs are piling up in the Galaxy. Assuming that the formation rate of pre–CVs has decreased markedly since the early epochs of the Galaxy, there is no corresponding problem with the space density of pre–CVs. Note that if we do not make the latter assumption, the space density problem is inevitable in *any* picture: CVs pile up either as post–minimum or pre–contact systems, as we presumably cannot destroy the white dwarfs in either state.

(iii) *The LMXB minimum period.* Magnetic braking acts more slowly on LMXBs than CVs, as the binary inertia is greater. Thus we might expect LMXBs to have longer P_0 cutoffs than CVs – consistent with observation (see Fig. 1) – as they will presumably be unable to reach such short periods in the age of the Galaxy.

(iv) *The faint transient problem.* King (2000) points out that LMXBs with very low mass transfer rates, such as any which have passed the equivalent of the CV global minimum period, will be readily observable as faint transients. Although some such faint systems are observed, the total number in the Galaxy is much too low compared with the number of 'normal' LMXBs to interpret them as post–minimum systems in the standard picture. Again this is as expected if most LMXBs have not yet reached the global minimum. We shall see a further feature of these systems explained in the next section.

3.　　Thermal–Timescale and Nuclear Evolution

The list (i –iv) above shows that BAP has interesting consequences for CV and LMXB evolution. Unsurprisingly there are more. The longer timescales envisaged for orbital decay via angular momentum loss open the possibility that nuclear evolution of the secondary star might bring the binary into contact instead,
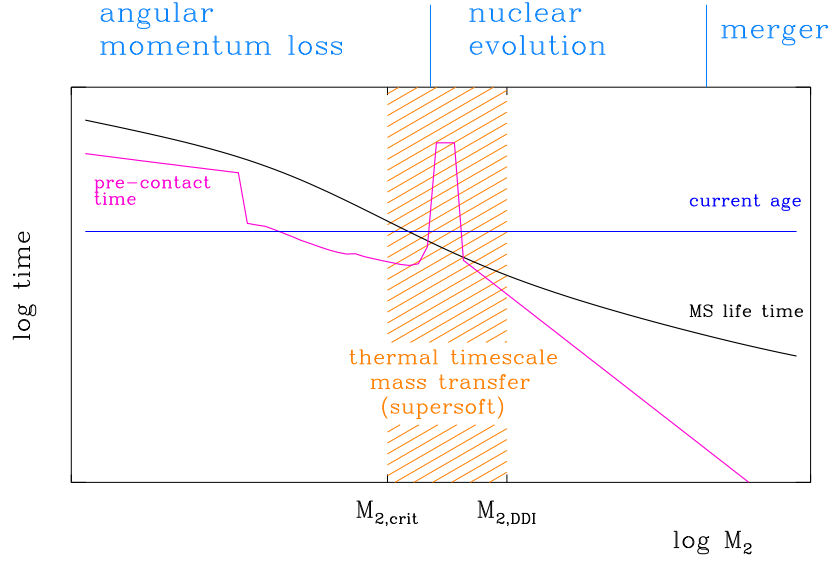
Figure 3.   Schematic comparison of the duration of pre-contact evolution with other timescales for close binaries (see text for discussion).
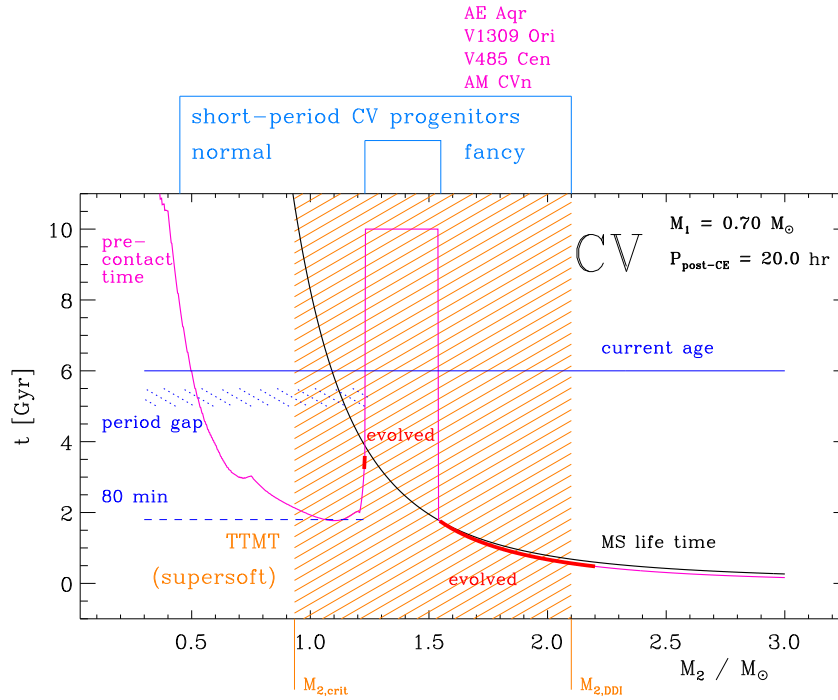

Figure 4.   Typical CV case within the BAP model: Two progenitor groups forming the current short-period population of CVs (see text for details).
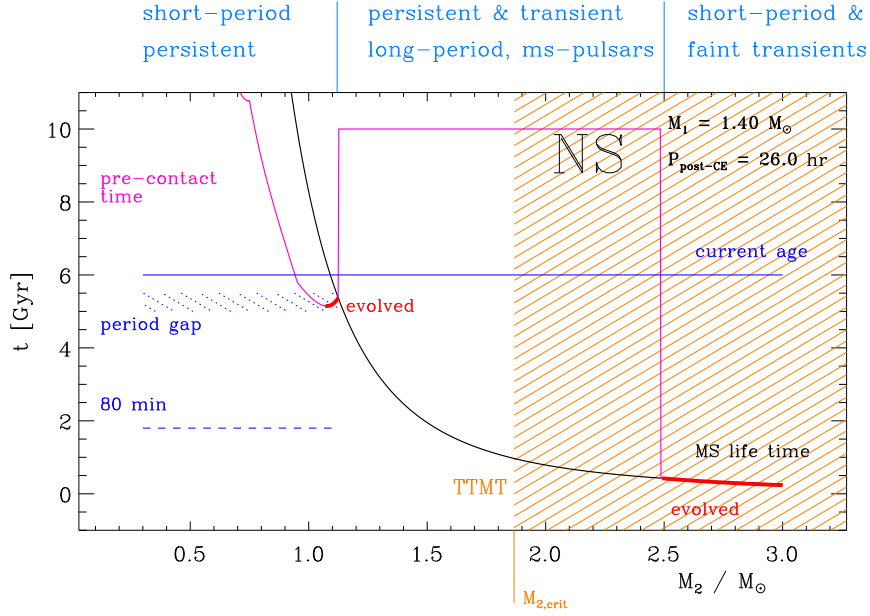
Figure 5.   Typical NS case within the BAP model: Systems with unevolved donors are scarce and cannot have evolved below periods around 2..3 hr (see text for details).
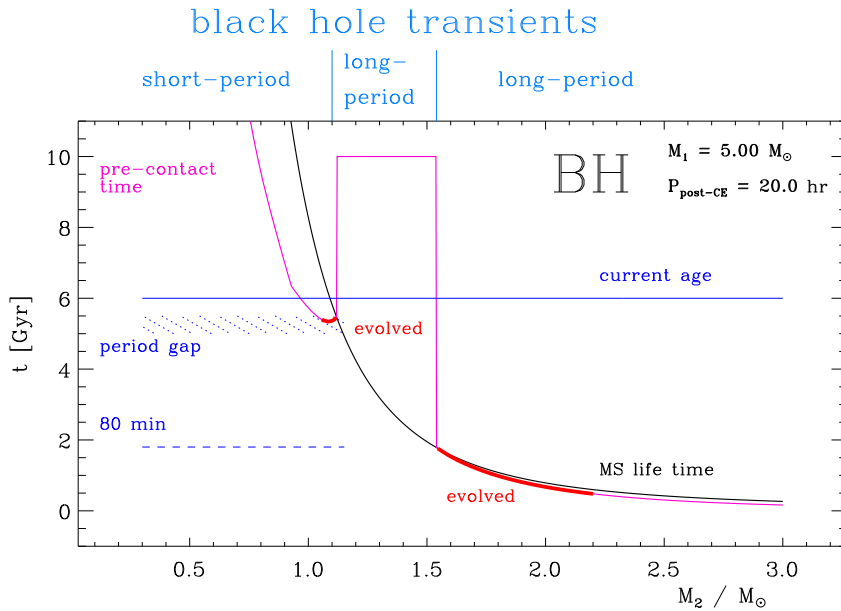

Figure 6.   Typical BH case within the BAP model: Systems coming into contact at the higher mass branch do not pass through a TTMT phase and form long-period LMXBs instead (see text for details).

in direct contrast to the older proposition 4. detailed in the Introduction. This possibility becomes even more pressing when we allow for the fact that white–dwarf and neutron–star binaries can survive a phase of thermal–timescale mass transfer (TTMT) in which $M_2 \gtrsim M_1$ (with M_1, M_2 the primary and secondary masses). For white dwarf systems the TTMT phase, at least in mild cases with M_2 not too large compared with M_1, is probably what drives many supersoft X–ray binaries. The realisation that some neutron–star systems, notably Cyg X–2, must have survived quite violent (highly super–Eddington) TTMT is relatively recent (King & Ritter, 1999; Podsiadlowski & Rappaport, 2000; King & Begelman, 1999). TTMT may be observable in systems such as SS433, and the ultraluminous X–ray sources recently identified in external galaxies (King, Taam & Begelman, 2000; King et al, 2001).

Figure 3 shows schematically how angular momentum loss and nuclear evolution may compete in bringing a compact binary into contact. For low (initial) secondary masses M_2 the nuclear evolution timescale is longer than the age of the Galaxy, so angular momentum loss automatically dominates. For large M_2 nuclear evolution is rapid, and wins over angular momentum loss. For intermediate secondary masses thermal–timescale mass transfer may occur if $M_2 \gtrsim M_1$, although this phase eventually becomes dynamically unstable (the 'delayed dynamical instability') for M_2 larger than some critical value $M_{2,\mathrm{DDI}}$. If some nuclear evolution has already occurred, this phase can shrink the binary drastically and strip the hydrogen–rich envelope from the donor, ultimately producing an ultrashort–period system with a low–mass, hydrogen–poor and probably degenerate secondary.

Figure 4 shows the situation for the specific case of CVs. The important result is that BAP hypothesis allows a numerous population of significantly nuclear–evolved CVs to coexist with the familiar unevolved CVs envisaged in the standard picture (cf assumptions 1 – 4 above). The accompanying paper (Schenker & King, this volume) considers this in more detail, and shows that the resulting distribution has several desirable properties, such as possibly explaining the spread in mass transfer rates above the CV period gap.

Figure 5 shows the situation for neutron–star LMXBs. This is qualitatively similar to the CV case. However the slower orbital decay here leads to a larger cutoff period P_0 (as noted earlier) and a much stronger tendency to nuclear evolution. Thus many systems evolve to long orbital periods (days), while as for CVs the short–period systems include many with significantly evolved secondaries. This agrees with the deduction by King, Kolb & Burderi (1996) that the neutron–star soft X–ray transients observed at such periods must have nuclear–evolved secondaries, as are now indeed observed in some cases (e.g. Haswell et al., 2000). As in the CV case, ultrashort–period neutron–star LMXBs may form after a TTMT phase.

The black–hole case is shown in Figure 6. The larger M_1 and consequently still slower orbital decay intensifies the trends towards larger P_0, more long–period systems, and a greater degree of chemical evolution in short–period systems noted for neutron stars. The major difference here is that the smaller mass ratio M_2/M_1 makes a TTMT phase unlikely. As a result very few ultrashort–period LMXBs with black hole primaries can form, at least by this channel. If as seems likely the faint transients discussed above are LMXBs with low–mass

highly–evolved secondaries, either already at ultrashort periods or evolving towards them, this offers a natural explanation for the observation that almost all of them appear to contain neutron stars.

A general point emerging from this discussion is that *short–period LMXBs are exceptional*: for most LMXBs nuclear evolution wins, leading to long orbital periods $\sim 10 - 100$ d. Ironically these systems spend almost all of their lifetimes as soft X–ray transients with enormously long recurrence times (cf Ritter & King, this volume), and thus remain undiscovered. The greater observational prominence of short–period systems results from their being either persistent X–ray sources (neutron–star plus unevolved secondary) or soft X–ray transients with fairly short recurrence times (all other short–period LMXBs).

4.   Conclusion

The BAP idea that even the first generation of CVs and LMXBs have yet to complete their evolution represents a radical break with the standard picture of CV and LMXB evolution. However it appears to have some promising aspects. Given the difficulties with the standard picture, it seems worthwhile to consider it further.

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