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BLACK HOLE BINARIES AND X-RAY TRANSIENTS

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ABSTRACT

We consider transient behavior in low-mass X-ray binaries (LMXBs). We show that if this results from a disk instability, the secondary star must be significantly evolved when mass transfer starts, particularly if the primary is a neutron star. For $P \lesssim 2$ days, most neutron star systems will be persistent X-ray sources, whereas the slower orbital evolution of black hole systems means that most of them are likely to be transient. Both types of transient system must have extreme mass ratios (<0.1). For orbital periods $P \gtrsim 2$ days, most LMXBs will be transient regardless of whether the primary is a neutron star or a black hole.

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

1. INTRODUCTION

In recent years, several soft X-ray transients (SXTs) have been found to have large mass functions, which strongly suggests that the accreting star is a black hole. The incidence of these black hole systems among SXTs with known orbital periods (eight of 14) is much greater than any likely estimate of their incidence among persistent low-mass X-ray binaries (LMXBs) (one of 29). Moreover, estimates of the mass of the secondary star in the black hole binaries consistently show that this star must be larger than its main-sequence radius if it is to fill its Roche lobe. In this Letter, we shall show that in the context of the disk instability model for SXTs (see, e.g., Cannizzo, Wheeler, & Ghosh 1982; Lin & Taam 1984), these facts are natural consequences of long-term LMXB evolution.

2. CONDITION FOR A DISK INSTABILITY

The essential ingredient of the disk instability model is the possibility that hydrogen can exist in either neutral or ionized states, depending on circumstances. If a steady state exists in which all of the disk is above the hydrogen ionization temperature $T_{\rm H} \sim 6500$ K, the instability will be suppressed, and the source will appear as persistent. As is well known, the effective temperature of a steady state accretion disk powered by local viscous dissipation is given by (see, e.g., Frank, King, & Raine 1992)

$$T_{\rm eff}^4 = \frac{3GM\dot{M}}{8\pi\sigma R^3} \quad (1)$$

at disk radii R much larger than that of the central object (M is the mass of this star, $\dot{M}$ is the accretion rate, G is the gravitational constant, and σ is the Stefan-Boltzmann constant). Since $T_{\rm eff}$ decreases as $R^{-3/4}$, the condition $T_{\rm eff} > T_{\rm H}$ for steady accretion is most stringent at the outer edge R_d of the disk. We define a critical accretion rate $\dot{M}_{\rm crit,\,eff}$ by the equation

$$T_{\rm eff}(R_d) = T_{\rm H}\,. \quad (2)$$

Thus the disk instability is suppressed for $\dot{M} > \dot{M}_{\rm crit}$, and we can try to discriminate between steady and outbursting systems by checking this condition.

When applied to calaclysmic variables (CVs), this procedure correctly predicts that all disk-accreting systems below the period gap should be dwarf novae (see § 3). Recently, van Paradijs (1996a, 1996b) has emphasized that LMXB disks are likely to be strongly influenced by irradiation from the central X-ray source and that this will raise their surface temperatures and tend to stabilize them at lower accretion rates. Specifically, irradiation produces an effective temperature given by

$$T_{\rm irr}^4 = \frac{\eta\dot{M}c^2(1-\beta)}{4\pi\sigma R^2}\left(\frac{dH}{dR} - \frac{H}{R}\right), \quad (3)$$

where η is the efficiency of rest-mass energy conversion into X-ray heating, β is the X-ray albedo, and $H(R)$ is the local disk scale height. Since the factor in parentheses is typically $\propto H/R \sim$ constant (see below), we see that $T_{\rm irr}^4$ falls off only as R^{-2} compared with R^{-3} for $T_{\rm eff}^4$. At the outer disk edge R_d, we then expect $T_{\rm irr} > T_{\rm eff}$, and we should define a new (lower) critical accretion rate $\dot{M}_{\rm crit,\,irr}$ by the requirement

$$T_{\rm irr}(R_d) = T_{\rm H} \quad (4)$$

rather than equation (2). To evaluate equations (2) and (4), we assume that R_d is about 70% of the primary's Roche lobe radius R_L, for which in the regime of interest ($M_1 > M_2$, with M_1, M_2 the primary and secondary masses), the approximation $R_L \simeq [0.38 - 0.2\log(M_2/M_1)]a$ (Paczyński 1971) holds. Here a is the binary separation. For typical mass ratios $M_2/M_1 \sim 0.1$, this gives $R_d \simeq 1.2 \times 10^{11} m_1^{1/3} P_d^{2/3}$ cm, where m_1 is the primary mass measured in $M_\odot$ and P_d is the binary period in days. For $T_{\rm irr}$, we need an estimate of $H(R)$: simple disk theory (see Vrtilek et al. 1990) shows that for an irradiated disk H lies between the two laws $H \propto R^{9/7}$, $H \propto R^{9/8}$, while $H/R \simeq 0.2$ and $\beta \simeq 0.9$ (de Jong, van Paradijs, & Augusteijn 1996, and references therein). Using these results and $\eta = 0.11$ in equations (2) and (4) gives

$$\dot{M}_{\rm crit,\,eff} \simeq 2.9 \times 10^{-9} P_3^2 \; M_\odot \;{\rm yr}^{-1}\,, \quad (5)$$

and

$$\dot{M}_{\rm crit,\,irr} = \dot{M}_{\rm irr} m_1^{2/3} P_3^{4/3}\,, \quad (6)$$

with $\dot{M}_{\rm irr} \simeq 5 \times 10^{-11}\; M_\odot\;{\rm yr}^{-1}$ and $P_3 = P/(3\;{\rm hr})$.

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3. LMXB EVOLUTION

From the reasoning above, we can decide whether a given LMXB evolutionary sequence is likely to produce transient systems simply by comparing its predicted mass transfer rates with $\dot{M}_{\rm crit,\,irr}$. It is generally accepted that the LMXB phase follows a common envelope episode; this leaves a detached system with a compact star (neutron star or black hole) and a low-mass main-sequence secondary star in an orbit with a typical period ~0.5–10 days.

The system reaches contact and becomes an LMXB under the influence of two processes: (1) nuclear expansion of the secondary (eventually off the main sequence), on a timescale $t_{\rm MS}$, and (2) shrinkage of the orbit on the angular momentum loss timescale $t_{\rm AML}$. We get three cases, depending on the relative size of the two timescales and the initial masses and binary separation (see Pylyser & Savonije 1988a, 1988b; Singer, Kolb, & Ritter 1993; Ritter 1994). (We consider only stable mass transfer in this Letter, generally assured for $M_2 \lesssim M_1$.)

Case 1. $t_{\rm MS} \ll t_{\rm AML}$.—The secondary has time to evolve off the main sequence before angular momentum losses shrink the Roche lobe sufficiently to cause mass transfer. The secondary evolves as a subgiant and transfers mass on its nuclear timescale $t_{\rm nuc}$, the binary evolving to longer periods (up to hundreds of days).

Case 2. $t_{\rm MS} \gg t_{\rm AML}$.—Angular momentum losses shrink the binary orbit too rapidly for significant nuclear evolution of the secondary before mass transfer starts. The binary evolves to short periods (hours) with the secondary essentially unevolved at all times.

Case 3. $t_{\rm MS} \sim t_{\rm AML}$.—The secondary is significantly evolved before mass transfer starts, but angular momentum losses shrink the binary orbit more rapidly than it expands. Once contact is established, further nuclear evolution of the secondary is frozen. The binary evolves to short periods as in case (2), but this time with a secondary that is significantly larger than its main-sequence radius.

In case (1), the entire structure of the secondary is controlled by the mass of its helium core, quite independently of the secondary's total mass M_2: a semianalytic description is available (Webbink, Rappaport & Savonije 1983) that can be used to show that (King 1988)

$$-\dot{M}_2 \simeq 4.0 \times 10^{-10} P_d^{0.93} m_2^{1.47}\ M_\odot\ {\rm yr}^{-1}\,, \qquad (7)$$

where m_2, P_d are M_2, P measured in $M_\odot$ and days, respectively. Comparison with equation (6) shows that, except possibly for rather massive secondary stars, the systems are likely to be transient. Since this evolution requires binary periods $\gtrsim$2 days and cases (2) and (3) have shorter periods, we can already predict that most LMXBs with periods $\gtrsim$2 days will be transient. We note that this conclusion is independent of whether the primary is a neutron star or a black hole. The observational data are sparse but are not in conflict with this conclusion, particularly when we take account of the obvious selection effect against finding transients (in a subsequent paper, we shall show that the recurrence times of long-period systems are probably so long that most will remain undiscovered).

Case (1) cannot supply the low values ($\lesssim$2 days) that characterize the majority of measured SXT periods. For these we must turn to the other two cases. Case (2) is familiar from CV evolution: the mass transfer rate is a function of the orbital period. Figure 1 shows evolutionary sequences calculated using a bipolytrope evolution code (Kolb & Ritter 1992) for various primary masses. For $M_1 = 1.4\ M_\odot$, the predicted transfer rate is well below $\dot{M}_{\rm crit,\,eff}$ for systems below the period gap ($P < 2$ hr), showing that disk instabilities can occur at these periods. This agrees with the observation that all nonmagnetic CVs at these periods are dwarf novae. As is well known, the situation is much less clear above the period gap, since $\dot{M}_{\rm crit,\,eff}$ is very close to the predicted transfer rate; this is slightly higher than for the LMXB case shown as the typical primary mass in CVs is smaller (see, e.g., Kolb 1996).

If irradiation is allowed, as appropriate in LMXBs, we see immediately that all these systems are likely to be steady. We thus reach another conclusion: short-period LMXBs contain-

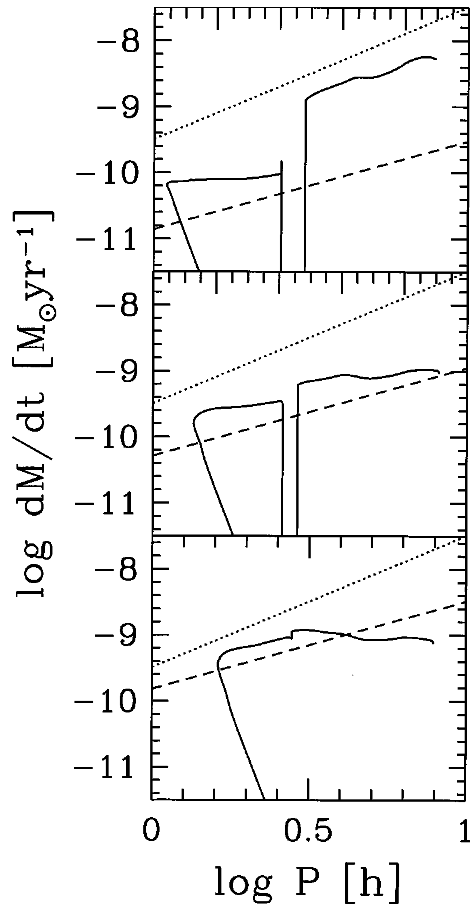

FIG. 1.—Mass transfer rate $\dot{M}$ vs. orbital period P for LMXBs with various primary masses and an unevolved secondary of initial mass 1 $M_\odot$. Magnetic braking according to eq. (9) is assumed to operate only as long as the secondary has a radiative core. The dotted and dashed lines are the critical mass transfer rates eqs. (5) and (6) for standard and irradiated disks, respectively. Systems with lower mass transfer rates have thermally unstable accretion disks and are transient. *Top panel*: 1.4 $M_\odot$ neutron star primary. A detached phase occurs when the secondary becomes fully convective, followed by the resumption of mass transfer below the period gap. For CVs with a typical primary mass $\simeq 0.6\ M_\odot$, the mass transfer rate above the period gap is $\simeq$1.8 times higher than shown and is therefore very close to the classical instability line (see, e.g., Kolb 1996). *Middle panel*: 10 $M_\odot$ BH primary. The mass transfer rate is below the standard stability limit eq. (5) but above the limit for an irradiated disk, i.e., the system is stable at all periods. *Bottom panel*: unphysically massive 50 $M_\odot$ BH primary. Mass transfer via magnetic braking is reduced and that via gravitational radiation is increased, so the period gap disappears, and the minimum period is longer than for lower primary masses.

ing neutron stars and main-sequence secondaries are likely to be persistent rather than transient.

In contrast to the nuclear evolution case (1), the mass transfer rate in case (2) is quite sensitive to the primary mass M_1. First, larger M_1 raises the orbital angular momentum of the binary as $J \propto M_1^{2/3}$ for $M_1 \gg M_2$: if the angular momentum loss rate $\dot{J}$ is independent of M_1 (as is the case for, e.g., magnetic stellar wind braking), the transfer rate is reduced as $-\dot{M}_2 \propto M_2^{-2/3}$, since

$$-\frac{\dot{M}_2}{M_2} \sim -\frac{\dot{J}}{J} \quad (8)$$

(see, e.g., King 1988). On the other hand, we know that angular momentum loss via gravitational radiation actually increases, with $-\dot{M}_2 \propto M_1^{2/3}$ (see eq. [9], below). Since magnetic braking dominates for periods above the gap, where most LMXBs are found, the net effect is to reduce the predicted transfer rates but to flatten the curve of $-\dot{M}_2$ versus P at shorter orbital periods, where gravitational radiation becomes more important. This can be seen in Figure 1 (*middle panel*), with $M_1 = 10\ M_\odot$. The smaller contrast between the angular momentum losses above and below the period gap means that the latter is narrower, and indeed the minimum period is longer. (For sufficiently high M_1, the gap actually disappears altogether; see Fig. 1 [*bottom panel*], where M_1 is an unrealistically high 50 $M_\odot$.) Mukai (1994) proposed that the reduced transfer rates for $M_1 = 10\ M_\odot$ were responsible for the prevalence of black hole systems among SXTs: however, while $-\dot{M}_2$ is indeed reduced below $\dot{M}_{\rm crit,\,eff}$, disk instabilities are still forbidden by irradiation, i.e., $-\dot{M}_2 > \dot{M}_{\rm crit,\,irr}$. We have to extend our conclusion that LMXBs with main-sequence secondaries are likely to be persistent rather than transient to the black hole case also.

Thus, to explain the occurrence of SXTs at periods $\lesssim$2 days, we are forced to consider case (3). The main difference between this and case (2) immediately above is that the secondary has a lower mass for a given orbital period, i.e., $M_2 < M_2({\rm MS})$, where $M_2({\rm MS}) \simeq 0.33 P_3\ M_\odot$ is the mass of a main-sequence star that would just fill the Roche lobe at the current period. Simple scaling suggests that this effect significantly lowers the expected transfer rates. Using the form of Verbunt & Zwaan (1981) for the magnetic braking rate, with the radius of gyration set to $(0.2)^{1/2}$ and the calibration parameter to unity, and the standard form (see, e.g., Landau & Lifschitz 1958) for the gravitational radiation losses, the mass transfer rate is

$$-\dot{M}_2 = \dot{M}_{\rm MB} m_1^{-2/3} \hat{m}_2^{7/3} P_3^{5/3} + \dot{M}_{\rm GR} m_1^{2/3} \hat{m}_2^2 P_3^{-2/3}, \quad (9)$$

with $\hat{m}_2 = M_2/M_2({\rm MS})$, $\dot{M}_{\rm MB} \simeq 2 \times 10^{-9}\ M_\odot\ {\rm yr}^{-1}$, and $\dot{M}_{\rm GR} \simeq 7.6 \times 10^{-11}\ M_\odot\ {\rm yr}^{-1}$, and we have assumed $M_1 \gg M_2$. For neutron star primaries ($m_1 \simeq 1.4$), even quite evolved secondary stars still give rather high transfer rates, driven essentially by the magnetic braking term above; for example, $\hat{m}_2 \simeq 0.6$ implies $-\dot{M}_2 = 10^{-8}\ M_\odot\ {\rm yr}^{-1}$ for the period $P = 18$ hr of Sco X-1. However for black hole primaries ($m_1 \sim 10$), it appears possible to arrange $-\dot{M}_2 < \dot{M}_{\rm crit,\,irr}$, as required for SXT behavior, if M_2 is significantly below the main-sequence mass. Figure 2 shows the result of a computation using a full stellar evolution code (Mazzitelli 1989, adapted to treat binary evolution by Kolb & Ritter 1992), which confirms this impression. We can get a simple analytic representation of this by combining equations (6) and

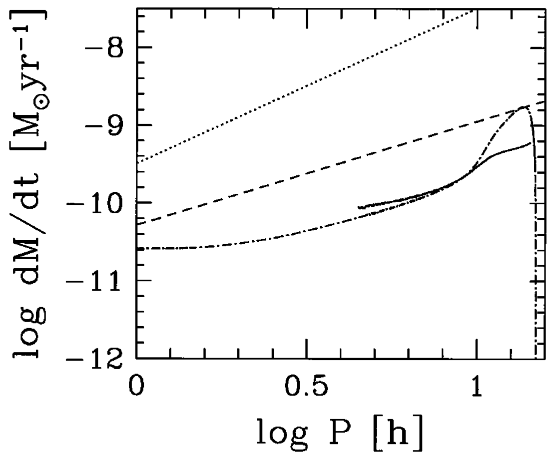

FIG. 2.—Mass transfer rate $\dot{M}$ vs. orbital period P for a 10 $M_\odot$ BH binary with a slightly evolved secondary. At the onset of mass transfer, the 1.2 $M_\odot$ secondary was close to the end of central hydrogen burning (central H mass fraction 2%). Also shown as a dash-dotted curve is the corresponding track for a CV with 1 $M_\odot$ white dwarf primary, taken from Singer et al. (1993). For a better comparison, the CV track was shifted downward in log $\dot{M}$ [$M_\odot$ yr^{-1}] by 2/3 to compensate for the less massive primary, as eq. (9) suggests. For short orbital periods, the BH mass transfer rate is above the rescaled CV transfer rate since gravitational radiation begins to dominate over magnetic braking. The secondary never becomes fully convective, so there is no detached phase. The disk instability lines eqs. (5) and (6) are again shown as dotted and dashed lines; see Fig. 1. The system is always transient.

(9), obtaining an expression for the minimum primary mass required for SXT behavior:

$$M_1({\rm min,\ SXT}) = \frac{M_{\rm min} \hat{m}_2^{7/4} P_3^{1/4}}{(1 - h \hat{m}_2^2 P_3^{-2})^{3/4}}, \quad (10)$$

where $M_{\rm min} = (\dot{M}_{\rm MB}/\dot{M}_{\rm irr})^{3/4}\ M_\odot \simeq 16\ M_\odot$ and $h = \dot{M}_{\rm GR}/\dot{M}_{\rm irr} \simeq 1.52$. Clearly, SXT behavior is impossible for any primary mass unless the denominator in equation (10) is positive, i.e.,

$$\hat{m}_2 \lesssim k P_3 \quad ({\rm GR\ alone}), \quad (11)$$

where $k = (\dot{M}_{\rm irr}/\dot{M}_{\rm GR})^{1/2} \simeq 0.81$, which is simply the requirement that the mass transfer rate driven by GR alone must certainly be less than the critical rate. If the GR rate is well below this value, the second term in the denominator of equation (10) is negligible, and magnetic braking gives the requirement

$$M_1 > M_1({\rm min,\ SXT}) \simeq 16\ M_\odot \hat{m}_2^{7/4} P_3^{1/4} \quad ({\rm MB\ alone}). \quad (12)$$

Clearly *both* the requirements equations (11) and (12) must hold for SXT behavior, and indeed the true condition equation (10) is stronger than either. For example, the SXT UY Vol (= 0748−676) has a neutron star primary, since it shows X-ray bursts. With $M_1 = 1.4\ M_\odot$ and $P = 3.82$ hr, we find $M_2/M_2({\rm MS}) < 0.235$ from equation (10).

4. CONCLUSIONS

We can summarize our conclusions in Table 1. As can be seen, evolved secondaries are required for SXT behavior, except possibly for some fairly massive black hole systems. Clearly, the combination of a black hole and an evolved secondary is strongly favored, in agreement with observation. However, we need to explain not only why black holes are common among SXTs but also why they are far more common (eight of 14) among transient than persistent LMXBs (one of

TABLE 1

SXTs among LMXBs

	Primary	
Secondary	Neutron Star	Black Hole
Main sequence	All persistent	Persistent/some SXTs?
Evolved	Persistent/SXTs	All SXTs

29); see King et al. (1996) or McClintock (1996). Table 1 shows that this must mean that sufficiently evolved companions are more common in black hole than in neutron star systems. There is an obvious explanation for this: in the precontact phase (see § 3), the orbital evolution time $t_{\rm AML}$ of black hole systems is significantly longer (by a factor $m_1^{2/3} \sim 4$) than for neutron star systems, for the same reason that the postcontact mass transfer rate is lower for black holes, i.e., that $(\dot{J}/J)_{\rm MB}$ is smaller (see the first term of eq. [9]). The secondaries in black hole systems have on average 4 times as long to evolve along or off the main sequence before there is any possibility of their being driven to short periods by angular momentum losses. Yet equation (10) requires that the secondaries in neutron star systems should be significantly *more* evolved ($\hat{m}_2 \lesssim 0.25$) than in black hole systems ($\hat{m}_2 \lesssim 0.75$) for SXT behavior to occur. Thus, for similar initial separations, a considerably smaller fraction of neutron star than black hole binaries will become SXTs. Of course, a full population synthesis will be required to demonstrate that this conclusion is quantitatively as well as qualitatively valid. A further consequence of the low value of $\hat{m}_2$ in neutron star SXTs is that the mass ratio must be very small in both types of transient: for $P \lesssim 2$ days, we have $M_2/M_1 \simeq 0.33 P_3 \hat{m}_2/m_1$, giving $M_2/M_1 \lesssim 0.059 P_3$ and $M_2/M_2 \lesssim 0.025\ P_3$ for neutron star transients with $M_1 = 1.4\ M_\odot$ and black hole systems with $M_1 = 10\ M_\odot$, respectively. Such extreme mass ratios are a ubiquitous feature of observed SXTs, which lends support to the picture presented here.

We conclude that soft X-ray transient events probably result from accretion disk instabilities. In line with this, King & Ritter (1996) find outburst and recurrence times of SXTs in good accord with those expected from simple extrapolations from dwarf nova outbursts, provided that due account is taken of the larger disk size in SXTs. The arguments presented here show that the high incidence of black hole identifications in SXTs given by dynamical mass estimates directly reflects the underlying population rather than observational selection.

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