TRANSIENTS AMONG BINARIES WITH EVOLVED LOW–MASS COMPANIONS

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ABSTRACT

We show that stable disk accretion should be very rare among low–mass X–ray binaries and cataclysmic variables whose evolution is driven by the nuclear expansion of the secondary star on the first giant branch. Stable accretion is confined to neutron–star systems where the secondary is still relatively massive, and some supersoft white dwarf accretors. All other systems, including all black–hole systems, appear as soft X–ray transients or dwarf novae. All long–period neutron–star systems become transient well before most of the envelope mass is transferred, and remain transient until envelope exhaustion. This complicates attempts to compare the numbers of millisecond pulsars in the Galactic disk with their LMXB progenitors, and also means that the pulsar spin rates are fixed in systems which are transient rather than steady, contrary to common assumption. The long–period persistent sources Sco X–2, LMC X–2, Cyg X–2 and V395 Car must have minimum companion masses $M_2 \gtrsim 0.75 \mathrm{M}_{\odot}$ if they contain neutron stars, and still larger M_2 if they contain black holes. The neutron–star transient GRO J1744-2844 must have $M_2 \lesssim 0.87 \mathrm{M}_{\odot}$. The existence of any steady sources at all at long periods supports the ideas that (a) the accretion disks in many, if not all, LMXBs are strongly irradiated by the central source, and (b) mass transfer is thermally unstable in long–period supersoft X–ray sources.

Subject headings: accretion, accretion disks — binaries: close — black hole physics – instabilities

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1. INTRODUCTION

In a recent paper King, Kolb & Burderi (1996; hereafter KKB) considered the question of which low–mass X–ray binaries (LMXBs) should be transient according to the disk instability model. They concentrated mainly on systems with short orbital periods $P \lesssim 2$ d, showing in particular that neutron–star systems required secondaries which were somewhat nuclear–evolved before mass transfer began if they were to be transient, while this requirement is much weaker for black–hole systems, so that most are likely to be transient at these periods. The neutron–star result implies a significant constraint on LMXB formation, which is discussed further by King & Kolb (1997).

KKB also briefly discussed the occurrence of transients in longer–period LMXBs whose evolution is driven by the nuclear expansion of an evolved companion. They concluded that almost all of these systems should be transient (their equations 6 and 7). While this conclusion is essentially correct and in agreement with the observational data, the need for a more exact discussion of long–period transients has been thrown into sharper relief by the recent work of King et al. (1996). This shows that LMXBs with evolved companions are potentially subject to a violent instability arising from irradiation of the companion by the accreting primary. If unquenched this instability would lead to super–Eddington accretion rates and catastrophic evolution through a common–envelope phase to an ultrashort–period binary. Observed LMXBs with evolved companions must therefore be protected against the instability. King et al. (1996) identify two ways in which this can happen: first, the companion may be shielded from the irradiation by an extensive accretion disk corona or some similar structure. Second, and more commonly, the instability is quenched by the short duty cycles observed in soft X–ray transients.

Accordingly we examine here in more detail the possibility of transient behaviour in such systems. In particular we allow for the higher mass transfer rates implied by mass ratios close to unity, something neglected by KKB, but which can suppress transient behaviour. We assume throughout that the orbital periods are long enough ($P \gtrsim 1 - 2$ d) that nuclear–driven evolution always dominates over angular momentum loss by magnetic braking (cf KKB and Pylyser & Savonije 1988a, b). We restrict our discussion to systems with a secondary mass $\lesssim 2\mathrm{M}_\odot$ where the giant donor has a degenerate helium core and is well–established on the first giant branch. Hence our considerations (and those of KKB) do not apply to the black–hole transient GRO J1655-40. The optical observations of Orosz & Bailyn (1996) show that the companion star is not one of the low–mass giants considered here but is instead in a very short–lived evolutionary phase (crossing the Hertzsprung gap). Evidently this evolution does allow for phases of rather slow radius expansion, giving the low mass transfer rates required for transient behaviour, but a full evolutionary calculation is needed to check this.

2. CONDITION FOR A DISK INSTABILITY IN LMXBs

In this section we essentially follow the arguments of KKB and van Paradijs (1996), with a few refinements which we shall discuss explicitly. The condition for a disk instability can be summarized as the requirement that some part of the disk should have a temperature below the hydrogen ionization temperature $T_{\rm H} \sim 6500$ K. If a steady state exists in which all of the disk is above this temperature the instability will be suppressed. Since the effective temperature $T_{\rm eff}(R)$ in a steady–state accretion disk decreases outwards with distance R from the central accretor as $R^{-3/4}$ (cf eqn. 9 below) this suppression is hardest to achieve at the outer disk edge R_d, and the condition $T_{\rm eff}(R_d) > T_{\rm H}$ defines a minimum accretion rate $\dot M$ above which the disk will be steady. However in LMXBs, van Paradijs (1996) has emphasized the dominant importance of irradiation of the disk surface by the central accreting source, which produces an effective temperature $T_{\rm irr}$ given by

$$T_{\rm irr}^4 = \frac{\eta \dot M c^2 (1-\beta)}{4\pi\sigma R^2}\frac{H}{R}\left(\frac{{\rm d}\ln H}{{\rm d}\ln R} - 1\right) . \tag{1}$$

Here σ is the Stefan–Boltzmann constant, β the albedo of the disk surface, and $H(R)$ the local disk scale height. The factor η measures the efficiency of conversion of potential energy into irradiating flux. This necessarily absorbs a number of unknown factors of order unity which arise from e.g. limb darkening, the spectral energy distribution of the emergent flux, or the fact that the effective mass–radius relation of the accretor is not exactly known. Hence we do not distinguish between the neutron star and the black hole case and set $\eta = 0.11$ as in KKB. Any contribution to η from nuclear burning of the accreted matter is negligible (< 0.007) for a neutron star, but need not be for a white dwarf. The last pair of factors on the rhs are typically $\propto H/R \sim$ constant (see below). They represent $\sin\alpha$, where α is the very shallow angle between the incident radiation from the central point source and the disk surface, assuming small α, H/R and ${\rm d}H/{\rm d}R$.

From (1) we see that $T_{\rm irr}$ decreases only as $R^{-1/2}$, and so is likely to exceed $T_{\rm eff}$ at R_d. Accordingly we define a new (lower) critical accretion rate $\dot M_{\rm crit,\ irr}$ by the requirement

$$T_{\rm irr}(R_d) = T_{\rm H} . \tag{2}$$

To evaluate $\dot M_{\rm crit,\ irr}$ we assume that R_d is about 70% of the primary's Roche lobe radius R_1. Here we make the first refinement: in place of the Paczyński (1971) formula for the latter quantity, which introduces an awkward logarithmic dependence, we use instead the fact that for mass ratios $0.03 < M_2/M_1 < 1$ the ratio of primary and secondary Roche lobes can be approximated to better than 5% by

$$\frac{R_1}{R_2} = \left(\frac{M_1}{M_2}\right)^{0.45} . \tag{3}$$

We now assume that R_2 is equal to the thermal–equilibrium radius R_e of a (sub)giant of core mass M_c, using the approximate expression

$$R_e(M_c) = 12.55{\rm R}_\odot \left(\frac{M_c}{0.25{\rm M}_\odot}\right)^{5.1} , \tag{4}$$

(Webbink, Rappaport and Savonije 1983; King 1988). Combining (1 – 4) we find

$$\dot{M}_{\rm crit,\ irr} \simeq 3.81 \times 10^{-9} \left(\frac{M_1}{M_2}\right)^{0.9} \left(\frac{M_c}{0.25{\rm M}_\odot}\right)^{10.2} \left(\frac{{\rm d}\ln H}{{\rm d}\ln R} - 1\right)^{-1} {\rm M}_\odot\ {\rm yr}^{-1}\,, \tag{5}$$

where we have used $\beta = 0.9$ and $H/R = 0.2$, as in KKB. As long as the mass transfer rate $-\dot{M}_2$ is above the limit (5) disk accretion is always stable. Hence $-\dot{M}_2 < \dot{M}_{\rm crit,\ irr}$ is a necessary condition for a disk instability to occur.

We can compare (5) with the mass transfer rate driven by nuclear evolution

$$-\dot{M}_2 = 9.74 \times 10^{-9} (\zeta_e - \zeta_{\rm R})^{-1} \left(\frac{M_2}{{\rm M}_\odot}\right) \left(\frac{M_c}{0.25{\rm M}_\odot}\right)^{7.1} {\rm M}_\odot\ {\rm yr}^{-1}\ ; \tag{6}$$

obtained by requiring the stellar radius to move in step with the Roche lobe (see Webbink et al. 1983, or King 1988); here ζ_e is the thermal equilibrium mass–radius index (taken as zero in the two papers quoted) and $\zeta_{\rm R} \simeq 2M_2/M_1 - 5/3$ gives the corresponding Roche lobe motion. This is an improvement on equation (7) of KKB, which implicitly assumed $M_2 << M_1$ and thus took the factor $(\zeta_e - \zeta_{\rm R})^{-1}$ as constant. As we shall see, mass ratios $M_2/M_1 \gtrsim 0.7$ can raise $-\dot{M}_2$ significantly towards $\dot{M}_{\rm crit,\ irr}$.

We see from (5, 6) that $\dot{M}_{\rm crit,\ irr}$ increases faster with M_c than $-\dot{M}_2$. Thus disk accretion is unstable above a critical core mass

$$M_{c,{\rm crit}} = 0.338{\rm M}_\odot (\zeta_e - \zeta_{\rm R})^{-0.32} \left(\frac{M_2}{{\rm M}_\odot}\right)^{0.32} \left(\frac{M_1}{M_2}\right)^{-0.29} \left(\frac{{\rm d}\ln H}{{\rm d}\ln R} - 1\right)^{0.32}\,. \tag{7}$$

The critical core mass is plotted against M_2 in Figure 1, with $\zeta_e = -0.2$ (King et al. 1996) and $H \propto R^{9/7}, R^{9/8}$ (KKB) for a neutron star ($M_1 = 1.4{\rm M}_\odot$) and a black hole ($M_1 = 10{\rm M}_\odot$). We also show the evolutionary tracks $M_c \sim M_2^{-0.288} M_1^{-0.392}$ (cf King 1988). The companion star specified by a pair of values (M_2, M_c) on Fig. 1 would fill its Roche lobe in a binary of orbital period P given by

$$M_c = 0.23{\rm M}_\odot \left(\frac{P}{10\ {\rm d}}\right)^{0.13} \left(\frac{M_2}{{\rm M}_\odot}\right)^{0.065}\,. \tag{8}$$

As the dependence on M_2 is extremely weak we can regard P as given purely by M_c; we mark the corresponding P–values on the right–hand scale in Fig. 1. Mass transfer in systems with a $1.4{\rm M}_\odot$ neutron star and a giant donor with mass $\gtrsim 1{\rm M}_\odot$ is either dynamically or thermally unstable; such systems would not appear as LMXBs (cf. Kalogera & Webbink 1996). There is no such limit for systems with more massive black hole accretors, so that the lower panel of Fig. 1 could easily be extended up to $M_2 \simeq 2{\rm M}_\odot$ by obvious extrapolation of the curves shown.

The same donor mass limits apply to systems with asymptotic giant–branch donor stars. These binaries have very long orbital periods (several years) and a much more complicated mass loss history; the mass transfer rate is highly modulated by thermal pulses and the wind mass loss rate is substantial (e.g. Pastetter & Ritter 1989).

It is clear from Fig. 1 that all long–period black–hole LMXBs with donors on the first giant branch must be transient, as observed. We also see that in LMXBs with a neutron star primary, the disk can be stable if the companion mass is high enough, so that the system is close to thermally unstable mass transfer $((\zeta_e - \zeta_{\rm R}) \to 0)$. These two conclusions imply stringent constraints on the known persistent LMXBs with long orbital periods. These are currently Sco X–2 (P = 13.94 d, Southwell et al. 1996) LMC X–2 (P = 12.54 d), Cyg X–2 (P = 9.84 d), and V395 Car = 2S0921-630 (P = 9.01 d, e.g. Mason et al. 1987, although the claimed periodicity is disputed by Krzeminski & Kubiak 1991). As X–ray irradiation of both the accretion disc and the companion star must dominate the optical emission the precise nature of the companions is not easily deduced from observation. However, we know that they must be evolved stars, since they must fill the Roche lobe in a relatively wide binary. Thus the low–mass subgiant evolution considered here gives the lowest possible companion mass. In this case Figure 1 requires minimum companion masses $M_2 \gtrsim 0.75{\rm M}_\odot$ for all four systems. This latter value is consistent with Mason et al.'s mass function for V395 Car. If the secondary masses are close to this lower limit, all four systems must contain neutron stars rather than black holes (this is already suspected for Cyg X–2 as it has shown evidence of X–ray bursts). In GRO J1744-2844, the only known long–period neutron–star transient with accurately determined orbital period (P = 11.88 d), the small mass function $1.36 \times 10^{-4}{\rm M}_\odot$ found by Finger et al. (1996) and the low eccentricity strongly point to an evolved low–mass companion. From Fig. 1 we find a maximum secondary mass $M_2 \lesssim 0.75{\rm M}_\odot$ for the slope 9/7 ($0.87{\rm M}_\odot$ for 9/8). With $M_1 = 1.4{\rm M}_\odot$ and the above mass function this requires inclinations $i \gtrsim 7^\circ$ (9/7) and $\gtrsim 6^\circ$ (9/8), respectively.

Figure 1 shows that all low–mass neutron–star systems ultimately become transient as M_2 is reduced. As is well known, the endpoint of the binary evolution of such systems (when $M_2 = M_c$) is a millisecond radio pulsar in a wide ($\sim$ 100 d) orbit with a low–mass white dwarf, the remnant core of the (sub)giant companion after envelope exhaustion. Our result means that the spin rate of the pulsar at the end of the mass–transfer phase is determined by this transient phase, rather than in a system transferring mass steadily at the rate $-\dot{M}_2$, as is usually assumed. Combined with the prediction that all black–hole systems are transient, the prevalence of transients among neutron–star systems agrees with the fact that persistent systems are rather rare among long–period LMXBs (e.g. van Paradijs 1995).

From (6) we see that even with the most extreme assumptions ($M_2 \approx M_c \approx 0.15{\rm M}_\odot$, corresponding to short orbital periods $P \sim$ few days) the mass transfer rate in LMXBs with evolved secondaries is $\gtrsim 10^{-10}{\rm M}_\odot$ yr^{-1}. In transients essentially all of this mass must be accreted during outbursts. With typical transient duty cycles $\lesssim 10^{-2}$ it follows that the outburst accretion rates must be at least $10^{-8}{\rm M}_\odot$ yr^{-1}, i.e. at or above the Eddington limit for a $1.4{\rm M}_\odot$ neutron star. For larger M_c (longer orbital periods) or shorter duty cycles the rates are still higher. These predictions agree with observations of transient outbursts (e.g. V404 Cyg had a peak outburst luminosity $\sim 10^{39}$ erg s^{-1}, cf Tanaka & Lewin 1995; King 1993).

3. STABILITY OF UNIRRADIATED DISKS

The arguments above apply to disks where irradiation is dominant in determining the surface temperature of the disk. If irradiation does not act upon the disk surface, as e.g. in CVs, we must replace (1) by the standard effective temperature for a steady disk powered by local viscous dissipation (e.g. Frank, King & Raine 1992)

$$T_{\rm eff}^4 = \frac{3GM_1\dot{M}}{8\pi\sigma R^3} \ . \tag{9}$$

For mass transfer driven by nuclear evolution we follow the same steps as in Section 2, and find a new critical core mass (independent of the nature of the primary)

$$M_{\rm c,crit} = 0.097(\zeta_e - \zeta_{\rm R})^{-0.12}\left(\frac{M_1}{{\rm M}_\odot}\right)^{0.29}\left(\frac{M_2}{{\rm M}_\odot}\right)^{-0.04} \ . \tag{10}$$

The lowest value of M_c possible in the nuclear–driven evolution we are considering is $\sim 0.15{\rm M}_\odot$. Thus except for thermally unstable mass transfer $((\zeta_e - \zeta_{\rm R}) \longrightarrow 0)$, the critical value of M_c given by (10) is so small that we expect unirradiated disk accretion to be unstable in any system with an evolved low–mass companion.

Since white dwarfs cannot exceed the Chandrasekhar limit, mass transfer stability demands low–mass companions. We conclude that all long–period CVs should be dwarf novae, while the supersoft sources (thought to be undergoing thermal–timescale mass transfer, cf. e.g. DiStefano & Nelson 1996) can have stable disks. The only two known CVs at long enough orbital periods for our considerations to apply, namely V1017 Sgr ($P = 5.714$ d) and GK Per ($P = 1.997$ d) are both observed to have dwarf nova outbursts. For LMXBs we would conclude that unirradiated steady disks are impossible for long orbital periods. The fact that persistent systems are nevertheless observed at such periods (see Section 2) shows that irradiation must effectively determine the surface disk temperatures in these systems, and presumably most or all LMXBs.

4. CONCLUSIONS

We have shown that stable disk accretion is very rare among LMXBs and CVs with evolved companions on the first giant branch. Apart from a few systems (such as Sco X–1, cf KKB) with short enough orbital periods that magnetic braking dominates nuclear evolution, it is confined (at best) to the early part of neutron–star binary evolution, i.e. systems with quite large secondary masses M_2, and some of the supersoft white–dwarf X–ray sources. All long–period CVs and black–hole systems with donors on the first giant branch, as well as most neutron–star systems at these periods, have unstable disks and appear as dwarf novae or soft X–ray transients. These conclusions are in excellent agreement with observation, and strongly support the view (van Paradijs 1996) that X–ray irradiation determines the disk temperatures in most if not all LMXBs. Since the neutron–star transients will ultimately produce millisecond pulsars it is clear that any claims of possible discrepancies between the numbers of the latter and those of their LMXB progenitors (at least in the Galactic disk) must deal with the complex selection effects involved in the discovery of transients. Further, all millisecond pulsars in long–period detached binaries must have descended from transients, and this must be considered in trying to work out their spin histories.

Even when the stringent conditions (cf Fig. 1 and Section 2) for steady disk accretion are met, persistent LMXBs still have somehow to suppress the violent instability resulting from irradiation of an evolved companion (King et al. 1996). Since one cannot invoke transient behaviour (by definition), these systems must shield the companion from this radiation in some way, probably by means of an accretion disk corona. We note that the presence of such coronae is inferred in Cyg X–2 and V395 Car, and that indeed none of the persistent LMXBs where the period is known or suspected to be long is observed to have a clear star–by–star eclipse. This supports the idea that accretion disk coronae do not merely make it impossible to observe eclipsing sources, but are essential to the survival of the systems themselves.

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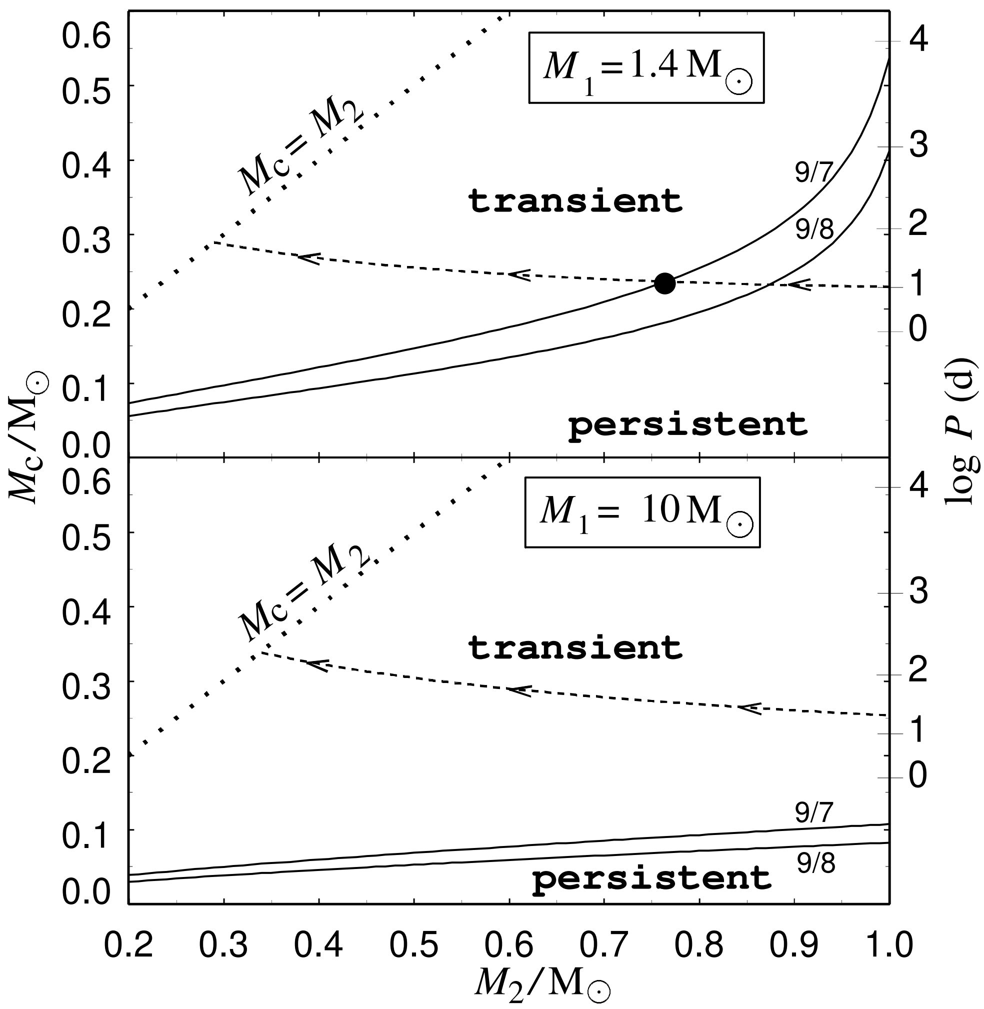

Fig. 1.— (*a*) The critical core mass vs total secondary mass for an LMXB with a $1.4\mathrm{M}_\odot$ neutron–star primary (see text for assumptions). The two solid curves give the boundaries between persistent and transient behaviour for disk scale heights varying as $H \propto R^{9/7}, R^{9/8}$ respectively. The scale on the right–hand axis gives the approximate binary period P at which the companion would fill its Roche lobe (cf equation (8) of the text). Also shown (dashed) is the track in the $M_c - M_2$ plane followed by a binary driven by nuclear expansion of the companion. This star has core and total masses $M_c(0) = 0.23\mathrm{M}_\odot$, $M_2(0) = 1.5\mathrm{M}_\odot$ at the start of mass transfer. The positions of Sco X–2, LMC X–2, Cyg X–2 and V395 Car corresponding to the minimum allowed secondary masses for persistent behaviour are all very close to the filled circle. The maximum secondary mass for the neutron–star transient GRO J1744-2844 is again close to $0.75\mathrm{M}_\odot$ (for slope 9/7), or close to $0.87\mathrm{M}_\odot$ (for slope 9/8). (*b*) As (*a*), but now for a $10\mathrm{M}_\odot$ black hole primary. All these systems are transient.