THE EVOLUTIONARY HISTORY OF X-RAY BINARIES

E.P.J. van den Heuvel* and G.J. Savonije
Astronomical Institute,
University of Amsterdam, the Netherlands.

*Also at the Astrophysical Institute, Vrije Universiteit, Brussels.

1. SUMMARY AND INTRODUCTION

The most important recent observational discoveries in the field of X-ray binaries are probably those of the slow pulsars and of the winds of normal early-type main-sequence stars. These facts yield key information on the evolutionary history of the X-ray binaries and on the rotational slow-down mechanism for a neutron star in a stellar wind, as will be pointed out in section 3. In the theoretical field, the X-ray binaries have triggered much fundamental work, notably on the detailed processes of mass transfer and on tidal evolution, which will be considered in sections 2, 4 and 5.

2. MASS TRANSFER MECHANISMS IN X-RAY BINARIES

The X-ray binaries can be divided into the massive ones like Cen X-3, Cyg X-1, and the low-mass ones like Her X-1 and Sco X-1. The principal physical cause of this division is thought to be a difference in the type of mass transfer, viz. "stellar wind" vs. "Roche-lobe overflow" (cf. van den Heuvel 1975, however, see also section 4). Roche-lobe overflow from the more massive to the less massive component ("first type of Roche-lobe overflow") takes place roughly on a thermal timescale of the envelope of the normal star, yielding an accretion rate of about

$$\dot{M}_a = 2.6 \times 10^{-8} M_1^{\ 3} \quad [M_\odot/yr] \tag{1}$$

where M_1 is the mass of the normal component (cf. van den Heuvel 1977). For $M_1 \gtrsim 2\, M_\odot$ equation (1) yields $\dot{M}_a > 10^{-7} M_\odot/yr$ and any X-rays from the companion are expected to be suffocated. (The critical rate for spherical accretion onto a neutron star is about $1.5 \times 10^{-8} M_\odot/yr$. In case of non-spherical accretion this rate may perhaps be exceeded by an order of magnitude (cf. McCray 1977)). It is also possible that the star which overflows its lobe is less massive than its compact companion ("second type of Roche-lobe overflow"). In that case the transfer will for $M_1 \lesssim 2.5\, M_\odot$ take place on a nuclear timescale, yielding a transfer rate

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some 300 times smaller than for the first type of Roche-lobe overflow. This may possibly power the globular cluster X-ray sources, as globular clusters do not contain normal stars more massive than about 0.9 $M_\odot$, and the two known masses of neutron stars are 1.3 $M_\odot$ and 1.6 $M_\odot$ (Avni 1977). In such systems also the emission of gravitational waves may partly be driving the mass transfer (Chau and Lauterborn 1976).

2.1. Refined considerations about Roche-lobe overflow

The masses of the normal star and the neutron star in the Her X-1 system are about 2.0 $M_\odot$ and 1.3 $M_\odot$ respectively (cf. Avni 1977). Nevertheless, the observed X-ray luminosity of Her X-1 suggests a mass transfer rate of only 10^{-9} $M_\odot$/yr, i.e. about two orders of magnitude smaller than expected from equation (1). Pratt and Strittmatter (1976, here abbreviated as PS) suggested that, in order to explain this discrepancy the "classical" assumptions of co-rotation and of conservation of orbital angular momentum of the system during the mass exchange, should be abandoned. Indeed, for stars with radiative envelopes the timescale for tidal re-synchronisation might be much longer than the thermal timescale which governs the mass transfer (cf. Lecar et al. 1976). PS therefore used the following refined assumptions: (1) conservation of total mass and total angular momentum of the system; (2) at the onset of the mass transfer the primary star co-rotates with the orbital motion; (3) a fraction s of the angular momentum of a transferred mass element goes to the secondary and the fraction (1-s) is directly converted into orbital angular momentum; (4) no tidal torques spin up the primary during the mass transfer. Further, they adopt circular orbits and Roche geometry. With these assumptions the mass transfer causes the rotation of the primary star to slow down, as a mass element lost from the first Lagrangian point has a much larger specific angular momentum than the primary star as a whole. PS assume s=0 which seems reasonable for disk accretion onto the secondary star. The resulting decrease of the centrifugal acceleration causes the Roche lobe to shrink much slower (or at first: even increase slightly) than with the classical assumptions. Consequently, for some time the radius of the star may be able to adapt to changes of the Roche lobe by transferring mass at a very low rate. For a system with components $M_1 = 1.5\, M_\odot$, $M_2 = M_\odot$, $P = 0.7$ days, PS find that for some 1.8×10^8 yrs after the onset of Roche-lobe overflow the primary star transfers mass at a rate of only $\sim 4 \times 10^{-10}\, M_\odot$/yr (whereas eq. (1) would have yielded $\sim 10^{-7}\, M_\odot$/yr). This timescale is a semi-nuclear one, which is due to the fact that, at the onset of the mass transfer, the primary star was still in the hydrogen-burning stage, with its radius expanding on a nuclear timescale (so-called case A mass transfer). Three remarks can be made about PS's computations: (i) they may apply to X-ray binaries such as Sco X-1 and Cyg X-2, which both have periods around 0.8 days (cf. Hutchings 1977); (ii) they will not apply to Her X-1, since this system is so wide ($P = 1.7$ d) that, in order to fill its Roche-lobe, the primary star must be in its post main-sequence stage of envelope expansion. Hence, here the slow transfer is expected to take place on a semi-thermal timescale; (iii) since tidal synchronisation occurs on timescales of order 10^6 yrs (cf. Zahn 1976) the neglect of tidal torques

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is not justified if transfer timescales $\gtrsim 10^6$ yr are involved. The points (ii) and (iii) led Savonije (1977) to make computations for the early stages of Roche-lobe overflow in a system with $M_1 = 2\,M_\odot$, $M_2 = M_\odot$, P=1.7 d, under various assumptions, as follows: (a) "classical"; (b) PS's assumptions; (c) assumptions (1) - (3) of PS, but taking tidal spin-up of the primary star into account (for stars with convective envelopes he used eddy viscosity; for stars with radiative envelopes: shear turbulence friction in the tidal bulge, cf. section 5); (d) the same as (c), but with half of the transferred mass leaving the system, carrying a specific orbital angular momentum of twice that of the(less massive) neutron star.

Figure 1 depicts the results. The figure shows that the assumptions (a) and (b) represent extremes, causing $\dot{M}_{ac}$ to reach the Eddington limit 4×10^4 yrs and 2.3×10^6 yrs after the onset of the overflow, respectively. For (c) and (d), which seem the most realistic assumptions, the Eddington limit is reached in about 4×10^5 yrs. Similar calculations for systems with other primary masses (in case A as well as B, and compact secondaries $\lesssim 1.5\,M_\odot$) show that for $M_1 \gtrsim 3\,M_\odot$ the duration of the slow stage of mass transfer is generally negligible (however, see Savonije 1977).

3. EVOLUTIONARY INFORMATION DERIVED FROM THE SLOW PULSARS

Table 1 lists the presently known pulsating X-ray sources and their optical counterparts (cf. Davison 1977). Two or three slow pulsars are associated with peculiar B0 emission stars, in particular X Persei (cf. Maraschi et al. 1976; Stier and Liller 1976). The progenitors of the neutron stars in massive X-ray binaries were helium stars (cf. section 4). Tidal torques on helium stars in close binaries are negligible (Savonije and van den Heuvel 1977) and the rotational evolution of these stars proceeds as for single stars. Consequently, the core collapse will

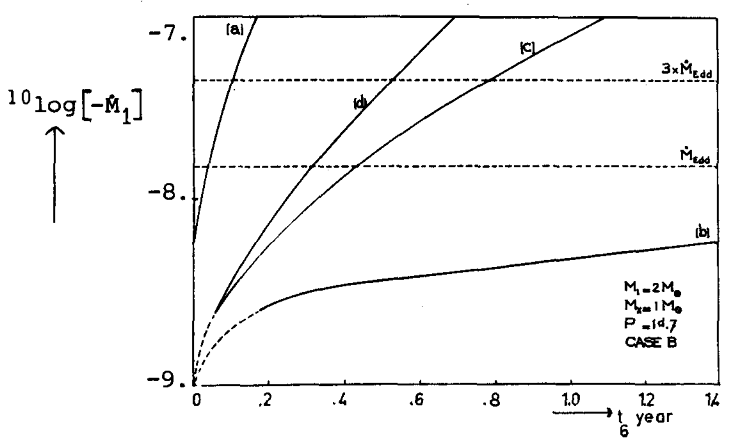

Figure 1. Rate of mass transfer (in $M_\odot$ yr^{-1}) vs. the time since the onset of Roche-lobe overflow (in 10^6 yrs) for a system similar to Hercules X-1. Curves (a) - (d) refer to the various assumptions described in the text.

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Name	P_{pulse} (sec)	L_x (ergs/sec)	Spectrum of Companion
Her X-1	1.24	$\sim 10^{38}$	F (HZ Her)
Cen X-3	4.84	$\sim 10^{38}$	O 6.5 III (Krzminski's star)
SMC X-1	0.71	$\sim 10^{39}$	B0 Ia (Sdk 160)
3U0352+30	835	$5\ 10^{33}$	O 9.5 pe (X Per)
A0535+26	104	Transient	B0e
3U0900-40	283	$\sim 10^{37}$	B 0.5 Ia (HD77581)
A1118-61	405	Transient	B0pe
3U1223-62	697	$\sim 10^{37}$	B 1.5 Ia (Wra 977)
3U1727-33	490 (or 73?)	$\sim 10^{37}$	A 0 Ia (CD - 33° 12119)?
3U1728-24	138-122	?	--
3U1813-14	1914	?	--

Table 1. The pulsating X-ray sources (references: cf. Davison 1977).

produce a rapidly rotating neutron star. The association of some of the slow pulsars with B0 emission stars ($M \sim 20\ M_\odot$) in or close to the main sequence indicates that these pulsars have ages of less than $\sim 5 \times 10^6$ yrs. In order to slow down the rotation from $P \lesssim 0.1$ sec to ≥ 100 sec in this time, the characteristic timescale for (exponential) slow down t_{sd} should be $\lesssim 6 \times 10^5$ yrs.

3.1. Proposed slow-down mechanisms

(i) The propellor mechanism (Illarionov and Sunyaev 1975) yields spin down timescales of 10^7 - 10^8 yrs, even if very strong winds of $\dot{M}_w \sim 10^{-7} M_\odot$/yr are adopted during the entire main-sequence life of the companion (Wickramasinghe and Whelan 1975). Recent UV observations show, however, that normal and emission-line main-sequence stars around B0 have only weak stellar winds ($\dot{M}_w \sim 10^{-8.5} M_\odot$/yr; $v_w \sim 1000$ km/sec, cf. Rogerson and Lamers 1975; Snow and Marlborough 1975). Hence, the propellor mechanism cannot be responsible for the observed rapid spin down.
(ii) Kundt (1976) showed that for a neutron star spinning in a stellar wind very large electromagnetic friction on the magnetosphere is to be expected as soon as the infalling wind matter is able to penetrate inside the velocity of light cylinder. This occurs for spin periods around one second for the above quoted wind strength for a B0 main-sequence star. Already for such a (weak) wind, Kundt's equations yield a very satisfactory spin-down timescale of only about 3×10^5 yrs for a neutron star with $P = 1$ sec, $B_s = 10^{12}$gauss, at a distance of 10^{12} cm from the star.

The spin-down terminates when the pulsar has reached the equilibrium spin rate at which the co-rotation velocity at the magnetospheric boundary equals the Keplerian velocity around the neutron star (Davidson

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and Ostriker 1973). This equilibrium period is given by (cf. Wickramasinghe and Whelan 1975):

$$P_{eq} = 30(B_s/10^{12}\text{gauss})^{6/7}(1.5\ 10^{-11}M_\odot/\text{yr}/\dot{M}_{ac})^{3/7}(M_\odot/M_n)^{5/7}\ \text{sec} \qquad (2)$$

where M_n is the mass of the neutron star and B_s its surface magnetic field strength. Computing $\dot{M}_{ac}$ from the above quoted wind parameters for a B0 main-sequence star, with $B_s = 10^{12}$ gauss, $a = 50\ R_\odot$ (as for 3U0900-40) one obtains $P_{eq} = 167$ sec. With $\dot{M}_w = 10^{-9}\ M_\odot$/yr one obtains 277 sec. These periods agree excellently with the spin periods of the slow pulsars. An exceptional case is 3U0900-40; here the $\dot{M}_{ac}$ value of 10^{-10} to 10^{-9} $M_\odot$/yr derived from its present X-ray luminosity yields $P_{eq} \sim 3.5$ to 9.4 sec (with $M_n = 1.6\ M_\odot$), implying that this source was spun down in a much weaker wind than the one presently observed for its companion (Wickramasinghe and Whelan 1975). On the other hand, for Cen X-3 and SMC X-1 the $\dot{M}_{ac}$-values of $10^{-9}\ M_\odot$/yr and $10^{-7.5}\ M_\odot$/yr, respectively, as derived from their X-ray luminosities yield $P_{eq} = 3.5$ sec and 1.1 sec, respectively. As B_s and M_n may be slightly different from the adopted values, these sources are therefore most probably spinning at their equilibrium rates.

From the equations given by Fabian (1975) and Fabian and Pringle (1976) one expects 3U0900-40 to spin up to $P = 60$ sec in about 2×10^4 yrs if $v_w = 400$ km/sec; for $v_w = 300$ km/sec this time is 7×10^3 and for $v_w = 200$ km/sec: 400 yrs. Also 3U1223-62 is expected to show a rapid spin-up. Indeed, the period of the latter source deceased by 5 seconds in 200 days (Swank et al. 1976; Davison 1977). An even faster spin-up has been observed for 3U1728-24: here the pulse period decreased from 136 seconds in 1971 to 122 seconds in 1975 (Becker et al. 1976).

4. REFINEMENTS IN THE EVOLUTIONARY SCENARIO OF MASSIVE X-RAY BINARIES

4.1. Effects of mass loss

In the scenario the compact star is the remnant of an evolved helium star which was the core of the original primary star, left after the first stage of mass exchange in a massive close binary (van den Heuvel and Heise 1972; Tutukov and Yungelson 1973). Such helium stars are thought to be identified with Wolf-Rayet (WR) stars and the direct progenitors of X-ray binaries are therefore thought to be WR binaries (van den Heuvel 1973). The scenarios presented so far are "conservative", i.e. mass and orbital angular momentum are assumed to have been conserved during the first stage of mass transfer (cf. De Loore et al. 1975).

Recent computations by Ulrich and Burger (1976), Flannery and Ulrich (1976) and Kippenhahn and Meijer-Hofmeister (1976) showed that in normal close binaries with mass ratios $\lesssim 0.6$-0.7 the secondary swells up as a result of the mass accretion and soon overfills its Roche-lobe. Consequently, loss of mass and angular momentum from the system is expected, as was already suggested by Meijer-Hofmeister (1974). One therefore expects that the normal components of WR binaries will have smaller masses than expected on the basis of conservative evolution. The same is expected for the normal components

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of the X-ray binaries. Also, the binary periods are expected to be shorter than with conservative evolution, due to the angular momentum lost with the matter.

For a representative WR binary such as V 444 Cygni (WN6+B1) with component masses of 9.5 $M_\odot$ + 24.1 $M_\odot$ and P = 4.2 days (Kuhi 1973) this may imply a progenitor system of about 28 $M_\odot$ + 20 $M_\odot$ (in stead of 28 $M_\odot$ + 5.3 $M_\odot$ in the conservative case).

Furthermore, main-sequence stars with masses > 25-30 $M_\odot$ are observed to lose mass by stellar wind at a high rate ($\sim 5.10^{-6} M_\odot$/yr for the 40-50 $M_\odot$ star ζPup, Lamers and Morton 1976). So, the progenitor of V444Cyg may perhaps have started out as 40 $M_\odot$ + 25 $M_\odot$, having been reduced to 28 $M_\odot$ + 20 $M_\odot$ at the onset of the first stage of mass transfer, and to 10 $M_\odot$ + 24 $M_\odot$ after the first stage of transfer. Consequently, WR binaries and massive X-ray binaries may have descended from systems that were originally more than twice as massive.

This mass loss is expected to have considerable quantitative effects on the predicted masses and periods of WR binaries and massive X-ray binaries. However, the general qualitative outline of the evolutionary scenario seems not greatly affected.

4.2. Overluminosity and evolutionary status of the primaries of massive X-ray binaries

In comparing the positions of the normal components of massive X-ray binaries with evolutionary tracks of massive stars (without mass loss) it has been noticed that Krzminski's star (Cen X-3), Sdk 160 (SMC X-1) and HD77581 (3U0900-40) fit to tracks of stars of about 30 $M_\odot$ to 40 $M_\odot$, whereas the actual masses of these stars, derived from the X-ray Doppler orbits are only around 20 $M_\odot$ (cf. Conti 1976, Hutchings 1976a; Ziolkowski 1976). A similar overluminosity (or undermassiveness) was found by Conti (1976a) and Hutchings (1976b) for components of many luminous early-type binaries. To explain this phenomenon, Ziolkowski (1976) has suggested that the primaries of some of the X-ray binaries resemble the remnants of case A mass transfer, i.e. are stars that underwent mass loss after having burnt part of the hydrogen in their cores. Such remnants, which are still burning hydrogen will resemble overluminous giant stars. He showed that with Y_{He} = 0.8 to 0.9, in a core containing two thirds of the mass of an 18 $M_\odot$ star, the observed overluminosity of Krzminski's star can be explained.

The overluminosity is due to the large relative mass of the helium-rich core. Ziolkowski suggested that stellar winds during the hydrogen burning stage ($\sim 5 \times 10^{-6} M_\odot$/yr as observed in ζPup, see above) were the cause of the mass loss. This suggestion seems beautifully confirmed by computations by De Loore et al. (1976) (made in order to check Conti's (1976b) suggestions about the evolutionary history of Of and WR stars) of evolutionary tracks of massive stars with mass loss by radiation-pressure-driven stellar winds. The mass loss was assumed to start on the ZAMS and to be driven by 300 absorption lines (cf. Castor et al. 1975). Here the hydrogen-burning tracks become more horizontal and extend much further to the right in the HR diagram than without mass loss, and the stars become gradually more and more overluminous. De Loore et al. find that a star of initially 40 $M_\odot$ is reduced to 23 $M_\odot$ at the end of its

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hydrogen burning; at that moment its luminosity is equal to that of a $32\,M_{\odot}$ star that evolved without mass loss.

An important point, noticed by Ziolkowski is that the radii of these hydrogen-burning models do not increase much if mass is lost. Therefore, Cen X-3 may be in a slow stage of Roche-lobe overflow; this is probably not the case in the wide systems of Cyg X-1 and 3U0900-40, where the supergiants are more likely to be in the stage of helium burning.

5. TIDAL EVOLUTION

The very small orbital eccentricities of Cen X-3 (0.001), Her X-1 (<0.01) and SMC X-1 (<0.03) (cf. Fabbiano and Schreier 1976; Primini et al. 1976) imply that the timescale for tidal circularisation cannot exceed some 10^6 yrs (cf. Sutantyo 1974). This timescale can be expressed in terms of the orbital elements together with an effective viscosity $<\mu>$ (Alexander 1973; Sutantyo 1974; Wheeler et al. 1974; 1975; Lecar et al. 1976). The value of $<\mu>$ is $10^{11} - 10^{15}$ cm^2 sec^{-1}. The normal plasma and radiative viscosities in stars are of the order of only $10^2 - 10^4$ cm^{2}sec^{-1}. Low-mass companion stars ($M_1 < 2M_{\odot}$) have convective envelopes with high turbulent viscosity ($\sim 10^{12}$ cm^{2}sec^{-1}) sufficient to explain the circularisation of the orbit of Her X-1 on a short timescale (Lecar et al. 1976). However, the companions in massive X-ray binaries have radiative envelopes with negligible viscosity, and the turbulent viscosities produced in their convective cores are too small to be effective (Sutantyo 1974). The most promising suggestions put forward to resolve this difficulty are those by Press et al. (1975) and by Zahn (1975, 1976). Press et al's mechanism involves shear turbulence produced by the motion of the tidal bulge across the stellar surface. If this turbulence is indeed generated (cf. Seguin 1976) the resulting turbulent viscosity will be sufficient to circularise the orbit of Cen X-3 on a timescale of order 10^6 yrs.

Zahn's (1975) mechanism involves radiative damping acting on the dynamical tide. An essential point is that the star should have a convective core. Zahn (1976) showed that this mechanism can explain the small orbital eccentricity of Cen X-3. Most of the tidal friction is produced here when the star is near the zero-age main sequence where the convective core is largest.

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DISCUSSION

R.P. Kraft - Could you comment on the evolutionary history of the low-mass X-ray binaries such as Sco X-1 and Cyg X-2. You did not mention those in your talk.

E.P.J. van den Heuvel - Basically, two scenarios can be thought of, which I have summarized at IAU Symposium Nr. 73 (van den Heuvel 1976). The first one, proposed by Gursky, and in a somewhat different form by Canal and Schatzmann, departs from a cataclysmic variable binary consisting of a massive white dwarf and a low-mass main-sequence star. The white dwarf is supposed to be driven over the Chandrasekhar limit by mass transfer,leading to an implosion. The implosion and the formation of the neutron star may have been violent, as in a type I Supernova, or perhaps non-violent as in the Canal-Schatzman picture. In the case of a violent implosion with mass ejection, very few binaries will have survived the supernova; only with a suitably directed asymmetric mass ejection can the system have survived the explosion as was shown for instance by Flannery and van den Heuvel; the resulting system will have a high runaway velocity (> 100 km/sec). These types of scenarios can, most probably, not work for Her X-1, as was shown by Sutantyo. Here the neutron star must have originated from a direct core implosion, presumably of an evolved helium star of 3 - 4 $M_\odot$. The progenitor system may have resulted from a massive close binary which suffered large mass loss during its first stage of mass transfer, presumably as a consequence of a very large difference in mass between the components.

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