LATE STAGES OF CLOSE BINARY SYSTEMS

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Abstract. The expected final evolution of massive close binaries (CB) in case B is reviewed. Primary stars with masses $\gtrsim 12-15\,M_\odot$ are, after loosing most of their envelope by mass exchange, expected to explode as supernovae, leaving behind a neutron star or a black hole.

Conservative close binary evolution (i.e. without a major loss of mass and angular momentum from the system during the first stage of mass transfer) is expected to occur if the initial mass ratio $q_0 = M_2{}^0/M_1{}^0$ is $\gtrsim 0.3$. In this case the primary star will be the less massive component when it explodes, and the system is almost never disrupted by the explosion. The explosion is followed by a long-lasting quiet stage ($10^6 - 10^7$ yr) when the system consists of a massive main-sequence star and an inactive compact companion. After the secondary has left the main-sequence and becomes a blue supergiant with a strong stellar wind, the system becomes a massive X-ray binary for a short while ($2-5 \times 10^4$ yr).

The numbers of Wolf-Rayet binaries and massive X-ray binaries observed within 3 kpc of the Sun are in reasonable agreement with the numbers expected on the basis of conservative CB evolution, which implies that several thousands of massive main-sequence stars with a quiet compact companion should exist in the Galaxy. About a dozen of these systems must be present among the stars visible to the naked eye. During the second stage of mass exchange, large loss of mass and angular momentum from the system is expected, leading to a rapid shrinking of the orbit. The supernova explosion of the secondary will in most cases disrupt the system. If it remains bound, the final system will consist of two compact stars and may resemble the binary pulsar PSR 1913 + 16.

In systems with $q_0 \lesssim 0.2-0.3$ large mass loss from the system is expected during the first stage of mass exchange. The exploding primary will then be more massive than its unevolved companion and the first supernova explosion disrupts the system in most cases. In the rare cases that it remains bound, the system will have a large runaway velocity and, after a very long ($10^8 - 10^9$ yr) inactive stage evolves into a low-mass X-ray binary, possibly resembling Her X-1.

1. Introduction

The X-ray binaries clearly represent a late stage in the evolution of close binaries. In three of these systems the X-ray emitting component is a pulsar, which is most probably an accreting rotating magnetized neutron star (cf. Pringle and Rees, 1973); in one other (Cyg X-1) it may be a black hole (cf. Giacconi, 1975). Accreting white dwarfs are not expected to appear as strong sources of hard X-rays (e.g. Peterson, 1973; Giacconi, 1975), which is confirmed by the absence of any appreciable flux of hard (and in most cases even soft) X-rays from the cataclysmic variables (Heise *et al.*, 1975).

The X-ray binaries can be divided into at least two groups, the massive ones and the low-mass ones, listed in the upper and middle parts of Table I, respectively. The data on the masses were taken from the references listed in the last column of the table. A third type of binary containing a neutron star is represented by the binary radio pulsar PSR 1913 + 16, whose system parameters are listed in the lower part of the table.

The Crab and Vela pulsars show that neutron stars are born in supernova events. The same is probably true for black holes. We therefore must conclude that the three types of binaries listed in Table I have survived a supernova explosion. It has long been known (Zwicky, 1957; Blaauw, 1961; Boersma, 1961) that rapid spherically symmetric mass loss from a component of a binary has two effects, *viz.*: (1) it turns an initially circular

P. Eggleton et al. (eds.), Structure and Evolution of Close Binary Systems, 35–61. *All Rights Reserved.*

orbit into an eccentric one – the orbit becomes hyperbolic if the lost amount of mass ΔM exceeds half the total mass of the system; in a close binary this is unlikely to happen, because of the occurrence of extensive mass transfer prior to the explosion (van den Heuvel, 1968; van den Heuvel and Heise, 1972); (2) it accelerates the center of gravity of the system to a certain run-away velocity, which can be as large as a few hundred km s^{-1}.

In two of the systems of Table I these two supernova effects can be clearly seen; (1) the very large orbital eccentricity of PSR 1913 + 16 must be due to the mass ejection in the supernova which produced the pulsar, since all normal close binaries with $P < 4^d$ have circular orbits (Plavec, 1970), presumably due to strong tidal interaction; (2) Her X-1 is about 3 kpc away from the galactic plane; nevertheless, it is a Population I object that must have originated in the galactic plane since its non-degenerate component has a mass of $\sim 2 M_\odot$ (lifetime $<10^9$ yr). To reach its present distance above the plane it must have been shot out of the plane with a z-velocity exceeding 125 km s^{-1} (Sutantyo, 1975); therefore, this system is clearly a run-away object.

It seems impossible to review all conceivable final stages of close binary evolution. Especially in cases A and C, in the terminology of Kippenhahn and Weigert (1967), our knowledge about the final evolution is still poor and the range of possibilities seems large.

For case B, however, in which the primary star fills its Roche lobe when it is in the stage of hydrogen shell burning around a helium core, the picture seems fairly clear and straightforward. Fortunately, nature has been so generous as to make this type of evolution the most common one among the observed unevolved close binaries, over 70% of which are expected to evolve according to this case (van den Heuvel, 1969). Just because of this sheer abundance, most of the late stages of CB evolution which we observe in nature must be products of case B evolution. We will therefore concentrate here only on this case. We will first, in Section 2, deal with so-called 'conservative' evolution, i.e. evolution in which the total mass and orbital angular momentum of the systems are assumed to be conserved. In Sections 2.7 and 3 we will give some rough considerations about non-conservative evolution, which is expected to be of importance for understanding origin of PSR 1913 + 16 and possibly also of Her X-1. For earlier reviews of close binary evolution, see Plavec (1968) and Paczynski (1971a). The latter paper contains some considerations on the fate of CB systems, which form the basis of the later work reviewed here.

2. Expected Evolution in the Conservative Case B

2.1. ASSUMPTIONS

The conservative assumptions – used in most computations of CB evolution up till now – are:

(1) Circular orbits;

(2) Conservation of the total mass of the system:

$$M_1 + M_2 = M = \text{const.} \tag{1}$$

(3) Conservation of total orbital angular momentum of the system:

$$J^2 = aM_1{}^2 M_2{}^2/(M_1 + M_2) = \text{const.}, \tag{2}$$

which, with Equation (1) leads to the following simple relation for the change of the orbital radius a during the mass exchange:

TABLE I

Close binaries containing a neutron star or a black hole

A. X-ray Binaries

Name	X-ray source		Optical candidate			Binary Period	Most plausible mass ($M_\odot$)		Ref.
	P_x (day)	t_{eclipse} (day)	Name	Spectral type	m_v (mag)	(day)	Primary	Secondary	
Cyg X-1	5.6 (soft X only)	–	HD 226868	O 9.7 I ab	8.9	5.6	$\gtrsim 20$	$\gtrsim 9$	1, 2
3 U 0900–40	8.95	1.7	HD 77581	B 0.5 I a	7.0	8.95	~25	$\gtrsim 2$	2
3 U 1700–37	3.412	1.1	HD 153919	O 6.5 f	6.7	3.412	$\gtrsim 25$	$\geqslant 1.4$	2
SMC X-1	3.89	0.6	Sk 160	B0 I	13.6	3.89	20–30	2.2–4	1, 2
Cen X-3	2.087	0.5	Krzeminski's star	O6.5 II–Ve	13.35	2.087	~18	~1	1, 2
Her X-1	1.7	0.24	HZ Her	B-F	13.1–14.7	1.7	2.0–2.5	1–1.3	1, 2
Sco X-1	–	–	V 818 Sco	Nova-like	12.4–13.6	0.787	~1	~1	2, 3

B. Binary pulsar

PSR 1913 + 16	$P_{\text{pulse}} = 0.059$ s	$P_{\text{orbit}} = 7^{\text{h}}45^{\text{m}}$	$e = 0.61$	$M_1 \sim M_2 \sim 1.4$	$d \sim 5$ kpc	4

References: 1. Avni and Bahcall (1975) – 2. Bahcall (1975) – 3. Hutchings (1976) – 4. Hulse and Taylor (1975).

$$a/a_0 = [M_1{}^0\ M_2{}^0/M_1\,(M-M_1)]^2 \tag{3}$$

where sub- and superscripts zero denote the initial situation.

(4) The stars co-rotate with the orbital revolution of the components, so that the stellar radius R cannot exceed the radius R_{Roche} of the Roche lobe, where R_{Roche} is in general defined as the radius of a sphere that has the same volume as the lobe.

In fact, assumption (3) and (4) are not consistent with each other; however, since even in contact systems the combined rotational angular momentum is less than 10% of the orbital angular momentum, the conversion of some orbital into rotational angular momentum will give only negligible disturbances to Equations (2) and (3).

Of course, the assumptions (2) to (4) cannot be fully justified in real-life binaries, since we observe mass loss from many systems. The most famous example is β Lyr (see Sahade's review in this volume). Nevertheless, in cases in which the initial mass ratio $q_0 = M_2{}^0/M_1{}^0$ is not too much different from unity (i.e. between ~0.3 and 1.0) these assumptions are probably not too bad since the changes in orbital radius during the mass exchange as inferred from Equation (3) are less than a factor of two, and the components are not expected to deviate too strongly from co-rotation during the exchange.

2.2. RESULTS OF THE FIRST STAGE OF MASS EXCHANGE IN CASE B

According to the definition of case B (Kippenhahn and Weigert, 1967) the primary star does not fill its Roche lobe before it has left the main sequence. At that moment it has a contracting helium core and an expanding hydrogen-rich envelope. All computations carried out for this case show that the mass transfer does not terminate before most of the hydrogen-rich envelope has been lost to the secondary star (Kippenhahn and Weigert, 1967; Paczynski, 1967, 1971a).

The most detailed computations for massive systems in this case were carried out by Kippenhahn (1969), Tutukov and Yungelson (1973a) and De Loore *et al.* (1975a, b). As an example, Figure 1 shows the results for a system with components of $20 M_\odot$ and $8 M_\odot$ and an initial orbital period of 4.70 days, computed by De Loore *et al.* (1975a).

Figures 2a, b, c depict the evolution of this system up till the end of the first stage of mass exchange. After 6.17×10^6 yr the primary fills its Roche lobe (b); in 3×10^4 yr it transfers $14.66 M_\odot$ to its companion. The mass loss terminates when core helium burning is ignited. The star then has a mass of $5.34 M_\odot$ and moves to the helium main sequence (see Figure 1); its companion has become a $22.66 M_\odot$ normal main-sequence star. Due to the growth of its convective core and the resulting mixing in of fresh hydrogen from the envelope, the secondary is very close to the zero age main-sequence (see Figure 1). From Equation (3) and Kepler's third law one finds that the binary period has increased to 10.86 days.

Systems like this one, consisting of a massive helium star and an unevolved early-type main-sequence star closely resemble the Wolf-Rayet binaries, as was pointed out by Paczynski (1967). Table II lists, as an example, the properties of a number of well studied Wolf-Rayet binaries. The Wolf-Rayet star has always a much smaller mass than its companion; nevertheless, these stars are very blue and luminous, as expected for a helium star (with possibly a small hydrogen-rich envelope). A careful discussion by Smith (1968, 1973) shows that many of the other properties of Wolf-Rayet binaries can also be understood on the basis of this model.

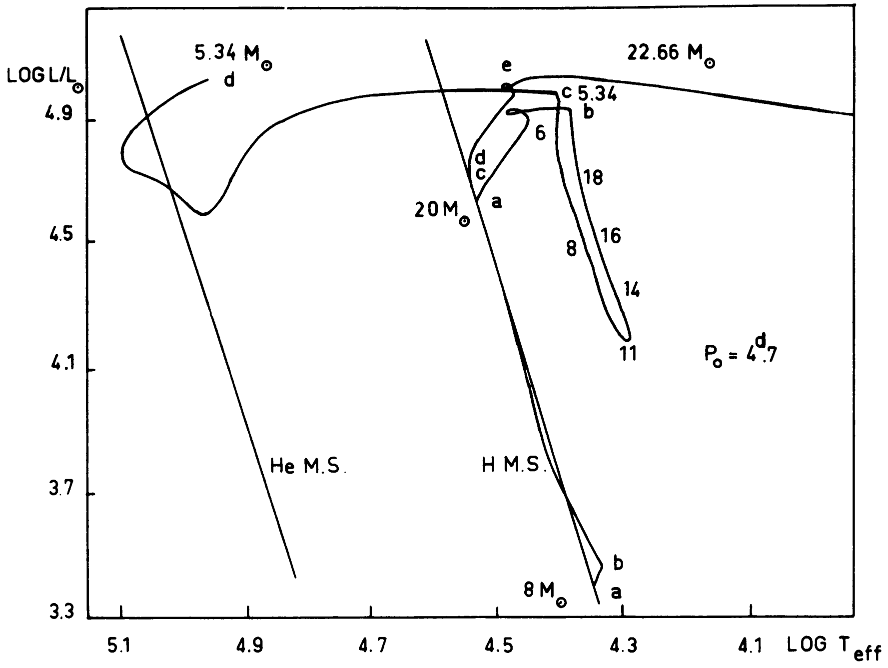


Fig. 1. Evolutionary tracks in the Hertzsprung-Russell diagram of the components of a close binary with initial masses of $20 M_\odot$ and $8 M_\odot$ and an initial period of 4.70 days, computed by De Loore *et al.* (1975a) with the assumptions of conservation of total mass and orbital angular momentum. Letters correspond to the evolutionary phases depicted in Figure 2. The first stage of mass transfer begins in *b* and terminates in *c*. In *d* the primary (a $5.34 M_\odot$ helium star) explodes as a supernova. In *f* the secondary reaches its Roche lobe and the second phase of mass exchange begins. Some values of the mass of the primary are indicated along its mass-loss track.

TABLE II

Double-lined and eclipsing WR binaries with known orbits

	Star	Spectral type	P(day)	$M_W \sin^3 i$	$M_{OB} \sin^3 i$	M_W / M_{OB}	P_F (day)	
							$M_F = M_\odot$	$M_F = 4M_\odot$
1	HD 152270	WC7 + O8	8.82	1.85	6.85	0.28	15.8	11.4
2	HD 186943	WN5 + OB	9.55	5.8	21.0	0.28	14.4	11.6
3	HD 193576 (V444 Cyg)	WN6 + B1	4.21	9.5	24.1	0.39	7.4	6.2
4	HD 211853	WN6 + B0	6.68	7.6	19.1	0.39	11.8	9.3
5	HD 214419 (CQ Cep)	WN5 + B1?	1.64	($f(m) = 4.38$)		–	2.5	1.99
6	HD 228766	WN7 + OB	10.6	4.6	22.3	0.21	14.3	11.2
7	HD 68273 (γ^2 Vel)	WC7 + O7.5	78.5	13.0	46.3	0.28	148	130
8	HD 168206	WN5 + O	29.67	8.2	24.8	0.33	51	42
9	HD 190918	WN5 + B0	85	0.21	0.78	0.27	145	119

2.3. EVOLUTION AFTER THE FIRST STAGE OF MASS EXCHANGE

The subsequent evolution of the system, now consisting of a helium star and an unevolved main-sequence star, depends on the mass of the helium star. Two cases are possible:

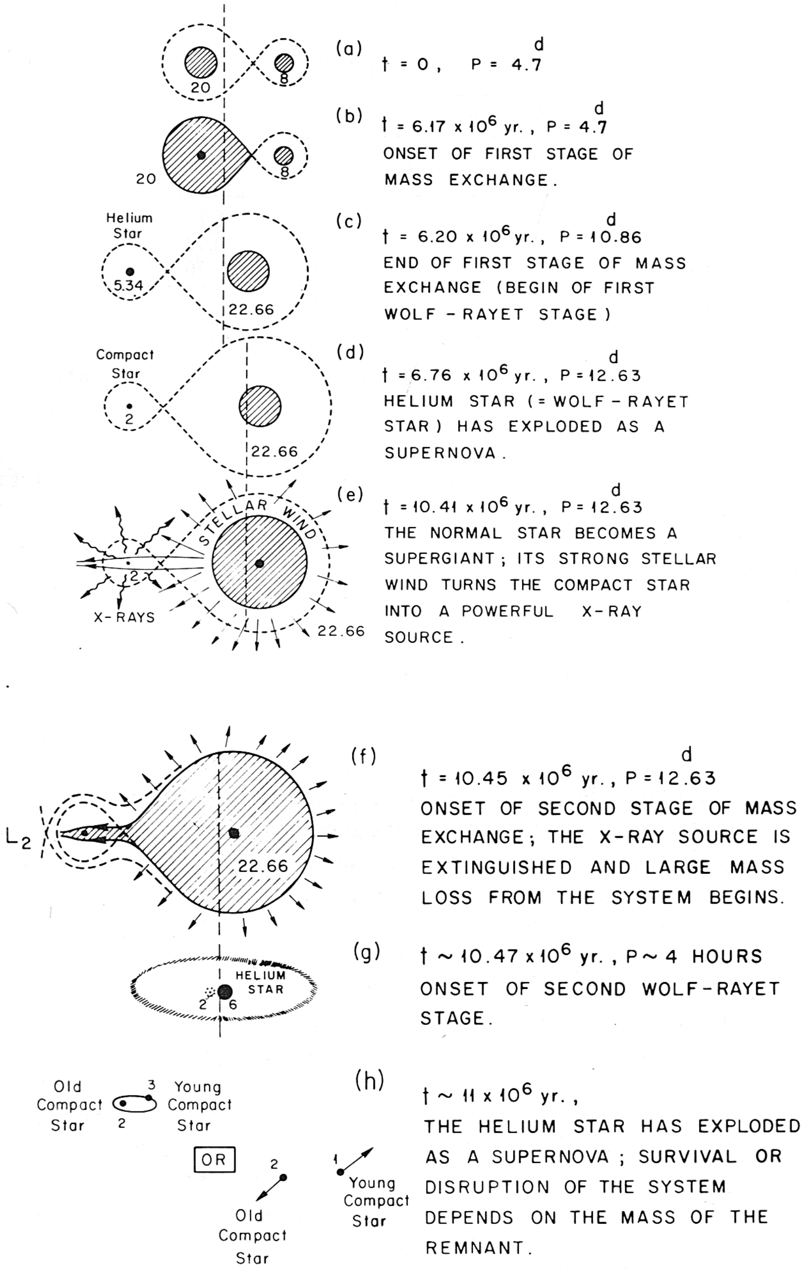
(i) If the helium star has a mass below $1.4 M_\odot$ (the Chandrasekhar limit) it can, without difficulty, finish as a white dwarf. A $1.4 M_\odot$ helium core corresponds to an initial primary mass $M_1{}^0$ of about $8 M_\odot$. For systems with $M_1{}^0 \lesssim 3 M_\odot$ the evolution to the white dwarf stage has been verified by computations (Kippenhahn *et al.*, 1967; further references in Paczynski, 1971a); here the mass of the helium star is too low for the ignition of helium burning and, after a long hydrogen shell burning subgiant phase, the star finishes as a helium white dwarf. For $M_1{}^0 \gtrsim 3 M_\odot$, the helium stars are more massive than $0.4 M_\odot$, and ignite helium.

(ii) For initial primary masses larger than $8 M_\odot$, the mass of the helium core is larger than $1.4 M_\odot$, and in order to see whether subsequent stages of mass transfer might bring its mass below the Chandrasekhar limit, one has to follow the detailed further evolution of the helium star.

Computations by Paczynski (1971b), Arnett (1972, 1973, 1974, 1975) and Savonije (1976) show that helium stars more massive than about $3 M_\odot$ do not expand to radii larger than about $2 R_\odot$ during helium and carbon burning, whereas helium stars with masses $\leqslant 2.25 R_\odot$ will, during helium shell burning move to the giant region. Table III, after Arnett (1975) lists the radii of helium stars with masses between $3 M_\odot$ and $16 M_\odot$ up to the onset of silicon burning. Since the subsequent lifetime of the stars is negligible, after this stage no further envelope expansion is expected until the collapse of the core. The table shows that in close binaries helium stars with $M > 3 M_\odot$ are not expected to have further mass transfer to their companion. As their masses are larger than the Chandrasekhar limit, and a collapsing iron core forms in their interior (Arnett, 1973, 1975) such stars are expected to finish their life with a supernova explosion, leaving behind a neutron star or a black hole. A helium star of $3 M_\odot$ is the core of a hydrogen-rich star of about $12 M_\odot$. Consequently, the lower mass limit for finishing with a supernova explosion, for primaries of mass-exchange binaries, is expected to be around $12 M_\odot$ (see also De Loore and De Grève, 1976). This limit may, in real life, be somewhat higher still if one takes into account that helium stars more massive than about $4 M_\odot$ or $5 M_\odot$ are likely to be identified with Wolf-Rayet stars, which are observed to undergo substantial mass loss by stellar wind. Mass loss rates between $10^{-6} M_\odot \mathrm{yr}^{-1}$ and $10^{-5} M_\odot \mathrm{yr}^{-1}$ have been reported for these stars (cf. Underhill, 1973). Although the total duration of the strong-wind stage of Wolf-Rayet stars is unknown it seems quite possible that during its $\sim 10^6$ yr lifetime a $4 M_\odot$ helium star may loose a solar mass in this way. In that case, in order to finish with a supernova, one might have to start with a helium star more massive than $4 M_\odot$ (initial mass $15 M_\odot$). Hence the lower mass limit for finishing with a supernova is, roughly, expected to be in the range $12 M_\odot$ to $15 M_\odot$. The above possibilities for the final evolution of the primaries of case B close binaries are put together in Table IV.

2.4. EFFECTS OF THE SUPERNOVA EXPLOSION ON THE ORBIT

As an example we follow the further evolution of the system of Figures 1 and 2c. Since here the helium star has a mass of $5.34 M_\odot$, we expect it to finish its life with a supernova explosion. The helium star reaches the end of carbon burning some 5.6×10^5 yr after the first stage of mass exchange. Due to neutrino losses, the duration of the subsequent



(a) $t = 0$, $P = 4.7^d$

(b) $t = 6.17 \times 10^6$ yr., $P = 4.7^d$
ONSET OF FIRST STAGE OF MASS EXCHANGE.

(c) $t = 6.20 \times 10^6$ yr., $P = 10.86^d$
END OF FIRST STAGE OF MASS EXCHANGE (BEGIN OF FIRST WOLF-RAYET STAGE)

(d) $t = 6.76 \times 10^6$ yr., $P = 12.63^d$
HELIUM STAR (= WOLF-RAYET STAR) HAS EXPLODED AS A SUPERNOVA.

(e) $t = 10.41 \times 10^6$ yr., $P = 12.63^d$
THE NORMAL STAR BECOMES A SUPERGIANT; ITS STRONG STELLAR WIND TURNS THE COMPACT STAR INTO A POWERFUL X-RAY SOURCE.

(f) $t = 10.45 \times 10^6$ yr., $P = 12.63^d$
ONSET OF SECOND STAGE OF MASS EXCHANGE; THE X-RAY SOURCE IS EXTINGUISHED AND LARGE MASS LOSS FROM THE SYSTEM BEGINS.

(g) $t \sim 10.47 \times 10^6$ yr., $P \sim 4$ HOURS
ONSET OF SECOND WOLF-RAYET STAGE.

(h) $t \sim 11 \times 10^6$ yr.,
THE HELIUM STAR HAS EXPLODED AS A SUPERNOVA; SURVIVAL OR DISRUPTION OF THE SYSTEM DEPENDS ON THE MASS OF THE REMNANT.

Figs. 2a-b. Subsequent stages in the evolution of the massive close binary of Figure 1. It is assumed that the supernova explosion of the primary leaves a $2 M_\odot$ compact star (neutron star or black hole).

TABLE III

Radii of helium stars at the onset of various burning stages (in $R_{\odot}$) (Arnett, 1975)

Burning stage	Stellar mass			
	$3M_{\odot}$	$4M_{\odot}$	$8M_{\odot}$	$16M_{\odot}$
He	0.4	0.5	0.76	1.1
C	1.4	1.2	1.05	0.75
Ne	4.5[a]	2	1.2	0.70
O	14[a]	2	1.2	0.75
Si	21[b]	2	1.3	0.8

[a] Shell ignition

[b] Last model has not yet ignited fuel; radius still increasing

evolutionary stages up to the core collapse is less than a few times 10^3 yr. It is therefore justified to assume that about 5.6×10^5 yr after the mass exchange the helium star explodes as a supernova. This is 6.76×10^6 yr after the birth of the system (Figure 2d). At that moment its $22.66 M_{\odot}$ companion is still very close to the Zero Age Main-Sequence; as indicated in Figure 1 it needs another 3.64×10^6 yr to terminate its hydrogen burning.

The effects of the supernova explosion on a binary system in which the less massive component explodes have been explored by various authors, in increasing degrees of detail (cf. van den Heuvel, 1968; van den Heuvel and Heise, 1972; van der Laan and Verhulst, 1972; Sutantyo, 1973, 1974a, 1975; Wheeler *et al.*, 1974, 1975; Cheng, 1974; De Loore *et al.*, 1975a,b).

The most important effects of the explosion on the orbit are due to:

(1) The sudden mass loss, which causes the binding energy of the system to decrease, thus increasing the separation and eccentricity, and giving the system a recoil velocity due to the orbital momentum carried away in the supernova shell.

(2) The impact of the supernova shell onto the companion which:

(i) directly imparts radial momentum to this star;

(ii) indirectly imparts radial momentum due to the backward blow-off of matter from this star ('rocket effect') produced by the reflection of the supernova shock wave against the density gradient in the stellar interior. The rocket effect amplifies the effect of direct impact by a factor of order $(1 + ln(V_{ej}/V_{esc}))$, where V_{ej} is the ejection velocity of the supernova shell ($\sim 10^4$ km s^{-1}) and V_{esc} is the escape velocity from the surface of the companion star (Colgate, 1970; McCluskey and Kondo, 1971; Wheeler *et al.*, 1975). For a massive main-sequence companion this factor is around 3.5;

(iii) blows some envelope matter off the companion in forward direction. For a $20 M_{\odot}$ companion and a binary period of a few days, the amount blown off does not exceed about one solar mass (Wheeler *et al.*, 1974, 1975; Cheng, 1974), but causes a considerable decrease in the stellar radius. This effect therefore considerably reduces the effective cross section of the star and therefore reduces the effects mentioned under (i) and (ii) (Wheeler *et al.*, 1974, 1975).

(3) Possible asymmetries in the mass ejection. Pulsar observations indicate that pulsars receive a kick of about 100 km s^{-1} at their birth (cf. Ruderman, 1972; Manchester *et al.*,

TABLE IV

Anticipated final results of case B mass exchange

Initial primary mass	$M_1{}^0 \lesssim 3M_\odot$	$3M_\odot \leqslant M_1{}^0 \leqslant 12\text{–}15 M_\odot$	$M_1{}^0 > 12\text{–}15 M_\odot$
Remnant of primary after first mass exchange	Hydrogen shell-burning subgiant with degenerate helium core (Algol system)	Almost pure helium star in the stage of core helium burning $M_{\mathrm{He}} \leqslant 3\text{–}4 M_\odot$	Almost pure helium star in the stage of core helium burning $M_{\mathrm{He}} > 3\text{–}4 M_\odot$
Further evolution of primary	Further loss of hydrogen-rich envelope on a nuclear time-scale	Further extensive mass transfer during helium shell burning	No further extensive mass transfer (but some mass loss by stellar wind during Wolf-Rayet stage)
Final remnant of primary	Pure helium white dwarf with $M \lesssim 0.4 M_\odot$	Probably a white dwarf with $M < 1.4 M_\odot$	Supernova, leaving behind a neutron star or a black hole

1974). An instantaneous kick of this magnitude – presumably due to asymmetries in the mass ejection – can be easily accounted for in the equations describing the orbital changes (e.g. cf. Flannery and van den Heuvel, 1975; Mitalas, 1976).

Figure 3a shows the resulting orbital eccentricity for the binary of Figure 2d, as a function of the kick angle Φ, as defined in Figure 3b. A kick velocity of 100 km s^{-1} was adopted and the compact remnant was assumed to have a mass of $2 M_\odot$. All other above mentioned effects of the mass loss and impact were included. Results are shown here for $V_{ej} = 10^4$ and 2×10^4 km s^{-1}. The figure shows that the system can only be disrupted for kicks in the direction of the orbital motion ($\Phi \sim 90°$). Assuming the kicks to have a random distribution of Φ-values, one observes from the figure that most (>80%) massive close binaries will survive the supernova explosion of the most evolved component. The figure further shows that with kicks in the backward direction ($\Phi \sim 270°$) the binary period after the explosion is about 6 days, i.e. considerably shorter than before.

If the explosion is symmetric, and the effects (1) and (2) are included, the binary period after the explosion is 12.63 days (for an adopted remnant mass of $2 M_\odot$) as depicted in Figure 2d. The runaway velocity imparted to the center of gravity of the system is given by

$$V_g = e_2 M_2 / M_1 \qquad (4)$$

where M_1 and M_2 denote the masses of the exploding star and its companion before the explosion, respectively, V_2 is the orbital velocity of the companion before the explosion and e is the orbital eccentricity after the explosion.

This equation is general and holds regardless whether or not the impact effects and kicks are taken into account (Sutantyo, 1975). In the case of systems like that of Figure 2, V_g is around 30–50 km s^{-1}

Since systems like the one of Figure 2c are thought to be identified with Wolf-Rayet binaries, one can calculate the orbital periods and eccentricities that would result if the

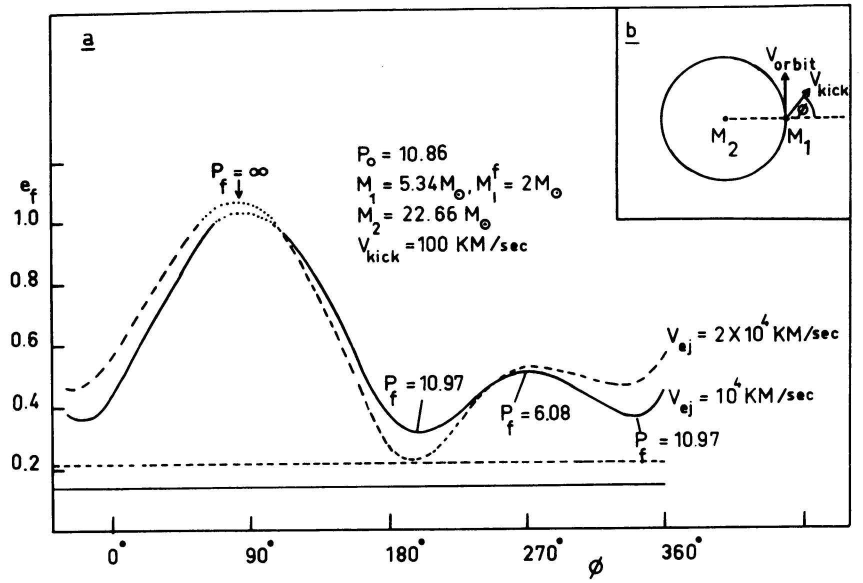


Fig. 3a. The effects of asymmetric mass ejection on the post-supernova orbital eccentricity of the system of Figure 2c–d, for two values of the ejection velocity of the supernova shell. It is assumed that the compact star receives at its birth a kick in the orbital plane of 100 km s^{-1}, directed under an angle Φ, as defined in Figure 3b. Effects of impact were taken into account. The straight lines represent the eccentricities resulting from symmetric mass ejection.

Wolf-Rayet stars in the systems of Table II would explode as supernovae. These periods, for remnant masses of $1 M_\odot$ and $4 M_\odot$, respectively, and spherically symmetric explosions are listed in the last columns of the table. One notices that for the shorter period systems the expected system parameters after the explosion closely resemble those of the massive X-ray binaries of Table I (cf. van den Heuvel, 1973a).

2.5. EVOLUTION OF THE SYSTEM AFTER THE SUPERNOVA EXPLOSION OF THE PRIMARY

The following stages are expected:

A. *Supernova remnant*

During the first 10^5 yr after the explosion an expanding supernova shell may be visible around the system. If the compact star is a neutron star, it may be very active, like the Crab pulsar, during the first $\sim 10^4$ yr of this stage, producing a large amount of relativistic particles and high energy radiation. During this relatively short timespan the system is expected to appear as a peculiar early-type star with, possibly, a flaring optical behaviour and a peculiar emission spectrum. If the compact star is a black hole, this stage is absent.

B. *Quiet stage*

After some 10^4 yr the energy emission from the pulsar will have dropped below one percent of the optical emission from its companion, and the system is expected to appear as a normal early-type single-lined spectroscopic binary with a small radial velocity amplitude. The bombardment with relativistic particles during the active period of the neutron star may have caused surface abundance anomalies: the spectroscopically peculiar helium-weak early B-type stars in OB associations may perhaps have been produced in this way (van den Heuvel, 1974).

The system remains in this quiet stage (between Figures 2d and 2e) for some $3.6 \cdot 10^6$ yr, i.e. *for about one third of its total lifetime.*

C. *X-ray stage*

Some 3.6×10^6 yr after the supernova explosion (10.41×10^6 yr after the birth of the system) the $22.66 M_\odot$ secondary has terminated its core hydrogen burning and begins its post main-sequence expansion phase. It then becomes an early-type supergiant.

Ultraviolet observations of such stars show evidence for considerable mass loss in the form of a stellar wind (cf. Morton, 1969). The observed mass loss rates of B0Ia supergiants are of the order of $10^{-6} M_\odot \mathrm{yr}^{-1}$, whereas main-sequence stars of similar type only show mass loss rates of the order of $10^{-9} M_\odot \mathrm{yr}^{-1}$ (Rogerson and Lamers, 1975). The winds of early supergiants are thought to be driven by the large radiation pressure in their envelopes, combined with low surface gravities (Lucy and Solomon, 1970; Castor *et al.*, 1975).

It is in this supergiant stage, when the star does not yet fill its Roche lobe but does have a large mass loss rate by stellar wind, that one expects the system to become an X-ray binary, as was suggested independently by Ostriker (1972) and Börner *et al.* (1972), (cf. Davidson and Ostriker (1973)). The compact companion captures only that fraction of the wind matter that passes it closely enough to be deflected over an angle of ~90°. Computations show that, due to the large observed wind velocities (600–1500 km s^{-1}), this fraction is only 10^{-5} to 10^{-3} of the total stellar wind flux (Davidson and Ostriker, 1973; van den Heuvel, 1975). This results, for supergiants, in an accretion rate of 10^{-11} to $10^{-9} M_\odot \mathrm{yr}^{-1}$ onto the compact star, which is sufficient to turn a $1-2 M_\odot$ neutron star or black hole into a $10^{35}-10^{37}$ erg s^{-1} X-ray source i.e. about the observed strength of the massive X-ray binaries (see also Rees, 1976). This X-ray stage is depicted in Figure 2e.

D. *Roche-lobe overflow*

When the radius of the supergiant reaches the critical (Roche or tidal) lobe, the rate of mass loss towards the companion will suddenly increase very much, as the envelope of the supergiant will become thermally unstable in the usual way. This results in mass loss on a thermal timescale, at a rate of some $10^{-4} M_\odot \mathrm{yr}^{-1}$. In view of the low outflow velocities along the first Lagrangian point, most of this matter will – at first – be gravitationally captured by the compact star. However, at such large accretion rates, the regions around the X-ray source become optically thick, and the X-rays will be degraded to photons of lower energy which finally escape as optical or ultraviolet radiation. As shown by Shakura and Sunyaev (1973), at accretion rates larger than $\sim 10^{-6} M_\odot \mathrm{yr}^{-1}$ the compact object will appear as a bright optical star, and no longer as an X-ray source. Therefore, soon after the supergiant reaches its critical lobe, the X-ray source will be extinguished, as is depicted in Figure 2f.

2.6. THE DURATION OF THE X-RAY STAGE

As a rough estimate of the duration of this stage we take the time-interval between the moments when the secondary star leaves the main-sequence and when it fills its Roche lobe. The rapid expansion of the supergiant's envelope terminates when core helium burning is ignited. The precise radius of the star at that moment depends on the detailed treatment of convection. Computations by Chiosi and Summa (1970), Simpson (1971), Sreenivasan and Ziebarth (1974), Tutukov and Yungelson (1973a, b), show that in any case stars with masses between $15 M_\odot$ and $30 M_\odot$ rapidly expand to a point where log $T_e < 4.15$, corresponding to $R > 40$–$60\ R_\odot$. In binaries with $P < 14$ days such stars will overfill their Roche lobes. Therefore the supergiant stage which we presently observe in the X-ray binaries is presumably still prior to helium ignition. However, if considerable mass loss from the envelope has taken place e.g. by enhanced winds, this statement needs no longer be true. Assuming that it is true, one expects from the evolutionary tracks computed by the above mentioned authors and by De Loore *et al.* (1975a, b) that the duration of the X-ray stage will be some 5×10^4 yr for a $15 M_\odot$ primary and some 2×10^4 yr for a $30 M_\odot$ primary. In Figures 1 and 2 an X-ray lifetime of 4×10^4 yr was adopted. Table V summarizes the duration of the various evolutionary stages of the system.

2.7. THE FINAL EVOLUTION OF THE MASSIVE X-RAY BINARIES

The evolution during the second stage of mass transfer is not well known in detail. Several lines of reasoning lead, however, to the conclusion that very probably the orbit will shrink rapidly in this stage (see also Section 2.10B). We give here two lines of rather speculative thought of how this might happen.

(i) *With the concept of Roche lobes.* When the accretion rate onto the compact star exceeds $10^{-6} M_\odot \text{yr}^{-1}$ the accretion luminosity will exceed the critical Eddington luminosity, and further accretion onto the compact star is inhibited (here corrections for neutrino losses were taken into account, cf. Wilson and Ruffini, 1975). However, the supergiant, when overflowing its Roche lobe, transfers some $10^{-4} M_\odot/\text{yr}$ to the compact star, i.e. 10^2 times the critical rate (see Figure 2f). The bulk of this matter cannot be accepted by the compact star, and will therefore pile up around it, and – if it is not immediately expelled – will form a very extended red supergiant-like envelope with a radius of some $1000 R_\odot$ (cf. Thorne and Zytkow, 1975). If the matter is expelled immediately (i.e. by the large radiation pressure around the compact star or by spinning off from the edge of an accretion disk around this star, it will carry away a specific angular momentum of the same order as the orbital angular momentum per unit mass of the compact star, i.e. a factor $q = M_s/M_c$ times the mean angular momentum per unit mass, of the system, where M_s and M_c denote the masses of the supergiant and the compact star. Therefore, the mass loss causes the mean specific angular momentum of the system to decrease rapidly, which results in a rapid shrinking of the orbit (van den Heuvel and De Loore, 1973). If the transferred matter is not expelled immediately, the envelope which forms around the compact star will extend to far beyond the second Lagrangian point L_2 (and that of the blue supergiant probably extends to beyond L_3). Matter beyond L_2 will be lost from the system and carries away per unit mass $(1 + 0.2/q)$ times the specific orbital angular momentum of the secondary, leading to an even faster shrinking of the orbit than considered above (cf. Webbink, 1975a).

(ii) *With the concept of 'spiralling-in'.* Another way of looking at the problem is to say that the compact star is engulfed by the envelope of the supergiant, inflates this envelope very much by its radiation pressure, and spirals down into it due to friction (cf. Ostriker and Dupree, 1975; Paczynski, 1976). This spiralling-in will certainly occur if in a synchronous orbit the ratio $Y = I_{\mathrm{orb}}/I_{\mathrm{rot}}$ of the orbital angular momentum and the rotational angular momentum of the non-degenerate star, is smaller than 3, since in that case the system becomes tidally unstable, and the compact star will spiral down into the primary on a timescale of less than 10^3 yr (Alexander, 1973; Sutantyo, 1974b; Wheeler *et al.*, 1974; De Grève *et al.*, 1975; Wheeler and Lecar, 1976).

It appears therefore, that in any conceivable case the orbit will rapidly shrink, and large mass loss from the system will occur. Roughly, the final orbital period can be calculated by equating the change in orbital energy

$$\Delta E_{\mathrm{orb}} = \tfrac{1}{2}\left(\frac{GM_1{}^0M_2}{a_0} - \frac{GM_1M_2}{a}\right)$$

to the binding energy of the envelope matter outside the orbit. It appears, for the system of Figure 2f, that this equality is fulfilled if a is reduced to $\sim 3R_\odot$ ($P \sim 4$ h); at that moment practically only the $6M_\odot$ helium core of the primary star is left. This situation is depicted in Figure 2g. Figure 4 (after van den Heuvel and De Loore, 1973) depicts the resulting final binary periods of X-ray binaries starting out with supergiants of $15M_\odot$ and $21M_\odot$, as a function of the mass of the remaining stripped supergiants core – and assuming this core to fill its Roche lobe.

The figure shows that the stripped helium cores still fit in binary systems with periods of only a few hours. Also from frictional energy dissipation arguments one expects that the end-products of spiralling-in are systems of this type (cf. Ostriker, 1976).

2.8. FURTHER EVOLUTION AFTER SPIRALLING-IN

The lifetime of the remaining very close system is determined by the evolution of the helium star. Also here the helium star will finally explode as a supernova. For a $6M_\odot$ helium star this occurs some 5×10^5 yr after the spiralling-in. In most cases the helium star will be more massive than its compact companion, and more than half of the total mass of the system will be ejected in the explosion, leading to disruption of the system. In that case two runaway compact stars are formed, one young (from the helium star) and one old (see Figure 2h). The condition for disruption in a symmetric explosion is

$$M_{\mathrm{He}} > 2M_{c2} + M_{c1} \qquad (5)$$

where M_{He}, M_{c2} and M_{c1} denote the masses of the helium star, its compact remnant and its compact companion, respectively. Equation (5) shows that, assuming the compact stars to have masses of about $1.4M_\odot$, systems with $M_{\mathrm{He}} > 4.2M_\odot$ will always be disrupted. Only if the helium star has a low mass, or if one of the compact stars is very massive (like in the Cyg X-1 system), the system may remain bound, in a very eccentric orbit. Figure 2h also depicts this possibility: since the helium star mass was fixed here, the alternative of a massive compact remnant had to be chosen. If one chooses $M_{\mathrm{He}} = 3.0M_\odot$, $M_{c1} = M_{c2} = 1.5M_\odot$, $P_0 = 2.5^{\mathrm{h}}$ (resembling the final state of the Cen X-3 system anticipated by van den Heuvel and De Loore, 1973), one obtains after the explosion of the helium star: $P = 8.7^{\mathrm{h}}$, $e \sim 0.5$, which closely resemble the parameters of the binary Pulsar PSR 1913 + 16 (Hulse and Taylor, 1975).

The small apsidal motion of this system ($\sim 4^0$ yr^{-1}) indicates that the companion of the pulsar is indeed very probably also a compact star. Therefore, it seems quite plausible

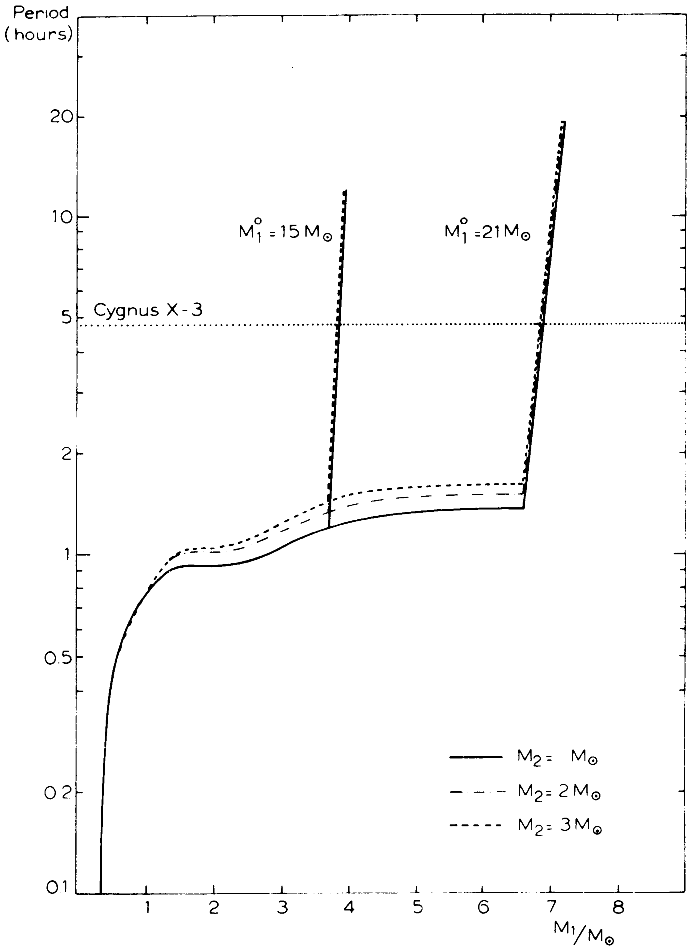


Fig. 4. Binary periods after spiral-in for systems resulting from massive X-ray binaries with initial supergiant masses $M_1{}^0$ of $15 M_\odot$ and $21 M_\odot$, for three values of the mass M_2 of the compact companion. The binary periods are plotted as a function of the mass M_1 of the remaining interior part of the supergiant, under the assumption that this star fills its Roche lobe. The sharp edges in the graphs indicate the transition from pure helium stars (nearly horizontal curves) to helium cores with a low-mass hydrogen-rich envelope (nearly vertical parts). After van den Heuvel and De Loore (1973).

that this system is the end-product of the evolution of a massive X-ray binary (Flannery and van den Heuvel, 1975; De Loore *et al.*, 1975b). From a discussion of all conceivable evolutionary scenarios for PSR 1913 + 16, Webbink (1975b) concludes that this is the only one which does not meet major objections.

2.9. THE NUMBERS OF MASSIVE BINARIES EXPECTED IN VARIOUS EVOLUTIONARY STAGES

A. *Assumptions*

We will assume here that all case B close binaries with $M_1{}^0 > 15 M_\odot$ follow an evolutionary pattern similar to the one of Figure 2, i.e. leading to an X-ray binary. Observations indicate that the birth rate of stars more massive than about $2M_\odot$ in the Galaxy was constant over the last 10^9 yr (Schmidt, 1959; Limber, 1960). Since the lifetime of a massive star ($>12-15M_\odot$) is only of the order of 10^7 yr, the number of such stars in the Galaxy will have reached a steady state in which the birth rate equals the death rate. Hence, the total number of massive close binaries (all evolutionary stages together) in the Galaxy will be constant in time, and the same will hold for the number of systems in each separate evolutionary stage. In such a steady state, the number of systems in each evolutionary stage is simply proportional to the lifetime spent in that stage.

The time spent in the various stages depends on (i) the initial mass of the primary star, $M_1{}^0$, (ii) the initial mass ratio, and possibly (iii) the amount of mass lost from the system during phases of mass transfer. Trimble's investigations (Trimble, 1974, 1976) show that the distribution of mass ratios of unevolved close binaries is bimodal, with an average value of around 0.4. Hence, the system of Figures 1 and 2 is roughly representative for the average massive close binary. Although the total lifetime of a system depends quite strongly on the value of $M_1{}^0$, the *fraction* of the total lifetime spent in each of the evolutionary stages is hardly dependent on $M_1{}^0$. Therefore, we will assume that the *ratios* of the lifetimes of the various evolutionary stages as listed in the second column of Table V are roughly representative for all massive close binaries in the conservative case B.

Hence, knowing the *total* number of unevolved close binaries (both components on the main-sequence) with $M_1{}^0>15M_\odot$ in the Galaxy, one can, with the second column of Table V, make a rough estimate of the number of systems expected in each of the subsequent evolutionary stages. The results obtained in this way appear to agree quite closely with those of more nearly exact computations, in which the distribution function of masses, mass ratios, etc. are taken into account (cf. van den Heuvel, 1969, 1973b).

B. *The total number of evolved systems expected in each stage*

The total estimated number of stars more massive than $15M_\odot$ in the Galaxy is about 20 000 (cf. van den Heuvel, 1974); within the observational uncertainties this number agrees well with that estimated by Ostriker *et al.* (1974). Blaauw and van Albada (1974) find that the percentage of close spectroscopic binaries with $q>0.17$ in four OB associations is between 25 and 33%. Assuming 20% of these systems to be unevolved and in case B, a conservative estimate of the number of such close binaries with $M_1{}^0>15M_\odot$ in the Galaxy in 4000.

From this number, together with the lifetimes from the second column of Table V, the numbers of case B systems in the later stages were computed, as listed in the five lowest lines of the third column of Table V. As to the expected number of bound systems of two collapsed stars (binary pulsars), f denotes the (unknown) probability that the system survives the second supernova explosion, and b is the probability that the observer is in the beam of the pulsar, assuming all remnants to be neutron stars.

C. *Comparison with the observations*

In order to compare the numbers from the third column of Table V with the observations, we also list, in the fourth column, the numbers of evolved systems expected within 3 kpc distance from the Sun, where the observational data on massive luminous stars are reasonably complete. A radius of the galactic disk of 13.5 kpc was adopted, as well as a uniform distribution of massive stars in the disk.

The fifth column of the table shows the observed numbers of those evolved systems on which data are available. We will discuss these here separately.

Wolf-Rayet binaries. In view of their high luminosities the survey of WR stars within 3 kpc is probably close to completeness. Stenholm (1975) lists 34 WR stars within this distance. About 50 per cent of all well studied WR stars are in close binaries with a more massive OB-type companion (Underhill, 1966); hence, the observed number of WR binaries within 3 kpc can be estimated as about 17, in good agreement with the theoretically expected number of 18.

Massive X-ray binaries. Three such systems are known within 3 kpc distance (Cyg X-1, 3U0900–40, 3U1700–37); in view of their high X-ray brightness, one does not expect more undetected systems of this type to exist within this distance. The statistical uncertainty in this small number is $\sqrt{3} \approx 1.7$.

Within the statistical and observational uncertainties, the theoretically expected (0.6 to 1.6) and observed (3 ± 1.7) numbers of these systems do reasonably agree, although the observed number seems somewhat larger than the expected.

Quiet systems. Two such systems might be known at present, *viz.* HD 108 (Hutchings, 1975) and HD 148937 (Conti, 1975). However, since such systems are very hard to distinguish from normal single-lined spectroscopic binaries, most of these systems will go undetected as such.

2.10. DISCUSSION AND CONCLUSIONS

A. *Evolution up to the X-ray stage; the expected number of systems with a quiet collapsed component*

The evolutionary scheme presented here still has a number of uncertain points. Notably, the effects of mass loss from the system during the exchange, and the details of the evolution during the second stage of mass transfer are far from being well known.

The estimated numbers of systems in various evolutionary stages as listed in Table V are uncertain by a factor two or three, since:

(1) the estimated number of stars with $M \gtrsim 15 M_\odot$ in the Galaxy may be wrong by ±50% (i.e. may be between 10 000 and 30 000);

(2) the fraction of unevolved systems in case B, and the lifetime as an X-ray binary both may be wrong by a similar ±50% (see Section 2.6).

Nevertheless, even if one takes all these uncertainties into account, the agreement between the observed and theoretically expected numbers of Wolf-Rayet binaries and of massive X-ray binaries within 3 kpc distance is quite good. The same holds for the agreement between the system parameters of the X-ray binaries and those of the binaries that would result from Wolf-Rayet systems if the Wolf-Rayet components would explode as supernovae (see Table II). Both facts give us confidence in the over-all plausibility of the evolutionary scheme for the massive X-ray binaries represented in Figure 2a-2e, which was conceived independently by van den Heuvel and Heise (1972) and Tutukov and Yungelson (1973b). Therefore, adopting this scheme, one cannot escape from the conclusion that there must be some 2400 systems in the galaxy that are in the 'quiet' stage, i.e. consist of a massive main-sequence star and a quiet collapsed (neutron star or black hole) close companion. According to Table V, the theoretically expected number of

TABLE V

Expected and observed numbers of massive case B close binaries in various evolutionary stages

Evolutionary Stage	Average relative lifetime (taken from the system of Figure 2).	Expected number in the Galaxy	Within 3 kpc from the sun	
			Expected number	Observed number
Unevolved CB with $M_1^0 \gtrsim 15 M_\odot$ and $q_0 > 0.3$	6.2×10^6 yr	[Observed ≈ 4000]		200
Double-lined Wolf-Rayet binary	5.6×10^5 yr	360	18	34 WR Stars, of which ~50% double.
Main-sequence star + compact star ['Quiet' stage]	3.6×10^6 yr	2400	120	? (possibly 2)
Massive X-ray binary	Roughly $(2-5) \times 10^4$ yr	~13–33	~0.6–1.6	3(± 1.7)
Binary Pulsar?	~5×10^6 yr	3000 fb	150 fb	0

quiet collapsar systems within 3 kpc distance is 120, with an uncertainty of about a factor of two or three.

Adopting this number, one finds that there must be some 12 such systems within 1 kpc distance, and some 50 within 2 kpc distance. Adopting $M_v < -4\overset{m}{.}5$ for a star with $M > 15 M_\odot$ and less than 1^m interstellar extinction within 1 kpc distance, one expects 12 systems to be brighter than $m_v = 6\overset{m}{.}5$, i.e. to be visible to the naked eye; the 50 systems within 2 kpc distance will still be brighter than about $m_v = 9^m$. Hence a considerable number of close binaries with a quiet collapsed component must be present among the brightest known early-type stars.

B. *Evolution beyond the X-ray stage*

The evolutionary picture for massive systems beyond the X-ray binary stage might seem rather speculative. Nevertheless, there seem no clear alternatives available. For instance, let us assume that the orbital radius would not decrease during the rapid mass loss stage which occurs when the supergiant in a massive X-ray binary overflows its critical lobe. In that case a system will result consisting of a helium star and a compact star in a wide orbit (~$30 R_\odot$) because in any case the envelope of the supergiant will become thermally unstable and will be expelled, since neither of the two stars can accept it. Such a wide binary, consisting of a Wolf-Rayet star and a collapsed star would certainly be observable as a strong X-ray source, since the system dimensions, wind velocities, mass loss rates, and column densities in that case are similar to those of systems like 3U 1700–37 and Cen X-3. Since helium stars live some 15 times longer than the supergiants in massive X-ray binaries before these reach their Roche lobe (cf. Figure 2), one would in that case expect the number of observable X-ray emitting Wolf-Rayet binaries to be some 15 times larger than the number of supergiant X-ray binaries. The absence of any X-ray emitting Wolf-Rayet binary (with the possible exception of Cyg X-3) can therefore only be explained by a very drastic decrease of the orbital radius of the systems during the second stage of mass exchange. This provides a strong observational argument in favour of the spiralling-in scenario.

3. Non-conservative Evolution of Close Binaries

3.1. BREAK-DOWN OF THE CONSERVATIVE ASSUMPTIONS

The assumptions of close binary evolution mentioned in Section 2.1 are certainly no longer valid if the mass ratio q_0 of the initial system becomes very small. Consider, for example, a system with components of $15 M_\odot$ and $2 M_\odot$ in an orbit of a = $30 R_\odot$ ($P \sim 5$ days). With the conservative assumptions, according to Equation (3) the minimum separation reached during the mass exchange is $a = 5.2 R_\odot$, which occurs when $M_1 = M_2 = 8.5 M_\odot$; the Roche lobes of the components then have radii of $2 R_\odot$. However, the radius of a zero-age main-sequence star of $8.5 M_\odot$ is already about $4 R_\odot$; so, long before reaching the minimum separation, the system will have grown into very deep contact. Furthermore, a reduction by a factor 5.8 in separation and by a factor 14 in orbital period, taking place on the thermal timescale of the primary star (10^4 yr), implies that co-rotation cannot be maintained during the mass exchange. On such a short time-scale tidal forces are certainly unable to speed up the rotation of the components by a factor 14. Hence, one certainly can no longer speak of Roche lobes.

Also, the time needed by the secondary star for accepting the matter transferred to it roughly equals its own thermal timescale. For very small q_0 values, this timescale is much longer than that of the primary star. Hence, the secondary will be unable to remain in thermal equilibrium during the mass transfer and – due to the rapid release of gravitational energy in the accreted matter – heats up so much that its envelope expands to overfill its own Roche lobe (cf. Benson, 1970; Webbink, 1975a), again leading to a contact configuration and mass loss from the system. Consequently, all conservative assumptions of close binary evolution will break down in this case.

What one expects to happen then is that, just like in the second stage of mass exchange of an X-ray binary, the secondary spirals down into the envelope of the primary (Ostriker and Dupree, 1975; Paczynski, 1976; Webbink, 1975a). There are at least three reasons for this to happen:

(1) Already before the onset of mass transfer, co-rotation cannot be maintained since the primary is in its stage of rapid post main-sequence expansion. Conservation of angular momentum during this expansion implies that its rotation becomes much slower than synchronous; the tidal forces exerted by the low-mass secondary are probably too weak to restore co-rotation on such a short timescale (cf. De Grève *et al.*, 1975). In such a case the radius of the primary can grow to within a few percent of the orbital radius before the occurrence of mass transfer (Lamers *et al.*, 1975); so when the mass transfer finally occurs the secondary will simply be engulfed by the envelope of the practically non-rotating primary star.

(2) When mass transfer occurs, the orbit will shrink so rapidly, according to Equation (3), that the orbital radius will soon be smaller than the radius of the primary.

(3) If in a synchronous orbit $Y = I_{\mathrm{orbit}}/I_{\mathrm{rot}} < 3$, the orbit will be tidally unstable and – even without mass transfer – the secondary will spiral down into the envelope of the primary on a very short timescale (see Section 2).

3.2. ROUGH ESTIMATE OF THE RESULTS OF SPIRALLING-IN

Consider – in the system of Section 3.1 – the secondary orbiting in the envelope of the primary. The amount of frictional energy released per unit time is

$$\mathrm{d}E/\mathrm{d}t = \pi R^2 \rho v \tag{6}$$

where R is the radius of the secondary, v its velocity relative to the envelope of the primary and ρ the density in this envelope, near the orbit.

Adopting $v = 200\ \mathrm{km\,s^{-1}}$ (about half the orbital velocity), $\rho = 10^{-7}$ to $10^{-6}\ \mathrm{g\,cm^{-3}}$, $R = 1.5\,R_\odot$ one finds $\mathrm{d}E/\mathrm{d}t = 10^{38}-10^{39}\ \mathrm{erg\,s^{-1}}$. Let us compare this dissipation rate with the change in binding energy during the spiral-in. The $15\,M_\odot$ star has a compact helium core of about $4\,M_\odot$ with a radius of only $0.7\,R_\odot$. Assume that the orbital radius decreases from $30\,R_\odot$ to $5\,R_\odot$, and the secondary only collects $0.5\,M_\odot$ during the spiralling in; then the amount of mass of the primary star inside the orbit changes from $15\,M_\odot$ to $4\,M_\odot$, and the orbital binding energy $E = -GM_1M_2/2a$ changes by an amount $\Delta E = -2.1 \times 10^{49}$ erg from -2.1×10^{49} erg to -4.2×10^{49} erg. This amount just roughly equals the binding energy of the envelope of the primary star. Therefore, when a decreases from $30\,R_\odot$ to $5\,R_\odot$, enough orbital energy is released in the form of frictional heating to remove the entire envelope of the primary. The timescale τ for this dissipation is roughly obtained by dividing ΔE by $\mathrm{d}E/\mathrm{d}t$ of Equation (6), resulting in $\tau \sim 10^3$ to 10^4 yr. Detailed numerical computations by Ostriker and Dupree (1975) yield similar results. This timescale is so short that the secondary will hardly have had time to collect any matter from the envelope of the primary; therefore, we assumed that it collected only $0.5\,M_\odot$. The resulting system is then expected to consist roughly of a $4\,M_\odot$ helium star with a $2.5\,M_\odot$ companion in an $a \sim 5\,R_\odot$ orbit ($P \sim 12$ h). Figures 5a–c schematically represent the evolution of this system. Notice that an important requirement for a stable configuration after spiral-in is that the primary star has a compact core, i.e. is in a post main-sequence stage of its evolution. If the star does not have a compact core, the spiral-in does not result in a decrease of the binding energy of the system. In that case (i.e. when the primary is on the main sequence) the only possible solution seems that the cores of the two stars will merge completely and that one single rapidly rotating star is formed. We will, in what follows, assume that the primary star did have a compact core, i.e. had left the main-sequence before filling its Roche lobe.

3.3. APPEARENCE OF THE SYSTEM AFTER SPIRAL-IN

Since helium stars more massive than about $4\,M_\odot$ are thought to be identified with Wolf-Rayet stars, the system in this stage is expected to resemble a single Wolf-Rayet star. Since the line-forming level in the outflowing atmosphere of a Wolf-Rayet star is situated at least some $5-10\,R_\odot$ above the stellar center (Castor and van Blerkom, 1970) one will not be able to notice the binary character of this star. In view of the high luminosity of the Wolf-Rayet star and the relatively low luminosity of its main-sequence companion, the system will appear as a single Wolf-Rayet star surrounded by a massive slowly expanding shell of matter (the expelled hydrogen-rich envelope).

Indeed a number of Wolf-Rayet stars are observed to be surrounded by a massive expanding shell, and it is a remarkable fact that these Wolf-Rayet stars are always single ones, and that no such shell has been found around a known double Wolf-Rayet star.

Therefore, it seems quite possible that such 'single' Wolf-Rayet stars are in fact very close doubles, resulting from the spiralling-in of a low mass companion into the envelope of an evolved massive star. A similar appearance is expected in case that the inspiralling low-mass companion was a compact star, like in the X-ray binaries, as depicted in Figure 2f. Also here the helium star will appear as a 'single' Wolf-Rayet star surrounded by an expanding shell; no X-ray emission is expected from such systems, as the column density in the outflowing Wolf-Rayet atmosphere outside the orbit of the compact star is expected to be more than 10 g cm^{-2}.

3.4. EVOLUTION OF THE SYSTEM AFTER SPIRALLING-IN

Also in the system of Figure 5c the helium star will finally explode as a supernova. Since it is in this case the more massive component which explodes, already the simple effects of the mass loss will make disruption of the system very likely. Moreover, due to the closeness of the system, the effects of the impact of the supernova shell on the companion are very much larger than in the system of Figure 2, and one expects hardly any such system to survive the explosion of the helium star (cf. Sutantyo, 1975). If the system would, by any accident, happen to remain bound, it will have a very large orbital eccentricity and thus, according to Equation (4), a large runaway velocity. This might in fact be what happened in the case of the Her X-1 system, as will be discussed in the next sections. The total anticipated evolution of a close binary with a low initial mass ratio is summarized in Table VI.

3.5. POSSIBLE SCENARIOS FOR THE ORIGIN OF HERCULES X-1 SYSTEM

A. *Constraints on the initial system parameters*

As noted in Section 1 the high galactic latitude of Her X-1 requires that this system was ejected from the galactic plane with a velocity $\geqslant 125 \text{ km s}^{-1}$. Equation (4) then implies that

$$e_f M_2 v_2 / M_1 > 125 \text{ km s}^{-1}, \tag{7}$$

where M_1, M_2 and v_2 correspond to the pre-explosion situation, and e_f is the eccentricity after the explosion. Since the present orbital period of the system is 1.7 days and since supernova explosions tend to enlarge the orbital period, it seems reasonable to assume an initial orbital period of the order of about one day or less. This implies, with Equation (7) and Kepler's laws, assuming a mass $M_2 = 2.5\, M_\odot$ for the nondegenerate component:

$$125 \text{ km s}^{-1} \leqslant e_f \frac{2.5}{(M_1 + 2.5)^{2/3}}\ 215 \text{ km s}^{-1}.$$

For $M_1 \geqslant 1.4\, M_\odot$ (Chandrasekhar limit) this results in a postsupernova eccentricity $e_f \geqslant 0.6$. For initial periods larger than one day, e_f becomes even larger. Hence, in any case the Her X-1 system must have had a very large eccentricity just after the explosion. Sutantyo (1975) has investigated what the initial system parameters of Her X-1, before the supernova explosion, might have been.

An important constraint on the orbits possible just after the explosion is that their total angular momentum should be equal to that of the present Her X-1 system, since the tidal dissipation which subsequently circularised the orbit cannot have changed the angular

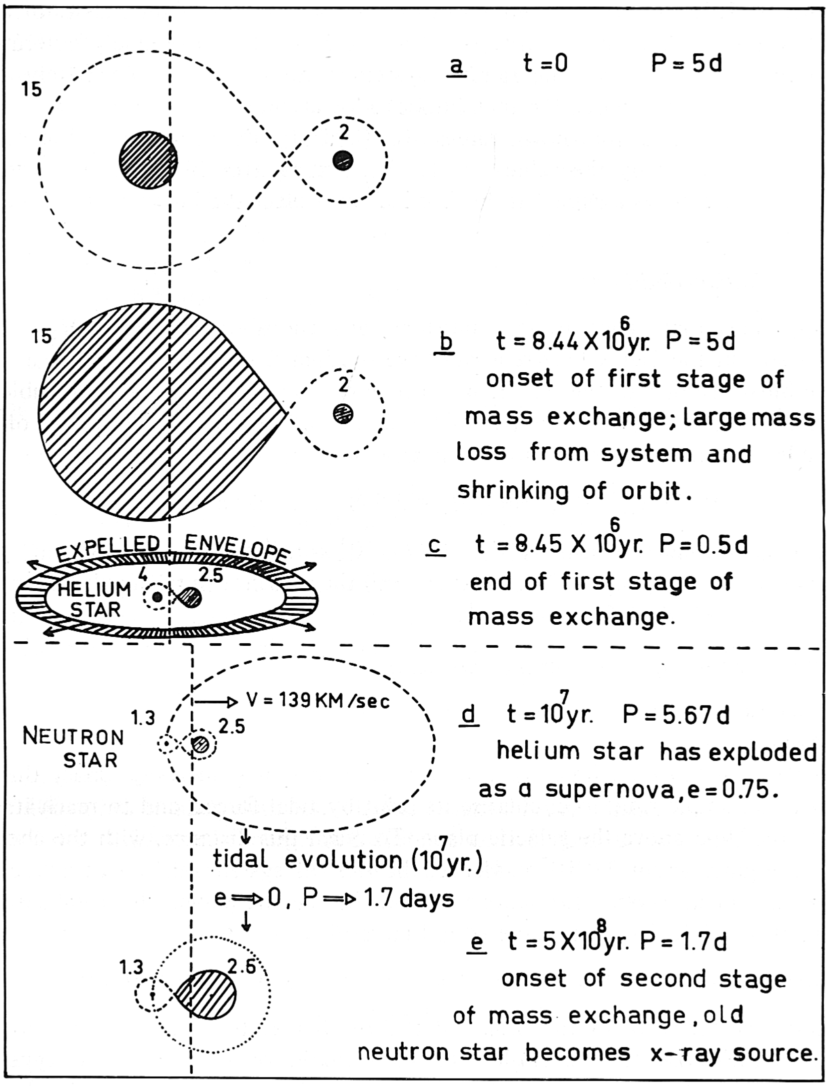


Fig. 5. 'Non-conservative' evolution of a massive close binary is expected when the initial mass ratio is very low. During the first stage of mass exchange (*b*–*c*) the system grows into very deep contact, resulting in large loss of mass and angular momentum from the system. Most of the hydrogen-rich envelope of the primary is expelled on a short timescale, the orbit shrinks rapidly and the secondary hardly collects any matter.

When the primary star explodes it still is the more massive component, and the system will practically always be disrupted. In the rare case that it remains bound, it will have a very large eccentricity and runaway velocity, as depicted in Figure 5*d*. Tidal evolution subsequently circularizes the orbit, reducing the period in this process. After a very long inactive stage the system evolves into a low-mass X-ray binary. The scenario depicted here was scaled in order to resemble the possible evolutionary history of Her X-1 (Sutantyo, 1975).

momentum. This condition, together with the present values of the masses of the components ($M_2 \sim 2.5 M_\odot$, $M_1^f \sim 1.3 M_\odot$, Avni and Bahcall, 1975) uniquely determines the (P_f, e_f) combinations which the Her X-1 system could have had immediately after the explosion. The condition $e_f \geqslant 0.6$ then implies a lower limit to P_f of 3.3 days.

On the other hand, for known values of M_1^f and M_2, the values of P_f and e_f are also uniquely determined by the values of M_1, V_{ej} and P_0 (the binary period prior to the explosion), since M_2 is assumed to be fixed if we neglect the blowing-off of matter due to impact.

B. *Possible initial conditions*

Sutantyo finds that, using these conditions, and the above given M_1^f, M_2 values, the neutron star in the Her X-1 system can have resulted from a helium star in a 'spiral-in' massive binary similar to the one depicted in Figure 5c. He finds that reasonable though not unique – since V_{ej} is a free parameter, and some variation in the values of M_1^f, M_2 is possible–system parameters prior to the explosion are:

$$M_1\ (=M_{\mathrm{He}}) = 4.00 M_\odot,\ M_2 = 2.5\ M_\odot,\ P_0 = 0.56\ \text{day}.$$

With a supernova ejection velocity $V_{ej} = 1.77 \times 10^4$ km s^{-1} and M_1^f (neutron star) = 1.3 $M_\odot$ one finds $P_f = 5.67$ day, $e_f = 0.75$ consistent with the present orbital angular momentum, and a runaway velocity of 138.9 km s^{-1}.

C. *Evolution of the system after the explosion*

At the moment of the explosion of the helium star the 2.5 $M_\odot$ companion is still near the Zero Age main sequence; only some 5×10^8 yr later this star will leave the main sequence and expand to its Roche lobe. Therefore, before becoming an X-ray binary this system will have had ample time to circularise its orbit by tidal forces, and to reach its present distance of 3 kpc above the galactic plane. To reach this distance, with the above given velocity, requires about 2×10^7 y. Hence, the Her X-1 system might – in this scenario – already have made several oscillations around the galactic plane. This total scenario for the formation of Her X-1 is represented in Figures 5c-e.

3.6. ALTERNATIVE SCENARIO FOR HER X-1: IMPLOSION OF A MASSIVE WHITE DWARF

An alternative scenario for the origin of the Her X-1 system was proposed by Gursky (1976): in analogy to the Whelan-Iben (1973) scenario for the formation of type I supernovae, he suggested that the neutron star in Her X-1 resulted from a white dwarf with a mass of about 1.4 $M_\odot$, which was driven over the Chandrasekhar limit by mass transfer from its companion.

Sutantyo (1975) computed also for this case the above indicated constraints on the initial conditions, set by the present orbital angular momentum, the runaway velocity and the allowed ranges of the present masses of the components. In this case the initial primary mass is fixed at 1.4 $M_\odot$. Using $M_1^f \geqslant M_\odot$ (the observational lower limit) and $M_2 \sim 2$ to 2.5 $M_\odot$ he finds that P_0 must have been $\geqslant 1.3$ days. This period is so long that the 2.5 $M_\odot$ star must have been in its post main-sequence expansion stage when it started the Roche-lobe overflow mass transfer that drove the white dwarf over the Chandrasekhar limit. However, as Sutantyo notices, this fact at the same time leads to an inconsistency in the scenario. Because, if the 2.5 $M_\odot$ star was already a post main-sequence star at the moment of the explosion, it would have immediately continued to expand and would, within 2×10^6 yr after the explosion, again have overflowed its Roche lobe, and produced an X-ray source. Since the lifetime of the X-ray stage is $\leqslant 5 \times 10^6$ yr (the thermal timescale of a $\geqslant 2 M_\odot$ star) the supernova in the Her X-1 system would, in this case, have taken place less than 7×10^6 yr ago. However, we know that, with the corresponding runaway velocity, the system needed at least 2×10^7 yr to reach its present position above the galactic plane. Therefore it seems that – unless the Her X-1 system is much closer to us than 5 kpc, and thus its distance above the galactic plane much smaller than 3 kpc – the neutron star in the Her X-1 system cannot have been produced by the implosion of a white dwarf with a mass near the Chandrasekhar limit*. In so far as we presently can judge, it seems therefore that the scenario of Figure 5 is the only one that is not inconsistent with all the observational evidence available on Her X-1.

3.7. DISCUSSION; RARENESS OF THE FORMATION OF SYSTEMS LIKE HERCULES X-1

In the scenario of Figure 5 the neutron star in the Her X-1 system is very old ($\sim 5 \times 10^8$ yr), i.e. much older than any of the radio pulsars. The present short pulsation period of Her X-1 can be explained in terms of speeding up by accretion – cf. Rees (1976). The scenario implies that systems like Her X-1 must be extremely rare since, as depicted in Figure 5, and also indicated by its large runaway velocity, the supernova of the (more massive) helium star will practically always disrupt such a system.

An additional argument indicating the rareness of the formation of such systems can be derived from the anticipated long X-ray lifetime for the Her X-1 system ($\sim 5 \times 10^6$ yr) in comparison with the $\lesssim 5 \times 10^4$ yr for the massive X-ray binaries. Since we know already 3 or 4 massive X-ray binaries within 5 kpc distance from the Sun, but only one Her X-1 system, we conclude that the formation rate of Her X-1 systems must be some 300 or 400 times smaller than that of the massive X-ray binaries. This implies either (i) a very low incidence of progenitor systems i.e. of massive close binaries with mass ratios <0.3 or (ii) a very large disruption probably of the systems after spiralling-in. Since there is no observational indication for a very low incidence of small mass ratios among unevolved CB systems, the second possibility seems to us the most natural one.

4. P Cygni, a Spiral-in Close Binary?

Let us consider the final evolution of a massive X-ray binary as described in Section 2.7 and depicted in Figure 2f. The calculations by Ostriker and Dupree (1975) concerning the spiral-in evolution after the onset of the second stage of mass exchange suggest that the timescale for spiralling-in is of the order of the thermal timescale of the envelope of the supergiant, which is about 10^4 yr. This is roughly of the same order as the lifetime of the preceding stage as an X-ray binary. We know three massive X-ray binaries among the stars brighter than $m_v = 9^m$ (namely 3U 0900–40, 3U 1700–37 and Cyg X-1). One therefore might expect that among the early supergiants brighter than $m_v = 9^m$ also a few stars are present which are just swallowing a compact companion. As argued in Section 2.7 such systems are expected to show an unusually large rate of mass outflow.

In this respect it is interesting to call attention to the $5\overset{m}{.}2$ star P Cyg. Apart from the

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* This inconsistency does not necessarily exist if the runaway velocity of the system after the SN explosion exceeded some 200 km s^{-1}.

TABLE VI

Evolutionary stages of massive close binaries ($M_1^0 \geqslant 15\,M_\odot$) with high and low initial mass ratios q_0 (cf. Figures 2 and 5)

	$q_0 > 0.3$	$q_0 \lesssim 0.2–0.3$
Systems after first stage of mass exchange	helium star with more massive main-sequence companion (double-lined Wolf-Rayet binary)	helium star with less massive main-sequence companion ('Single' Wolf-Rayet star?), surrounded by expanding massive shell
Result of supernova explosion of helium star (primary)	system practically always bound. Low runaway velocity (20–50 km s^{-1})	system practically always disrupted. If still bound (very rare!) system has high *e* and high runaway velocity (100–200 km s^{-1})
X-ray stage	After 10^6–10^7 yr in quiet stage, system becomes massive X-ray binary for ~(2–5) × 10^4 yr	After 10^8–10^9 yr in quiet stage, system becomes a low-mass X-ray binary for ~10^6–10^7 yr
After second stage of mass exchange	very close binary consisting of helium star and compact star	(probably: very close binary consisting of white dwarf and compact star)
Result of second supernova explosion	In most cases: two runaway compact stars. Very rarely: bound system of two compact stars	no second supernova

characteristic P Cyg lines, its underlying spectrum is that of a B1.5 Ia supergiant i.e. only slightly later than that of the supergiants in massive X-ray binaries; its absolute magnitude ($M_v \sim -7^m$) agrees with this classification (De Groot, 1969, 1973). However, the mass loss rate from this star is some 10^{-5} to $10^{-4}\,M_\odot\,\mathrm{yr}^{-1}$ (De Groot, 1969, 1973) i.e. some 100 times larger than for a normal B1.5 Ia supergiant. Two more facts make this system outstanding. First of all its very spectacular behavior in the past, which we briefly summarize here (cf. Underhill, 1966; De Groot, 1969, 1973). Before 1600 it was not visible to the naked eye. However, between 1600 and 1606 it had a brightness of $m_v = 3^m$ and between 1656 and 1659 it was at $m_v = 3\overset{m}{.}5$. Between these intervals, and between 1659 and 1715 it was much fainter and sometimes invisible to the naked eye ($m_v > 6^m$). Around 1715 it brightened to $m_v = 5\overset{m}{.}2$ and it has not appreciably changed since then. It is irregularly variable with amplitudes of at maximum a few tenths of a magnitude.

Such a behavior is difficult to understand for a normal early-type supergiant. A few more P Cyg stars have shown similar, though less drastic brightness changes; the genuine P Cyg stars are, however, very rare: only a few dozen stars of this type are known among the several thousands of catalogued supergiants (cf. De Groot, 1969). Although they are intrinsically very bright, they are not the brightest stars known; there are visual binaries in which a P Cygni star is the fainter companion to a normal early type star. Therefore the explanation that P Cyg stars are single stars that are too massive to be stable seems unlikely to us (cf. De Groot, 1969). During the times of maximum brightness the luminosity of P Cyg must have been around (1–2) × $10^6\,L_\odot$, some 7 times its present bolometric luminosity. Luminosities of this kind can probably without much difficulty be obtained from a temporarily supercritical accretion disk around a compact companion, as is demonstrated by the fact that the X-ray source SMC X-1 and some of the LMC sources sometimes have $L_x \sim 2 \times 10^5$ to $10^6\, L_\odot$. Such a super-critical disk might form during a period when the rate of mass transfer changes drastically, as will be the case when the supergiant begins to overflow its Roche lobe. For a $30 M_\odot$ star the mass loss rate reaches $\dot{M} > 10^{-6}\, M_\odot\,\mathrm{yr}^{-1}$ within a few centuries after the onset of the overflow. A fact which might support this type of binary model is that photometric observations made over a number of decades suggest that the light variations of P Cyg resemble those of a contact binary of the W UMa type with a period of about 0.5 day and an amplitude of about $0\overset{\mathrm{m}}{.}1$ (Magalashvili and Kharadze, 1967). The fact that these variations were not found during a single observing period of five days (Alexander and Wallerstein, 1967) does not rule out their possible presence. This is demonstrated by the case of Sco X-1, where even over periods of many months, the $0\overset{\mathrm{d}}{.}78$ periodicity does not clearly show up, and an analysis of observations made over decades was required to detect it; cf. Gottlieb *et al.* (1975).

If confirmed, this contact binary lightcurve would lend strong support to the possibility that P Cyg represents a later stage in the evolution of systems such as Cyg X-1 and Cen X-3. A final point in support of this hypothesis is the persistent double (and sometimes triple) structure of the absorption components of many lines of hydrogen and metals in the spectrum of P Cyg. Also in the X-ray binaries Cyg X-1, 3U 0900–40 and 3U 1700–37 (where the wind density is 10^2 to 10^3 times lower than in P Cyg) lines with P Cyg profiles do at certain phases show such doubling (Brucato and Zappala, 1974; Conti and Cowley, 1975; Zuiderwijk *et al.*, 1974; Wallerstein, 1974). This can be understood in terms of a spiral shaped outflowing stream or shock disturbance emerging from the secondary, which is superimposed on the general outflow pattern of the wind. In this model one absorption component arises in the stellar photosphere and one (or two) other in the expanding spiral-shaped disturbance. The persistence of this doubling (and sometimes tripling) of an absorption line seems hard to explain on any single star model and lends support to the possibility that P Cyg is a binary.

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DISCUSSION

Wilson: I have some results on the value of R (star)/R (Roche lobe) for SMC X-1, and the result is 0.98 to 0.99, from ellipsoidal variation. Since SMC X-1 is the most luminous X-ray source, this suggests that near filling of the lobe leads to large winds and large accretion rates.

Paczynski: If the wind is responsible for mass transfer in massive X-ray binaries, why is the OB star always very close to the Roche surface? I would like to remind you that in a classical picture of mass transfer in close binaries there is a fairly long initial phase (~10% of the Kelvin-Helmholtz time) when the transfer rate is slow. This was recently discussed by Ziołkowski in his study of β Lyr (1975, *Astrophys. J.*, in press).

Hutchings: How do undermassive supergiant primaries in X-ray sources fit into your scenario? Do they not suggest we are looking at post-rapid-mass-exchange epochs? I think Cen X-3 for example is definitely undermassive for any reasonable model by a factor of two or more.

Van den Heuvel: I do not think that they are in a post-rapid-mass-exchange stage, if by that you mean the second stage of mass exchange. There may have been some mass loss from the system during the first stage of mass exchange, as I mentioned. As a matter of fact, I don't believe that any of these stars is really very undermassive. For Cen X-3 the lower mass limit for the companion is around $16 M_\odot$. All the analyses of the (very noisy) light-curve give inclinations very close to 90°. This I don't believe. I think the accuracy of these analyses was highly overestimated, and the inclination might well be as low as 60° to 70°, which would make the companion mass $25 M_\odot$, i.e. normal for its spectral type.