LATE STAGES OF THE EVOLUTION OF CLOSE BINARIES*

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Abstract. Close binaries can evolve through various ways of interaction into compact objects (white dwarfs, neutron stars, black holes). Massive binary systems (mass of the primary M_1 larger than 14 to 15 M_0) are expected to leave, after the first stage of mass transfer a compact component orbiting a massive star. These systems evolve during subsequent stages into massive X-ray binaries. Systems with initial large periode evolve into Be X-ray binaries.

Low mass X-ray sources are probably descendants of lower mass stars, and various channels for their production are indicated. The evolution of massive close binaries is examined in detail and different X-ray stages are discussed. It is argued that a first X-ray stage is followed by a reverse extensive mass transfer, leading to systems like SS433, Cir X1. During further evolution these systems would become Wolf-Rayet runaways. Due to spiral in these system would then further evolve into ultra short X-ray binaries like Cyg X-3.

Finally the explosion of the secondary will in most cases disrupt the system. In an exceptional case the system remains bound, leading to binary pulsars like PSR 1913+16. In such systems the orbit will shrink due to gravitational radiation and finally the two neutron stars will coalesce. It is argued that the millisecond pulsar PSR 1937+214 could be formed in this way.

A complete scheme starting from two massive ZAMS stars, ending with a millisecond pulsar is presented.

1. Introduction

At this moment hundreds of strong galactic X-ray sources are known with X-ray energies exceeding 10^{36} erg s^{-1}. As pointed out by Ostriker (1977), Jones (1977), Maraschi *et al.* (1977), van den Heuvel (1980) these strong point sources can, according to their X-ray spectra, be divided into two groups: a first class contains the sources with relatively hard X-rays, often pulsating, with early type massive stars as optical counterparts situated near the galactic plane; a second group contains the sources with softer spectra, with low mass stars as optical counterparts, generally not pulsating (exceptions, e.g., Her X-1 with a pulse period of 1.24 s and 4 U 1626–27 with a pulse period of 7.67 s (Ilovaisky and Chevalier, 1978). The second group consists of the low mass steady X-ray binaries, the galactic bulge sources and the globular cluster sources. The hard X-ray sources belong to the extreme population I with ages of 5–10 million years. The group of the soft spectrum sources belong to the old disk population, with ages of 5–13 billion years.

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The same sources observed in our Galaxy are also found in the Magellanic clouds and in M31. The X-rays are produced by the accretion of matter, expelled by the companion, on a magnetized rotating neutron star.

Neutron stars in binary systems can be produced by the explosion of one of the components in a supernova event. About 50% of all stars are close binaries which means by definition that the components of these systems can fill their Roche lobes during the evolution. The expansion during core hydrogen burning or shell hydrogen burning can be interrupted by mass transfer and mass loss. The remnant is essentially determined by the evolutionary state of the star at the moment of onset of the mass transfer (Webbink, 1979; De Greve *et al.*, 1978).

Several review papers on binary evolution were published, e.g., Paczynski (1971), van den Heuvel (1976), Massevich *et al.* (1976), Paczynski (1979), and Tutukov (1981).

The evolution of close binaries starting from homogeneous zero-age Main-Sequence (ZAMS) models can be followed, taking into account mass transfer and eventual mass loss. The existence of X-ray binaries and binary pulsars as, e.g., PSR 1913+16 are striking examples of the fact that close binaries can loss significant fractions of their mass and angular momentum during explosive stages.

2. Observational Evidence of Compact Components in Binaries

Binary X-ray sources containing compact objects can in a crude way be divided into two groups: massive sources and low mass sources.

(a) *Massive sources*: $M > 15\ M_0$.

(1) *Strong permanent sources*: the optical component, a giant or supergiant star, is nearly filling its Roche lobe.

(2) *Weak or transient sources*: the optical component is in most cases a rapidly rotating Be-star. These binary sources have large periods, and the volume of the optical companion its much smaller than its Roche volume.

(b) *Low mass sources*: $M < 2\ M_0$. For only a few sources direct evidence of binary motion exists.

(1) *Pulsating sources*, with hard spectra, example, Her X-1.

(2) *Non-pulsating sources*, with softer spectra: example, Sco X-1. They have large X-ray luminosities.

(3) *Galactic bulge X-ray sources.*

(4) *Steady sources associated* with bursters. The latter two groups have optical and X-ray spectra similar to Sco X-1. The identified optical counterparts are faint and show the spectrum of an accretion disk, comparable with the spectra of cataclysmic binaries (Cowley, 1980; Lewin and Clark, 1980).

In Cen X-4, and Aql X-1 the spectrum of a faint K dwarf can be observed (Cowley, 1980; Van Paradijs, 1980). This evidence together with the fact that the optical companion has a low luminosity suggests that bursters and bulge sources are low-mass binaries, in which the mass of the companion of the compact object is $\lesssim 1\, M_0$, filling its Roche lobe (Joss and Rappaport, 1979; Lewin and Clark, 1980). Evidence that the bursters are neutron stars has been given by Van Paradijs (1978); moreover the high X-ray luminosity ($\log L_x \sim$ 36–38) points to neutron stars or black holes.

The same holds for globular cluster sources in our galaxy and in M31.

Only stars with $M > 15\, M_0$ or $M < 2\, M_0$ provide accretion rates for long lived X-ray sources (van den Heuvel, 1981), the first group by producing a sufficiently strong stellar wind, the latter category producing a sufficiently high-mass transfer rate by Roche lobe overflow. However also in stars of intermediate mass compact objects occur.

3. Final Evolution of Helium Stars

When the primary of a close binary system is filling its Roche lobe a phase of mass transfer (and eventually mass loss) starts, which ends as a result of the ignition of He in the core, the effect being that the layer separating the $\delta R/\delta t > 0$ region and the $\delta R/\delta t < 0$ region moves outwards, causing the mass loss to stop when it reaches the surface.

Hence, after the mass exchange phase the primary has lost practically its complete H-rich envelope, and only the core remains, consisting mainly of He (and heavier elements).

The further evolution is determined completely by the helium core.

Computations of the evolution of helium stars or helium remnants have been carried out by Paczynski (1971), De Greve and de Loore (1976). Arnett (1978), Savonije (1978), Delgado and Thomas (1980), and Sugimoto and Nomoto (1980). The minimum mass of the primary leading to a neutron star after supernova explosion was estimated by De Greve and de Loore (1977), at $\sim 14\, M_0$, and between 8 and 15 M_0 by Massevitch and Tutukov (1981).

The evolution of the helium core mass (M_{He}) occurs as follows:

$$M_{\mathrm{He}} > 2\, M_0.$$

The CO-core formed by helium burning degenerates and the outer layers expand.

A second phase of mass transfer starts leaving a degenerate CO star, with $M_{\mathrm{remnant}} < M_{\mathrm{ch}}$, cooling off to a CO with dwarf. Figure 1 shows the evolution of a $10\, M_0 + 8\, M_0$ binary, with an initial period of 8 days, calculated by De Greve and de Loore (1977), showing two phases of mass transfer.

The various evolutionary stages are shown in Table I.

$$2\, M_0 < M_{\mathrm{He}} < 3\, M_0$$

C-ignition occurs under not highly degenerate conditions and the star undergoes successive C-shell flashes (Miyaji *et al.*, 1980; Nomoto, 1980; Sugimoto and Nomoto, 1980).

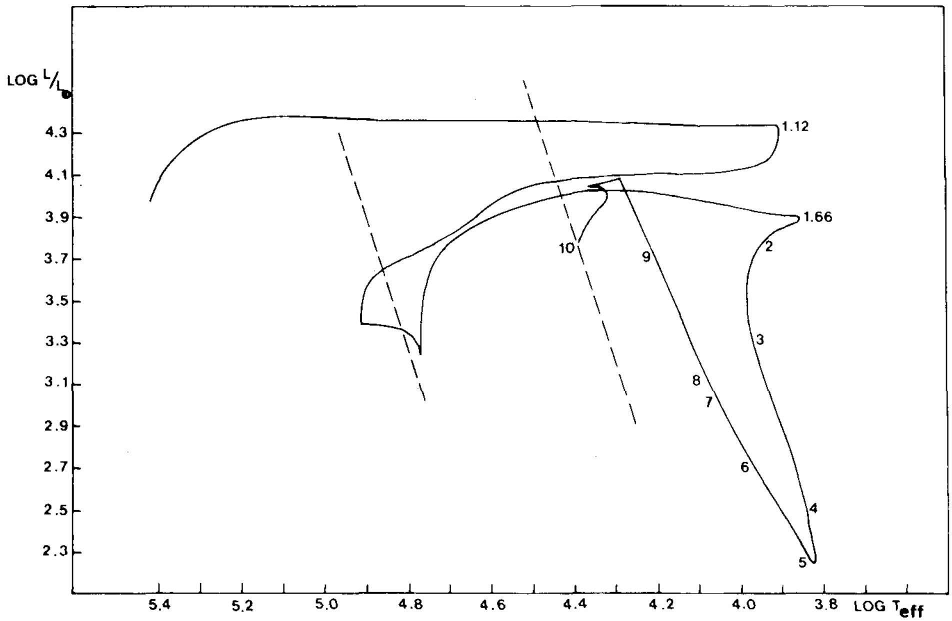

Fig. 1. The evolutionary track in the HRD of the primary of a $10\,M_0 + 8\,M_0$ binary system. The masses of the mass losing primary are indicated. ZAMS of hydrogen and helium are also given.

When the outer layers of the produced degenerate O–Ne–Mg core, which is increasing in mass, approach the He-burning shell, C burning finishes and due to He-shell burning the outer helium layers expand. Also in this case a second mass transfer stage occurs, leaving an O–Ne–Mg white dwarf with mass between 1.2 M_0 and 1.4 M_0, while

$$M_{\mathrm{He}} > 3\,M_0 .$$

The CO-core formed by He-burning is larger than the Chandrasekhar limit; Ne, O, and Si ignition occur under non degenerate condition.

Fe-photodesintegration in the core, leads to a supernova-explosion and the formation of a neutron star.

4. Mass Accretion by White Dwarfs

Accreting white dwarfs can be driven over their Chandrasekhar limit and undergo an electron capture supernova collapse (Myaji *et al.*, 1980; Sugimoto and Nomoto, 1980; Nomoto, 1980).

Computations were performed for a white dwarf of 1.2 M_0, with an accretion rate of $4 \times 10^{-6}\,M_0\,\mathrm{yr}^{-1}$; it was found that due to electron captures on ^{20}Ne and ^{24}Mg the core density increases, leading to a collapse.

TABLE I

The evolution of the 10 $M_\odot$ + 8 $M_\odot$ binary system

		$t \times 10^6$ yr	M_1	M_2	R_1	A	P	log $L/L_\odot$	log T_{eff}	M_{cc}	X_{at}	log T_c	log ρ_c	log $\dot{M}$
1	Initial model	0	10	8	4.22	23.63	3.15	3.77	4.39	2.93	0.7	7.48	0.91	
2	Start 1st mass exchange	15.149271	10	8	9.44	23.63	3.15	4.06	4.29	0.0	0.7	7.66	2.29	−5.0
3	Minimum luminosity	15.182579	4.82	13.18	10.51	37.43	6.29	2.24	3.81	0	0.7	7.73	2.59	−3.58
4	Helium ignition	15.264418	1.98	16.02	34.39	150.17	50.53	3.82	3.95	0	0.32	7.97	3.37	−4.86
5	End 1st mass exchange	15.310440	1.66	16.34	44.66	205.80	81.07	3.96	3.93	0.12	0.20	8.13	3.70	−5.20
6	End core helium burning	18.107183	1.66	16.34	0.26	205.80	81.07	3.41	4.91	0	0.0	8.37	4.07	
7	Start 2nd mass exchange	18.481810	1.66	16.34	44.66	205.80	81.07	4.12	3.97	0	0	8.64	6.22	−5.00
8	End 2nd mass exchange	18.512902	1.12	16.88	84.86	420.10	236.44	4.32	3.90	0	0	8.56	6.73	−5.40
9	End of the computations	18.517200	1.12	16.88	0.045	420.10	236.44	3.95	5.43	0	0	8.49	6.94	

5. Envelope Interaction

Constraints for conservative evolution are:

(1) the mass ratio $q = M_2/M_1$ is not too low ($\geqq 0.3$);

(2) the separation A is not too small;

(3) the envelope of the loser is in radiative equilibrium.

If these conditions are satisfied the change in the distance of the centers of gravity of the two components, given by

$$\frac{A}{A_0} = \left(\frac{M_{10}M_{20}}{M_1 M_2}\right)^2,$$

is not too much reduced.

M_1 and M_2 are the masses of primary and secondary respectively, the subscripts 0 denotes the initial value. If the conditions 1 and/or 2 are not satisfied the systems evolve into contact systems with a common envelope (Webbink, 1979).

If the envelope of the loser is convective and mass transfer occurs, the effect of the mass loss will be that the envelope expands, inducing a stronger amount of mass transfer. In this way the envelope grows in a catastrophic way, engulfes its companion, and produces also here a common envelope.

In convective envelopes the specific entropy of the gas decreases outwards so that no energy supply for the restoration of the equilibrium (as is necessary in radiative envelopes) is required. These stars have a tendency to expand further when the mass loss starts.

The mass loss ratios increase and the outflowing matter can reach velocities near the velocity of sound (even for low mass stars $\dot{M} > 10^{-3}\,M_0\,\mathrm{yr}^{-1}$). Only few detailed calculations have been carried out for this mode by Paczynski and Sienkiewicz (1972), Plavec *et al.* (1973), Webbink (1977a, b), all using the mass loss formalism developed by Jedrzejec (1969). Mass loss of this type occurs also in degenerate stars filling their Roche lobes. Classical novae and dwarf novae are associated with binaries which evolved according to this mode (Ritter, 1975, 1976; Webbink, 1975; Paczynski, 1976).

Binaries with not too long periods (< 100 to 1000 d) start mass transfer before the degenerate He-core is sufficiently massive for ignition and leave low mass He-white dwarfs of masses smaller than $\sim 0.5\,M_0$. Systems with longer periods (1000 to 10 000 d) start mass transfer after the primary has reached the giant branch, leaving CO-white dwarfs with masses between about a half and 1.4 solar masses.

6. Evolution of Massive Close Binaries from ZAMS to the Final Stage: Primaries Leaving Neutron Stars

The evolution of ZAMS massive close binaries occurs as follows (Table II). When the primary fills its Roche lobe mass is transferred towards the secondary, and a He-remnant is left. A system in this phase represents a Wolf-Rayet binary.

TABLE II

The evolution of massive stars

Primary S_1 type	Secondary S_2 type	M_1	M_2	Age (in 10^6 yr)	
OB	OB	20	8	0	$P = 4.56$ d
OB	OB	20	8	6.17	$P = 4.56$ d
fills Roche lobe					
	Direct mass exchange	S1 → S2			
He-star	OB	5.4	22.6	6.2	$P = 10.86$ d
	End of the first phase of mass transfer Wolf–Rayet binary Evolution to final stage of S1				
Neutron star OB Runaway	OB	2	22.6	6.78	
	1st Supernova explosion OB Runaway – Remnant of the Further Evolved Helium star is a young neutron star (Pulsar)				
Neutron star X-ray Binary	OB	2	22.6	11.186	$P = 11.7$ d
	OB star nearly fills its roche lobe enhanched stellar wind. accretion on the neutron star generates X-rays 1st X-ray phase.				
Neutron star	OB	2	22.6	11.209	$P = 11.70$
	Reverse Mass-transfer roche lobe overflow-mass leaves the system				
Neutron star	OB → He S2 on its way to WR star. accretion disk 2nd X-ray phase		Slow phase of mass transfer; optical star is 'on its way' to become a Wolf–Rayet star. (Ex. SS 433, Cir X-1).		
Neutron star	He	2	6.3	$t = 11.239 \times 10^6$ yr	
	Wolf–Rayet runaway end of the second mass loss stage. He star + neutron in common (expanding) envelope.				
Neutron star	He	2	6.3		
	Supercritical disk accretion; 3^d X-ray phase (Ex. CYG X-3) 2n supernova explosion system remains bound				
Neutron star	Neutron star Ex. PSR 1913+16 binary pulsar				$P = 7.75$ hr
Neutron star	Neutron star Coalescence of two neutron stars Ex. PSR 1937+214 Millisecond Pulsar. OR: system disrupted, two runaway neutron stars.				$P = 1.5$ s

The neutrino cooling shortens the C-, Ne-, Si-burning lifetimes to a few thousand years. Then the primary explodes and leaves a neutron star remnant of 1 or 2 solar masses. The system has a large probability to remain bound (de Loore *et al.*, 1975). The space velocity is 50–80 km s^{-1}, typical for OB runaways. The optical component can be removed during the optical component's lifetime to a distance of $\sim$ 100 pc, a typical distance for X-ray binaries.

The stellar wind matter is partially accreted by the compact companion which produces the X-rays. The X-ray luminosity remains weak until the optical component is nearly filling its Roche lobe. The Roche lobe overflow itself quenches the X-rays, and the time-scale of the X-ray phase is exactly determined by this behaviour. Thus the X-ray stage is of the order of 10^5 yr for X-ray binaries with an optical companion of $\sim 20\, M_\odot$ (Savonije, 1979). When the optical component fills its Roche lobe a common envelope is formed since the accretion by the neutron star is limited by its Eddington limit to $10^{-8}\ M_\odot\, \text{yr}^{-1}$, while the mass giving companion loses mass at a much higher rate. The common envelope stage was proposed by Paczynski and worked out numerically by Taam *et al.* (1978), Tutukov and Yungselson (1979).

It is suggested by Tutukov and Yungelson (1979) that η Car, P Cyg, and S Dor are common-envelope binaries. Now two possible branches exist for the further evolution: either the neutron is engulfed by its companion in the common envelope and this leads to a red supergiant with a compact core (Tutukov, 1981) or the bulk of the transferred matter will be expelled from the system, causing a rapid shrinking of the orbit as a consequence of the large specific orbital angular momentum of the expelled matter (van den Heuvel and de Loore, 1973). Remnants of such expelled envelopes can be observed during $\sim 2 \times 10^4$ yr as a bright nebula with a radius of $\sim$ 1 pc around a single Wolf–Rayet star (Massevich *et al.*, 1976). Mass loss rates of $\gtrsim 10^{-5}\ M_0\ \text{yr}^{-1}$ could transform the stars into IR sources with large space velocities.

In all cases neutron stars are formed with high space velocities. In this context slow pulsars ($\langle z \rangle \sim 80$ pc) should be the final products of wide binaries; fast pulsars ($\langle z \rangle > 150$ pc) should be the final products of close binary evolution.

7. Evolution of Stars of Intermediate Mass

When the primary fills its Roche lobe during core hydrogen burning the possibility exists that mass exchange leads to the formation of a common envelope. Later on this envelope can partially be removed and in this way a system consisting of a He or CO dwarf and a normal companion is produced. If the low-mass star with a convective envelope undergoes Roche lobe overflow then, owing to large mass and angular momentum losses very close cataclysmic variables can be formed (Meyer and Meyer-Hofmeister, 1979; Webbink, 1979; Taam *et al.*, 1978). The life-time of the system in the semi-detached stage (He or CO core with envelope, filling its Roche lobe and a normal secondary) is of the order of the thermal time-scale of

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the expanding envelope. The result of the mass exchange is a system composed by a Main-Sequence star and a degenerate He or CO dwarf. The overflow stage ends when the H in the envelope is exhausted or by a central He-flash. The non-degenerate component then evolves towards a red giant (or red supergiant) not yet filling its Roche lobe, but losing matter by stellar wind. The degenerate companion grows by accretion and this can lead to a supernova explosion and the formation of a neutron star.

In this way a progenitor system for X-ray bursters can be produced. Such systems could also be formed by capture in globular clusters, or in the galactic bulge. Mass decrease by stellar wind and later on by Roche lobe overflow could possibly change the non compact object into a red dwarf. This second, inverse, mass

TABLE III

The evolution of lower mass stars

ZAMS The primary fills its Roche lobe.	
Mass loss leads to a common expanding envelope which disappears later.	If strong gravitational radiation occurs, the large mass and momentum losses lead to a system of a degenerate and a red dwarf – later on a SN produces a neutron star – bursters could be produced
He or CO-dwarf + normal secondary. He or CO-dwarf + normal secondary.	Degenerate dwarf grows → Roche lobe overflow.
Primary fills its Roche lobe. Semi-detached stage (ex. Algol systems).	Supernova X-ray burster
He- or CO-dwarf + red giant with stellar wind mass loss.	
Secondary fills Roche lobe. Reverse mass transfer Increase of the mass of the CO-dwarf. (Such systems could also be produced by capture in globular clusters.)	Systems with large mass loss rates evolve into double core systems with a common envelope. (Ex. UU Sge, planetary nebula). Friction causes mass loss.
SN explosion-X-rays (Example: bursters).	Gravitational energy very high → system becomes very narrow → Roche lobe overflow; accretion by CO dwarf; SN → NS. (Ex.: X-ray bursters). High gravitational radiation. Common envelope disappears. (Example: V471 Tau).

transfer producing the X-rays could represent the burster stage. The evolution of lower mass stars according to this picture is shown in Table III.

If the systems evolving according to case *B* have an average mass loss rate satisfying the following criterion

$$\langle \dot{M} \rangle = \frac{M}{t_{\mathrm{KH}}} > 10^{-6}\, M_0\, \mathrm{yr}^{-1},$$

where t_{KH} is the Kelvin–Helmholtz time-scale, the evolutionary scenario is different.

The expansion of the non-degenerate star leads also in this case to a Roche lobe overflow stage but now two degenerate dwarfs in a common envelope can be formed. This phase has been investigated by Meyer and Meyer-Hofmeister (1979). The double core, revolving into the common envelope produces a very large friction and as a result the envelope is removed, leaving two degenerate dwarfs, at least when the gravitational energy of the two compact cores is sufficiently large to disperse the envelope. UU Sge could be an example of such a common envelope system. Common-envelope cores of this kind were discovered by Miller *et al.* (1976); further evolved systems (i.e., 10^4 yr later, when the envelope is dispersed, and merely consisting of two degenerate dwarfs) are also known, e.g., V471 Tau (Nelson and Young, 1970) and PG 1413+0.1 (Green *et al.*, 1978). Another possibility is that two degenerate objects merge and evolve into one single degenerate core hidden in a large envelope.

For lower masses (initial primaries $\lesssim 3\, M_0$) a long mass exchange stage may occur. The accreting degenerate dwarf thus can also be transformed into a neutron star after a supernova explosion. Further Roche lobe overflow and accretion by the neutron star can then produce X-rays. The less massive of the two degenerate dwarfs has the largest radius so that this star fills its Roche lobe first. Here again is a possibility for the formation of a neutron star by accretion in an explosive (or non explosive?) way, leading to an X-ray stage. In all these cases of neutron star formation the systems can remain bound, or can be disrupted, depending on the relative masses, the asymmetry of the explosion and the explosion conditions. In this way, either low mass X-ray binaries can be produced, or runaway neutron stars. If the mass ratio of the Roche lobe filling degenerate star and the companion is large (i.e., near 1) the former can be destroyed, and transformed into a disk surrounding the companion. Further evolution depends on the viscosity of the ring. If the viscosity is large enough the ring can be removed and a single star is formed.

8. Supernova Explosion – Probabilities for Disruption

Each of the two components of a massive close binary undergoes a supernova explosion. The effects of these events on the status of the system are completely different.

In the case of the first explosion the less massive star explodes, and consequently the probability that the system is disrupted is extremely low.

Hence, most systems remain bound so that many massive X-ray binaries exist.

During the second supernova explosion the more massive component explodes; in this case, the disruption probability is very large, so that two runaway neutron stars are produced, an old one, remnant of the first explosion and a young active one, just formed.

Computations of the disruption probabilities were carried out by De Cuyper (1981), de Loore *et al.* (1975). If we assume an extra kick of 100 km s^{-1}, a shell-expansion velocity of 10000 km s^{-1} and a post-supernova remnant of 1.5 M_0 these probabilities are of the order of 70–80% for ZAMS primaries between 40 and 100 M_0 for all mass ratios. For lower mass ZAMS primaries (20–40 M_0) the systems always remain bound.

As well in the case of Roche lobe overflow with reverse mass transfer and mass loss as in the case of spiralling in, the outer layers with the original composition leave the primary star, and more and more layers with larger helium abundances show up at the surface. The O star is 'on its way' to become a He-star, hence, shows more and more WR characteristics. The object SS433 is possibly an example of a binary in this stage (van den Heuvel *et al.*, 1980), as well as Cir X-1.

According to Firmani and Bisiacchi (1980) and Shklovski (1981) and the mass loss rate is $\sim 10^{-4}$ M_0 yr^{-1}, with an expansion velocity of 1000 km s^{-1}, and the spectral type ranges between Of and WR (from the relative strengths of Balmer- and Pickering-lines). This agrees with the conclusions of van den Heuvel *et al.* (1980) about the mass loss rate.

Probably the X-ray system is surrounded by an envelope of matter expelled by the non compact companion, and not by remnants of the supernova shell as is discussed by Shklovski (1981). An argument is given by the life-time of the object according to evolutionary computations (11×10^6 yr) and the large distance (3.7–4.7 kps). Hence, the picture of van den Heuvel *et al.* (1980) of SS433 to be a second X-ray stage, with mass expelled by the companion, the larger part of which is not accreted by the neutron star, but stored in a disk, sounds very attractive.

As more and more matter is expelled by the companion, more He-enriched layers will appear at the surface. Hence, the next evolutionary stage should be a second Wolf–Rayet stage, i.e., a helium star with a neutron star companion (de Loore *et al.*, 1975) (Figure 2). Since such systems are descendants from binaries through a supernova event, they are assumed to have a large runaway velocity, and are supposed to be found at large distances of their place of birth.

Further evolution with further spiralling in could then lead to ultra-short period binaries like Cyg X-3 (van den Heuvel and de Loore, 1973). Finally, these systems undergo a new supernova explosion, and are in nearly all cases disrupted, leaving two neutron stars, an old one and a young pulsar.

In exceptional cases binary pulsars are formed. A list of binary pulsars is given in Table IV.

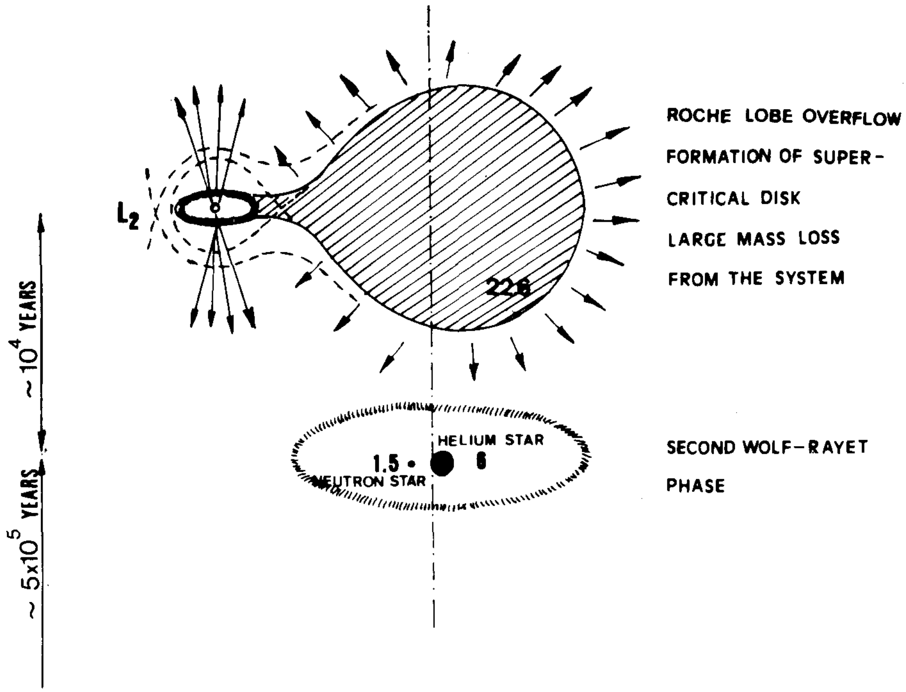

Fig. 2. The expected evolution of a massive X-ray binary after the X-ray stage. Roche lobe overflow of the non compact star transfers mass on a thermal time-scale, with mass loss rates of the order of $\sim 10^4$–10^{-3} M_0 yr^{-1}. A supercritical disk is formed, and heavy mass loss from the central disk regions occurs, probably in the form of beams.

9. The Evolutionary Status of Be-X-Ray Binaries

Massive close binaries with primaries of masses exceeding 30–40 M_0 evolve into Wolf–Rayet binaries (Conti *et al.*, 1983; Maeder, 1982).

The end products of intermediate systems after a case *B* of mass transfer could be identified with Be-systems (Vanderlinden, 1982). Further evolution of these binary systems leading to a supernova explosition of the primary, leaving a compact object should then explain the existence of the Be X-ray binaries as suggested by Rappaport and van den Heuvel (1982).

TABLE IV

Binary pulsars

Name	P_{orb}	P_{pulse}(s)	Eccentricity
PSR 0656+64	$24^{\mathrm{h}}41^{\mathrm{m}}$	0.196	0.06
PSR 0820+02	11:00 d	0.865	0
PSR 1913+16	$7^{\mathrm{h}}75^{\mathrm{m}}$	0.059	0.617
PSR 1937+215		0.0015	

In Figure 3 is depicted the evolution of a system of $15\,M_0 + 10\,M_0$, calculated simultaneously, starting with an initial period of 8 days. The results are given in Table V.

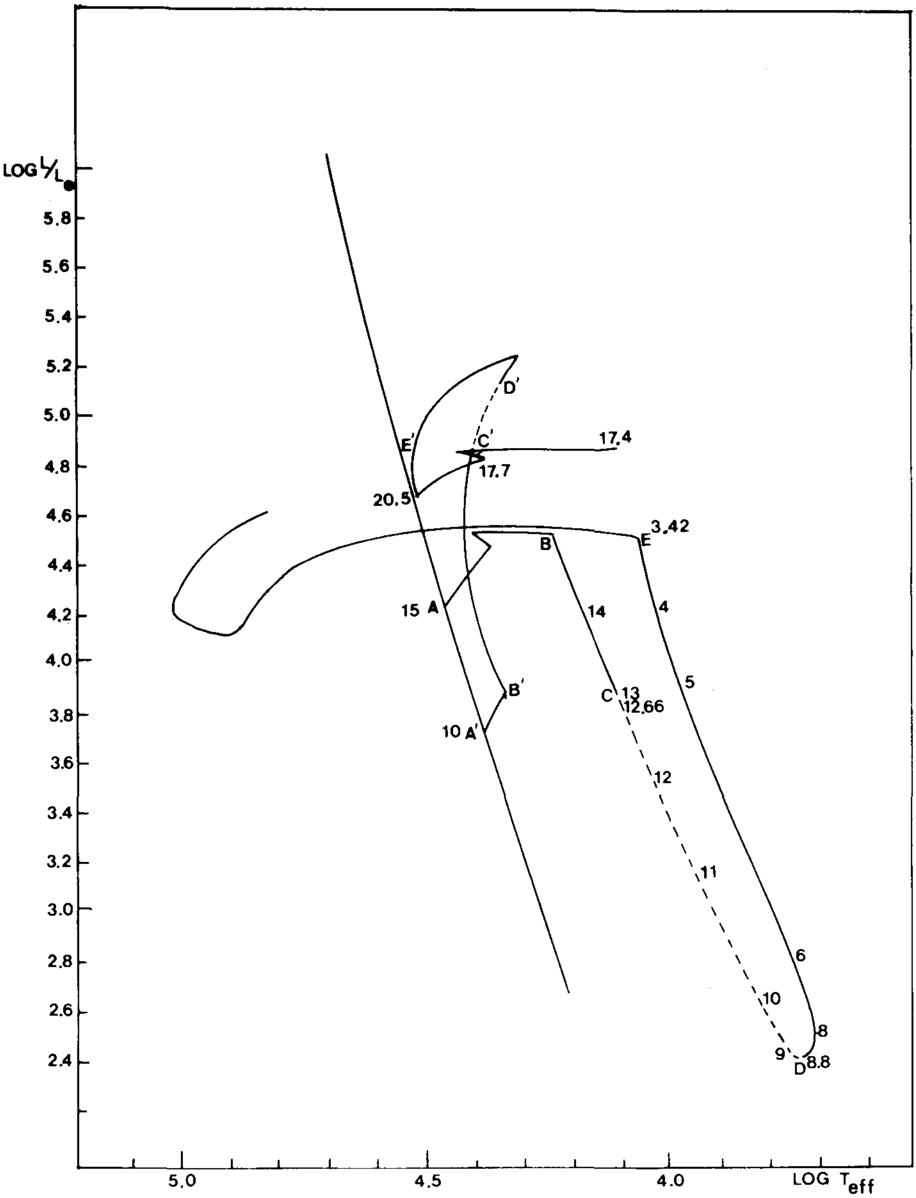

Fig. 3. The formation of a Be–X-ray binary. The simultaneous evolution of a $15\,M_0 + 10\,M_0$ binary with an inital period of $8\,M_0$. The changed mass of primary and secondary is indicated along the evolutionary tracks. The letters refer to Table II, A to F refer to phases of the primary, A' to F' to corresponding phases of the secondary. The dotted parts of the evolutionary tracks correspond with the contact phase.

TABLE V

Evolution of a 15 $M_0 + 10\ M_0$ close binary. The letters in the first column refer to Figure 3
(15 $M_0 + 10\ M_0$, $P_i = 8$ d, contact: 2230 yr, $\Delta M = 1.10$)

	Time (10^6 yr)	M_1	R_1	$\log T_{eff,1}$	$\log L_1$	X_{at1}	M_2	R_2	$\log T_{eff,2}$	$\log L_2$	X_{at2}	P	$\dot{M}$	β
$A A'$	0	15	5.14	4.47	4.26	0.70	10	4.12	4.39	3.73	0.70	8	– –	1
$B B'$	13.095 59	15	20.25	4.25	4.57	0.70	10	6.04	4.35	3.91	0.70	8	5.29 10^{-5}	1
	13.096 91	14.6	19.73	4.22	4.43	0.70	10.4	7.44	4.42	3.38	0.70	7.71	5.8 10^{-4}	1
	13.097 71	14.0	18.91	4.19	4.28	0.70	11.0	9.66	4.43	4.66	0.70	7.40	1.1 10^{-3}	1
$C C'$	13.098 32	13.0	17.76	4.12	3.95	0.70	12.0	14.88	4.40	4.91	0.70	7.11	1.73 10^{-3}	1
	13.098 52	12.66	17.47	4.10	3.82	0.70	12.34	17.07	4.39	4.97	0.70	7.08	1.87 10^{-3}	0.998
	13.098 88	12.0	17.18	4.04	3.60	0.70	12.85	17.50	4.38	4.96	0.70	7.18	1.96 10^{-3}	0.730
	13.099 35	11.0	17.10	3.94	3.20	0.70	13.57	18.40	4.38	5.00	0.70	7.60	2.05 10^{-3}	0.69
	13.099 85	10.0	17.30	3.80	2.62	0.70	14.34	20.04	4.37	5.05	0.70	8.32	2.15 10^{-3}	0.532
	13.100 37	9	17.86	3.75	2.45	0.70	15.12	22.18	4.37	5.11	0.70	9.48	2.21 10^{-3}	0.633[a]
$D D'$	13.100 39	8.79	18.09	3.75	2.45	0.70	15.29	22.87	4.36	5.13	0.70	9.79	2.21 10^{-3}	0.749
	13.100 55	8.43	18.49	3.74	2.45	0.699	15.60	23.94	4.36	5.15	0.70	10.39	2.28 10^{-3}	1
	13.100 73	8	19.07	3.73	2.45	0.699	15.97	25.50	4.35	5.18	0.70	11.23	2.35 10^{-3}	1
	13.101 13	7	21.07	3.73	2.51	0.699	16.90	30.45	4.33	5.24	0.70	14.03	2.63 10^{-3}	1
	13.101 52	6	25.00	3.77	2.82	0.699	17.90	35.70	4.31	5.29	0.699	18.76	2.47 10^{-3}	1
	13.102 10	5	32.32	4.00	3.98	0.582	18.90	27.44	4.36	5.26	0.697	27.5	1.17 10^{-3}	1
	13.104 31	4	41.16	4.06	4.43	0.409	19.90	10.96	4.51	5.06	0.683	46.23	1.33 10^{-4}	1
	13.109 96	3.62	45.56	4.06	4.51	0.330	20.28	6.86	4.54	4.78	0.673	58.77	4.87 10^{-5}	1[b]
	13.115 41	3.42	48.40	4.06	4.56	0.284	20.50	6.64	4.54	4.75	0.666	68.46	2.03 10^{-5}	1

[a] min L.

[b] Start He-burning.

M, R, T_{eff}, L are respectively the mass, radius, effective temperature and luminosity. Index 1 refers to the primary, index 2, to the secondary, X_{at} is the abundance of hydrogen (in primary and secondary respectively), $\dot{M}$ is the mass loss, and β is the fraction of the mass lost by the primary accreted by the secondary.

The computations show that the system becomes semi-detached after ~ 13 million years, and evolves into a contact phase some ~ 2900 yr later. During this period, lasting about 2200 yr, matter leaves the system (about 50% of the matter expelled by the primary). The system becomes again semi-detached until 15000 yr later, after the onset of helium burning the two components become detached again.

The final system, consisting of a primary of 3.42 M_0 and a secondary of 20.50 M_0 (hence, 1.08 M_0 has left the system), has a period of ~ 68 days.

The secondary component, starting from 10 M_0 accretes matter, and evolves parallel with the ZAMS.

When the slow phase of mass transfer begins, it moves towards the ZAMS, and later on evolves exactly like a normal ZAMS star of the same mass.

The helium remnant of the primary has meanwhile exploded. The system in this stage could represent a Be X-ray binary, with a B component of $\sim 20\,M_0$, a neutron star of $\sim 1.5\,M_0$, a period of ~ 81 d in the case of a symmetric explosion, and a runaway velocity of the system of ~ 11 km s^{-1}.

10. The Evolutionary Status of SS433

As well in the case of Roche lobe overflow with reverse mass transfer and mass loss (i.e., from the original secondary towards the compact object) as in the case of spiralling in, the outer layers, with the original composition, leave the star and deeper layers, containing more and more helium appear at the surface. The O star is 'on its way' to become a helium star; hence, shows more and more Wolf–Rayet characteristics.

The object SS433 is possibly an example of a binary in this stage (van den Heuvel *et al.*, 1980) as well as Cir X-1. According to Firmani and Bisiacchi (1980) and Shklovski (1981) the mass loss rate is $\sim 10^{-4}\,M_0$ yr^{-1}, and the spectral type, (determined from the relative strengths of Balmer- and Pickering lines) ranges between Of and WR.

Probably the X-ray system is surrounded by an envelope of matter expelled by the non-compact component. The life-time of the object, determined from evolutionary computations is $\sim 11 \times 10^6$ yr.

The compact star cannot collect more than some $10^{-8}\,M_0$ yr^{-1}, hence, the larger part of the mass expelled by the companion will be blown away by the radiation pressure produced by the compact star, when it arrives at the inner edge of an accretion disk (van den Heuvel, 1980).

The excess material will be expelled in directions perpendicular to the disk. The effect of this mass ejection will be a rapid decrease of the orbital period (van den Heuvel, 1973; van den Heuvel and de Loore, 1973). When matter is ejected at high velocities, symmetrically with respect to the center of the disk, its specific angular momentum is equal to the specific angular momentum of the compact star.

The change of the orbital period P is then (cf. van den Heuvel, 1980b) given by

$$\frac{P}{P_0} = \left(\frac{1+q_0}{1+q}\right)^2 \frac{q_0}{q} e^{3(q-q_0)};$$

where q is the ratio between the mass of the neutron star and the mass of its companion.

The subscripts zero refer to the original situation. The time scale for the shrinking of the orbital period calculated in this way is $\sim 3 \times 10^3$ yr.

The result of the evolution will be an extremely close binary system, consisting of the evolved He-core of the compact star, and a neutron star, resembling a WR star. The evolution is depicted in Table II.

11. The Millisecond Pulsar PSR 1937+214

This pulsar has an extremely short pulse period of 1.5 milliseconds and a very weak magnetic field strength of the order of 10^8 g.

The other known binary pulsars (see Table IV) have much larger magnetic fields, of the order of 10^{12} g, and longer periods.

The millisecond pulsar has a very large rotational energy and a small magnetic field, while the other binary pulsars have rotational energies three to four orders smaller, and a very large magnetic field, hence, it is not obvious that these objects evolved in a similar way. Various mechanisms for the explanation of the ms-pulsar have been presented. An analysis of these mechanisms has been carried out by Henrichs and van den Heuvel (1983) and a thorough investigation of the difficulties with the different models led them to the suggestion that the ms-pulsar is formed by coalescence of two neutrons stars.

11.1. Possible models

11.1.1. *Spin-up by Accretion in a Massive Binary During a Common–Envelope Phase*

In this model an old neutron star, with an age of several 10^6 yr starts accretion, so that it spins up to an equilibrium spin period, depending mainly on the magnetic field strength and the mass loss rate. Since PSR 1913+16 and PSR 0656+64 have periods of the order of a day, a spiral-in phase with large mass loss rates and large angular momentum losses must have occurred. The high orbital eccentricity of PSR 1913+16 shows that the companion star itself exploded in a supernova event, in such a way that the system was not disrupted, and collapsed to a neutron star.

If PSR 1937+214 was descendant from a massive X-ray binary the system was disrupted in the second supernova event. Since the remnant of the exploding star is a neutron star, the initial ZAMS mass of the progenitor or the final mass after accretion by mass transfer, from its companion, must have been at least 14 M_0 (De Greve and de Loore, 1977). The maximum possible Eddington accretion rate is $\sim 1.5 \times 10^{-8}\ M_{\odot}\ \mathrm{yr}^{-1}$.

The amount of required accreting matter M_0 for a spin up to the equilibrium period is $\sim 0.12\ M_\odot$ (Henrichs and van den Heuvel). Companions with masses exceeding 14 M_0 have lifetimes below $\sim 10^7$ yr, hence the ensuing average accretion rate is $\sim 1.2 \times 10^{-8}\ M_0\ \mathrm{yr}^{-1}$, this means that the average accretion rate should equal the maximum possible Eddington accretion rate: However such large transfer rates can only occur during short evolutionary stages.

The maximum possible amount of accretion is smaller than $\sim 0.01\ M_\odot$.

11.1.2. *After the Common Envelope Phase and Disappearance of the Wolf–Rayet Companion a Massive Disk* $> 0.1\ M_0$ *is Present Around the Neutron Star* (Alpar *et al.*, 1982)

The survival probability of the disk after the supernova of its companion is extremely low.

11.1.3. *Accretion From the Wind of an Intermediate Red Giant*

Spins up the neutron star to a very short period (Arons, 1983).

Consideration of the transferred mass and the possible accretion rate leads to a maximum of $\sim 0.005\ M_\odot$ for the accreted matter, which rules out also this model.

11.1.4. *Spin-up by Accretion in a Low-Mass X-ray Binary* (Alpar *et al.*, 1982; Arons, 1983).

Globular cluster sources and bulge sources contain most probably a neutron star, accreting matter from a low mass companion, in a phase of Roche lobe overflow (Lewin *et al.*, 1980, 1981), with very narrow orbits (e.g., for 4U1626–67 the orbital period is 41 min). The mass transfer in very close systems is driven by angular momentum losses produced by gravitational radiation (Verbunt and Zwaan, 1981). The companion becomes a fully convective red dwarf, a degenerate star, which can be represented by a polytrope of index $\frac{3}{2}$. In such a case the radius increases when the star is losing mass and the orbit becomes wider. The mass transfer rate decreases and vanishes (Paczynski and Sienkiewicz, 1981; Rappaport *et al.*, 1982).

According to Henrichs and van den Heuvel (1983) for a H-rich component, with an assumption on the gravitational radiation time-scale, a final period of a couple of hours is found, and a mass of $\sim 0.017\ M_\odot$ for the companion of a neutron star of 1.4 $M_\odot$. Such a system would show a periodic modulation of the pulse arrival times. The observed limits on the variation of the pulse period rule out the presence of such a companion star (Ashworth *et al.*, 1983; Backer *et al.*, 1983).

11.1.5. *Coalescence of a Close Binary System Consisting of Two Neutron Stars*

The binary radio pulsar PSR 1913+16 consists most probably of two neutron stars with masses of $\sim 1.4\ M_\odot$. The decay of the orbit occurs as predicted by the emission of gravitational radiation according to general relativity, leading to a coalescence of the system in $\sim 3.1 \times 10^8$ yr (Peters, 1964; Clark and Eardly, 1977). Clark and Eardley found that the two components coalesce directly if they have

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the same mass and the orbitis smaller than 30 km, and that a Roche lobe overflow occurs, with a spiral out and tidal disruption of the lower mass star, leaving a neutron star. The orbital period near corotation is $\sim$ 1 ms and the two magnetized neutron stars are corotating.

For rotation periods below 1.5 ms the neutron star is expected to be unstable to the radiation of gravitational waves by non-stellar modes (Papaloizou and Pringle, 1978); hence, the rotation period will not drop below 1.5 ms.

Hence, the coalescence of two orbiting neutron stars seems to be the most plausible explanation for the existence of the millisecond pulsar.

12. Global Picture of the Evolution of Massive Close Binaries

Considering typical objects such as SS 433, Cyg X-3, PSR 1913 + 16, and PSR 1937 + 214, and by comparing their characteristics with those of the standard X-ray sources a general picture for the evolution of massive stars emerges, starting from a pair of OB ZAMS components through successive stages of quiet and explosive mass loss, either leading to a binary pulsar lateron coalescing into a very short pulsar, or into two runaway neutron stars. Two massive stars with a period of $\sim$ 10 days start their mass transfer phase during shell hydrogen burning of the primary.

After the mass exchange stage a Wolf–Rayet binary is formed, later on evolving, after a SN explosion into an OB runaway, i.e., a massive star with a neutron star compagnon. As the massive star is nearly filling its Roche lobe; the enhanced stellar wind will be sufficient to produce X-rays, hence, a first X-ray stage occurs.

The secondary evolves through the shell hydrogen binary phase, expands, fills its Roche lobe. Matter has to leave the system since the neutron star is not able to accrete the material expelled by its companion. The optical star is on its way to become a Wolf–Rayet star. An accretion disk could be formed. This could represent a second X-ray stage; SS433 and Cir X-1 could be in this phase, a phase of slow mass transfer.

At the end of this second mass loss stage, the He-remnant and the orbiting neutron star represent run-away Wolf-Rayet stars.

Due to spiral in of the neutron star in the atmosphere of the WR star, a third X-ray stage could be produced, a WR-star and a neutron star with a very short period, such as Cyg X-3.

The He-star continues its subsequent nuclear burning phases, and finally explodes. If the system, remains bound a binary pulsar is produced, such as PSR 1913 + 16. The two neutron stars coalesce, hence, a very short period pulsar is formed, with a period of $\sim$ 1.5 ms.

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