THE FORMATION OF COMPACT OBJECTS IN BINARY SYSTEMS

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ABSTRACT

The various ways in which compact objects (neutron stars and black holes) can be formed in interacting binary systems are qualitatively outlined on the basis of the three major modes of binary interaction identified by Webbink (1980). Massive interacting binary systems ($M_1 \gtrsim 10$-$12\ M_\odot$) are, after the first phase of mass transfer expected to leave as remnants:
(i) compact stars in massive binary systems (mass $\gtrsim 10\ M_\odot$) with a wide range of orbital periods, as remnants of quasi-conservative mass transfer; these systems later evolve into massive X-ray binaries.
(ii) short-period compact star binaries (P ~ 1-2 days) in which the companion may be more massive or less massive than the compact object; these systems have high runaway velocities ($\gtrsim$ 100 km/sec) and start out with highly eccentric orbits, which are rapidly circularized by tidal forces; they may later evolve into low-mass X-ray binaries;
(iii) single runaway compact objects with space velocities of ~ 10^2 to 4.10^2 km/sec; these are expected to be the most numerous compact remnants.

Compact star binaries may also form from Cataclysmic binaries or wide binaries in which an O-Ne-Mg white dwarf is driven over the Chandrasekhar limit by accretion.

1. INTRODUCTION

We examine the various ways in which compact stars can be formed in binary systems. For simplicity we assume that the supernova collapse of a stellar core always produces a neutron star - keeping in mind, however, that the cores of very massive stars may also collapse into black holes.

We summarize, in section 2, the observational evidence on compact stars in binaries and possible selection effects affecting this evidence. In sections 3 and 4 we outline the various ways in which

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massive binaries can evolve through a first stage of mass exchange and leave compact remnants. In section 5 we consider the possible formation of compact objects in evolving binaries with one white dwarf component.

2. OBSERVATIONAL EVIDENCE ON COMPACT STARS IN BINARIES

A. X-ray binaries and binary pulsars

The binary X-ray sources that contain compact objects can - roughly - be divided into two groups, the massive ones ($M_S \gtrsim 15\ M_\odot$) and the low-mass ones ($M_S \lesssim 2\ M_\odot$) each of which can be subdivided further into several subclasses (M_S indicates the mass of the non-degenerate companion star). Notably, among the massive X-ray binaries there are two broad categories, the strong and permanent sources, in which the companion star is nearly filling its Roche-lobe (evidenced by the double-wave optical lightcurve) and is a giant or supergiant star; and the weak or transient ones, in which the companion is in most cases a rapidly rotating B-emission star (see table I a,b). In the latter case the binary periods are longer than $\sim$ 20 days and the star is deep inside its Roche-lobe. As to the low-mass systems, there are only a few for which there is direct evidence of binary motion: these are listed in table II. Among these there are already two types, viz: the pulsating ones, with hard X-ray spectra (example: Her X-1) and the non-pulsating ones with softer spectra, such as Sco X-1 and Cyg X-2. The large X-ray luminosities of the latter systems indicate that these also contain neutron stars, presumably surrounded by an accretion disk as evidenced by their optical spectra (cf. Cowley 1980; Ziolkowski and Paczynski 1980).

The galactic bulge X-ray sources and the steady sources associated with bursters have X-ray and optical spectra similar to those of Sco X-1; the several tens of identified optical counterparts are always intrinsically faint stars and show the spectrum of a bright accretion disk, somewhat similar to the spectra of cataclysmic binaries (cf. the reviews by Cowley 1980 and Lewin and Clark 1980). In two cases of such sources, Aql X-1 and Cen X-4 the spectrum of a faint K-dwarf has been detected (Cowley 1980; van Paradijs 1980).

In view of this evidence, and because of low optical luminosities of the companions it seems plausible that the bursters and bulge X-ray sources are low-mass close binaries in which the companion to the compact star has a mass of 1 $M_\odot$ or less (cf. Joss and Rappaport 1979; Lewin and Clark 1980). In order to have accretion, the low-mass star should fill its Roche-lobe, implying (if star is unevolved) binary periods of less than about ten hours. The high X-ray luminosities of these sources (10^{36} - 10^{38} ergs/sec) imply that also here the compact stars must be neutron stars or black holes. Van Paradijs (1978) has provided convincing evidence that the bursters are neutron stars. Similar arguments can be put forward for the globular cluster X-ray sources in our galaxy (a fraction of which are also burst sources) as well as those in M31 (cf. Lewin and Clark 1980; van den Heuvel 1980). The strongly radio emitting peculiar X-ray binaries Cyg X-3,

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Circinus X-1 and SS433 might form a separate category (table III). They are characterized by occasional strong radio outbursts with synchroton spectra and by large IR luminosities, probably indicating very dense stellar winds like those observed in Wolf-Rayet stars; Circinus X-1 and SS433 are surrounded by radio shells similar in appearance to supernova remnants. Finally, there are the three binary radio pulsars listed in table IV.

B. Reasons for the existence of the two groups of X-ray binaries; compact companions to stars with intermediate masses.

The existence of the two large groups does not mean that stars with masses between 2 $M_\odot$ and 15 $M_\odot$ cannot have compact companions but rather that only stars with $M \gtrsim 15\ M_\odot$ and $\lesssim 2\ M_\odot$ are able to provide accretion rates suitable for producing a relatively long-lived strong X-ray source (van den Heuvel 1975). The reasons are the following. Stars with $M \gtrsim$ 15-20 $M_\odot$ develop into blue supergiants and Of stars during later phases of H burning; also during helium burning they are blue supergiants; such stars have winds that are sufficiently strong ($\dot{M} \gtrsim 10^{-6}\ M_\odot$/yr) for feeding an X-ray source (Davidson and Ostriker 1973). In addition, in these stars beginning Roche-lobe overflow does not lead to a rapid growth of the mass transfer rate, especially not if strong stellar wind mass loss occurs (Ziolkowski 1977; Savonije 1978[1], 1979; McCray 1979). Consequently, such stars may remain close to their Roche-lobes for fairly long times (up to 10^5 yrs), powering their companions with Roche-lobe overflow accretion rates of $\sim 10^{-10}$ to $10^{-8}\ M_\odot$/yr, sufficient to produce a strong X-ray source. On the other hand, for $M \lesssim 15\ M_\odot$ stellar wind mass loss rates are below $10^{-8}\ M_\odot$/yr, insufficient for powering an X-ray source or for stabilizing beginning Roche-lobe overflow. The only mode of mass transfer available in this mass range is fully developed Roche-lobe overflow which for $M_S \gtrsim 2\ M_\odot$ leads to mass transfer on a thermal timescale at rates $\gtrsim 10^{-7}\ M_\odot$/yr which will quench the X-ray source (Shakura and Sunyaev 1973). Only for $M_S \lesssim 2\ M_\odot$ and especially if $M_S \lesssim M_C$ (M_C = mass of the compact star) where transfer can take place on a nuclear timescale, a long-lasting stage as a strong X-ray source ($\sim 10^{37}$ ergs/sec), powered by Roche-lobe overflow, is possible.
We conclude from the above that the existence of the two observed groups of X-ray binaries is just what one would expect if compact objects do exist as companions to stars *of any kind of mass.*
It seems therefore most reasonable to assume that also in the mass range 2 - 15 $M_\odot$ stars with compact companions do exist.

TABLE I. MASSIVE X-RAY BINARIES

a. Persistent strong sources

Source	Type	P_{orb}(d)	P_{pulse}	m $\sin^3 i$	e	Ref.
SMC X-1	B0I	$3^d.9$	$0^s.71$	0.8 + 12.5	0.00	(1)
LMC X-4	08III-V	1.4	--	2.5 + 22.5	0.00	(2)
0900-40	B0.5Ib	9.0	283^s	1.4 + 21.3	0.09	(1)
Cen X-3	06.5II-III	2.1	$4^s.84$	1.4 + 17.2	0.00	(1)
1223-62	B1.5Iab	35.0	698^s	1.4 + 31	0.44	(3)
1538-52	B0-1	3.7	529^s	2 + 20	?	(4)
1700-37	06.5f	3.4	--	1.3 + 27.1	0.00	(1)
1907+09	O-BI	?	--	?	?	(5)
Cyg X-1	09.7Iab	5.6	--	1.5 + 2.4 (i = 30°)	0.00	(1)

b. Weaker or transient pulsating sources

Source	Type	P_{orb}(d)	P_{pulse}	m $\sin^3 i$	e	Ref.
0115+634	B0	24.3	$3^s.6$	--	0.34	(6)
0352+309 (X Per)	09.5III-Ve	581(?)	853^s	--	?	(6)
0535+262	B0e	> 17	104^s	--	?	(6)
1118-615	B0e	--	405^s	--	?	(6)
1145-619	B1Vne	--	297^s or 292^s	--	?	(6)
1258-613 (GX304-1)	B0-5V	--	272^s	--	?	(6)
1728-247 (GX1+4)	M6III + + hot star	--	$138^s \rightarrow 116^s$	--	?	(6)

(1) Conti (1978)
(2) Hutchings et al. (1978)
(3) Kelley et al. (1979)
(4) Hutchings (1980)
(5) Schwartz et al. (1979)
(6) Bradt et al. (1978)

3. EVOLUTION TOWARDS CORE COLLAPSE IN PRIMARIES OF CLOSE BINARIES

3.1. Evolution of close binaries

In binaries with periods up to several tens of years the envelope of the primary star will, at some stage of the evolution, overflow a critical surface (Roche lobe or tidal lobe) and be lost to the companion star or from the system. Such binaries, in which the stars interact during some stage of their evolution, we will call "close". The way in which the two stars interact depends on the evolutionary state of the core of the primary star at the onset of the mass transfer, on the structure of the envelope of this star at that moment, and also on the mass ratio of the components. The classification, by Kippenhahn and Weigert (1967), in terms of the evolutionary state of the core at the onset of the mass

TABLE II. LOW-MASS X-RAY BINARIES

Source	Sp. Type	P_{orb}	P_{pulse}	M_{opt}	M_x	L_x/L_{opt}	z	ref.
Her X-1	A-F	$1^d.70$	$1^s.2$	2.2	1.3	35	3 kpc	(7)
Sco X-1	accr. disk	$0^d.787$	--	<1	--	$>10^2$	400 pc	(7)
1627-673	accr. disk	41^m	$7^s.7$	<0.5	$\sim$1.4	$>10^2$	--	(9)
2129+47	G-dwarf(?)	$5^h.2$	--	<1(?)	--	>10	--	(7)
Cyg X-2	F-giant	$9^d.843$	--	0.5-1.1	1.3-1.8	10-40	1.5 kpc	(7)
0620-003(transient)	K5-7V	8d(?)	--	--		80(outburst)	--	(7)

TABLE III. PECULIAR SOURCES WITH STRONG RADIO AND IR EMISSION

Source	Sp. Type	P_{orb}	P_{pulse}	M_{opt}	M_x	L_x/L_{opt}	z	ref.
Cir X-1	O-Be	$16^d.6$	--	--	--	10^{-2}	in gal.plane	(6)
SS433	{Wolf-Rayet like	$13^d.1$	--	--	--	10^{-3}	130 pc	(8)
Cyg X-3	--	$4^h.8$	--	--	--	?	in gal.plane	(6)

TABLE IV. BINARY RADIO PULSARS

Name	P_{pulse}	P_{orb}	e	Type of Companion	Ref.
PSR 0656+64	$0^s.196$	24^h41^m	0.00	Probably normal	Fowler (1980)
PSR 0820+02	$0^s.865$	3.2 yr	0.00	$M \sim 0.85\ M_\odot$ (?)	Manchester et al. (1980)
PSR 1913+16	$0^s.059$	7^h45^m	0.62	Compact star	Taylor et al. (1976)

(7) Cowley (1980); (8) Crampton et al. (1980).

(9) Middleditch et al. (1980)

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transfer is particularly useful if one wishes to study the possible final evolutionary state of the primary star, i.e. the kind of remnant that will be left. We will first concentrate, in the next section, on this problem. On the other hand, if one wishes to know whether or not the system will be disrupted by the supernova of the primary star, one should know how much mass is captured by the other star, and how the orbital period is affected by the mass transfer. These factors will be discussed in section 4.

3.2. The final evolution of the primary star

For the definition of Kippenhahn and Weigert's classifications A, B and C we refer to earlier reviews (Plavec 1968; Paczynski 1971, Thomas 1977, Van den Heuvel 1978; Webbink 1980). Since case A is relatively rare ($\lesssim$ 15% of all systems) we will only concentrate here on the cases B and C. In these cases after the onset of the mass transfer the primary star loses practically its entire hydrogen-rich envelope (either to the secondary or - partly - from the system, cf. section 4) and only the core, consisting of helium and (in case C) heavier elements, remains. The further evolution of the primary star can, therefore, relatively simply be described in terms of the evolution of the helium core. Calculations of the evolution of helium stars by Paczynski (1971), Arnett (1978), Savonije (1978[2]) and Delgado and Thomas (1980) show the following results (cf. especially Sugimoto and Nomoto 1980):

a. In helium stars with $M \leq 2\ M_\odot$ the C + O core formed by helium burning degenerates and during helium shell burning the outer layers expand to giant size. In binaries this produces a second phase of mass transfer (case BB of binary mass transfer cf. Delgado & Thomas 1980) such that a degenerate C + O star with $M < M_{ch}$ is left, which cools off to become a C + O white dwarf (cf. De Loore and De Greve 1976);
b. Helium stars with $M \approx 2\text{-}3\ M_\odot$ ignite carbon off center under non-degenerate (or at least: not highly degenerate) conditions and undergo a series of carbon shell flashes (Miyaji et al. 1980; Nomoto 1980; Sugimoto and Nomoto 1980) which leave behind a growing degenerate O - Ne - Mg core. When the boundary of this core approaches the helium-burning shell, carbon burning dies out and just like in stars with a degenerate C + O core, helium shell burning causes the outer (helium) layers to expand to giant size. The mass of the degenerate O - Ne - Mg core is then in the range 1.2 - 1.4$M_\odot$. In a binary system, the extended outer layers will be lost to the companion in a second stage of mass transfer (case BB or BC, etc.) and one expects an 1.2 - 1.4 $M_\odot$ O - Ne - Mg white dwarf to be left.
c. $M \gtrsim 3\ M_\odot$. In these helium stars the C + O core produced by helium burning has a mass larger than the Chandrasekhar limit and Ne, O and Si are ignited under non-degenerate conditions; here the core is expected to evolve directly to an Fe-photodesintegration collapse, giving rise to a supernova and the formation of a neutron star. This happens regardless of whether or not still a part (or even most) of the envelope matter is transferred to the secondary star in a case BB (or BC, etc.) mass transfer. Helium stars more massive than 4 $M_\odot$ do not reach radii larger than a few $R_\odot$ before the final core col-

lapse, and therefore in a binary are not expected to lose further mass to their companions. On the other hand, in the mass range 3 - 4 $M_\odot$ still considerable expansion of the outer layers occurs; the 3 $M_\odot$ helium star considered by Arnett reaches R = 21 $R_\odot$ at Si-ignition. Hence, in a binary with a period of less than about 10 days it may still lose part (or most) of its envelope by case BB mass transfer before the final core collapse. Similarly, Delgado and Thomas (1980) found that a 4 $M_\odot$ He-star in a $1^d.49$ period binary with a 14 $M_\odot$ companion still loses some 1.3 $M_\odot$ to its companion before the final core collapse. The mass range 3 - 4 $M_\odot$ seems particularly important since, although direct evolution to a supernova collapse seems unavoidable, the collapsing stars may have lost a considerable part of their envelopes, and in some cases (notably for M $\sim$ 3 $M_\odot$) it is conceivable that they are almost bare cores of about a Chandrasekhar mass.

d. In helium stars more massive than about 60 $M_\odot$ the oxygen core evolves to a pair-creation collapse again leading to the formation of a compact object with a mass of a few solar masses (cf. Arnett 1978).

The various types of core evolution as a function of initial primary main-sequence mass M_{ms} are depicted in figure 1. The almost vertical dashed line indicates the approximate lower mass limit for evolution towards direct core collapse after one or two phases of mass transfer (B or BB, C or CC, etc.). For short binary periods ($\sim$ 10 days) the main-sequence mass required for producing a helium core $M_{core} \sim 3$ $M_\odot$ is about 12 ($\pm$ 1) $M_\odot$ (the precise value depends on the initial abundances Y and Z and on the binary period and mass ratio; for P $\sim$ 4^d even initial masses as high as 14-15 $M_\odot$ may be required). For wide binaries (P $\gtrsim$ 100^d) where the core still has time to grow considerably by hydrogen shell-burning before the onset of mass transfer, the required initial mass is $M_{ms} \simeq 10$ ($\pm$ 1) $M_\odot$. The thick fully drawn line, similarly, indicates the lower mass limit, as a function of binary period, for leaving behind a 2 $M_\odot$ helium core. For short binary periods this limit is about 10 ($\pm$ 1) $M_\odot$, for long periods about 8 ($\pm$ 1) $M_\odot$. (The above quoted uncertainties are tentative and were obtained by comparing results computed by various authors (cf. Webbink 1980). Primary stars in the hatched region between the two curves leave O - Ne - Mg white dwarfs with masses of $\sim$ 1.2 - 1.4 $M_\odot$, after a second phase of mass transfer (BB or BC, etc.).

3.3. Evolution of O - Ne - Mg white dwarfs in binaries towards an accretion-induced core collapse

Myaji et al. (1980), Sugimoto and Nomoto (1980) and Nomoto (1980) have pointed out that when the secondary star evolves away from the main sequence and begins to transfer mass to the O - Ne - Mg white dwarf, this dwarf may be driven over the Chandrasekhar limit and undergo an electron capture supernova collapse. They carried out calculations for a 1.2 $M_\odot$ O - Ne - Mg white dwarf with an acretion rate of helium of 4.10^{-6} $M_\odot$/yr (about the rate at which such a core grows by helium shell burning inside a red giant) and found that electron captures on ^{20}Ne and ^{24}Mg cause the core density to rise, followed by a weak O-deflagration, that cannot prevent further electron captures which induce a total

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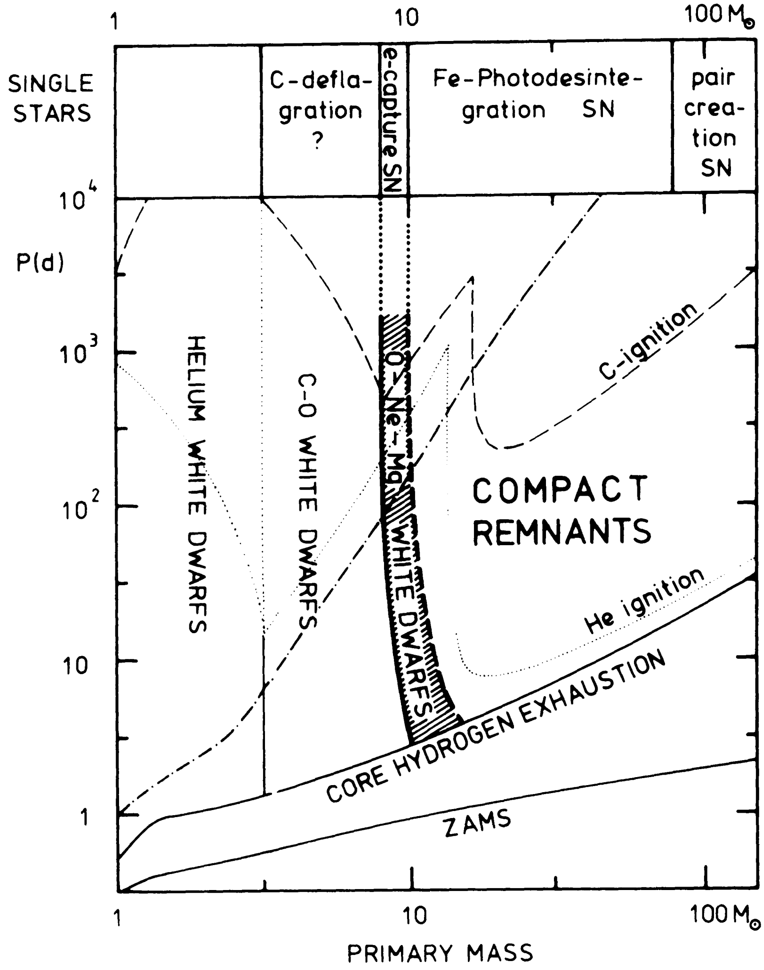

Figure 1. Classification of expected final evolutionary states of primary stars of close binaries as a function of primary mass and orbital period (partly after Webbink 1980). The orbital periods correspond to binaries in which the primary star just fills its Roche lobe (for mass ratio unity). At the top of the figure the expected final evolutionary states of single stars are indicate Dash-dot line indicates convective boundary (Hayashi-line).

collapse of the core. The reason why the collapse cannot be prevented is the reduction of the value of the Chandrasekhar mass due to the electron captures, which causes it to become almost equal to or even smaller than the actual core mass. Consequently, the O - Ne - Mg white dwarfs that result from the first stage of mass transfer in binaries with primary masses between 8 and 12 $M_{\odot}$ (the hatched area in figure 2) may (sometimes much) later, during the mass transfer from secondary to primary undergo an electron-capture SN. Since this may, if the secon-

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dary is a low-mass star, occur billions of years later, such SNe may also occur in old stellar systems. It seems attractive, therefore, to indentify this type of collapse with type I SNe (Sugimoto and Nomoto 1980; Nomoto 1980). In section 5 we will consider this type of SN model in more detail; it closely resembles the type I SN models proposed by Whelan and Iben (1973), Warner (1974) and Gursky (1976). Notice that, since the O - Ne - Mg white dwarfs are produced in quite a wide main-sequence mass range, this type of core collapse in binaries may be a fairly common type of event.

3.4 Precision of the boundaries between the various types of final evolution

Even for a fixed initial chemical composition the boundaries between the various types of final evolution sketched in figure 1 are, in fact, bands with a certain intrinsic width. This is due to the fact that the boundary masses also depend on the initial mass ratio - a factor which was assumed fixed in figure 1. Furthermore, the lower mass limit for evolving to a direct photodesintegration core collapse for helium stars in binaries may depend somewhat on the binary separation. Since helium stars in the mass range 2.6 to 3.0 $M_\odot$ are not expected to expand to full giant size (cf. Webbink 1980), in wide binaries perhaps even helium stars with masses as low as 2.6 $M_\odot$ may evolve to direct core collapse. Although all these uncertainies may shift the boundaries of the hatched region somewhat to higher or lower mass values, the total width of this region will remain as large as 2 to 2.5 $M_\odot$, which implies that O - Ne - Mg white dwarfs are expected to be produced in considerable quantities. At the top of figure 1 we have also tentatively indicated the approximate boundaries for various types of supernovae in single stars. The cores of single stars in the mass range $\sim$ 8 -10 $M_\odot$ (or possibly 7 - 12 $M_\odot$) evolve directly to electron-capture supernovae, whereas the primaries of binaries in this mass range terminate as O - Ne - Mg white dwarfs.

4. THE FATE OF THE ENVELOPE

4.1 Conservative evolution: formation of massive X-binaries

We consider primary stars which directly evolve to core collapse ($M_{core} \gtrsim 3\ M_\odot$). In binaries that evolve with conservation of total mass and orbital angular momentum ("conservative" mass transfer) the core will at the time of its collapse be the less massive component of the system. For circular orbits the conservative assumptions imply that the orbital radius a changes according to the equation (cf. Paczynski 1971):

$$a/a_o = \left[M_1^{o}(M - M_1^{o})/M_1(M - M_1)\right]^2 \qquad (1)$$

where index zero indicates the initial situation, M is the total mass of the system and M_1 is the primary mass. Since explosion of the less massive component is unlikely to disrupt the system, even if the effects of impact, ablation and asymmetries in the SN mass ejection are taken

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into account (Sutantyo 1974, 1975; Wheeler et al. 1975; Fryxell and Arnett 1978; De Cuyper 1980) one expects that the compact stars in conservatively evolving systems will practically always remain bound after the explosion. Apparently this was the case in the massive X-ray binaries (Van den Heuvel and Heise, 1972; Tutukov and Yungelson 1973). Their most likely evolutionary history, through an intermediate stage as a Wolf-Rayet (WR) binary has been extensively summarized elsewhere (Van den Heuvel 1976, 1978; see especially: Tutukov, this volume).

4.2. Limitations to conservative evolution

De Grève et al. (1978) have shown that in order to explain the presently observed system parameters of the WR binaries, conservative mass transfer is not fully adequate as it would predict too large orbital periods as well as mass ratios M_{WR}/M_{OB} which are a factor 1.5 to 2 smaller than observed. In order to explain the combination of mass ratio and short binary period of systems like CQ Cep ($P = 1^{d}.6$) and CX Cep ($P = 2^{d}.1$), one has to invoke considerable angular momentum loss ($\geq$ 50%) from the systems presumably during the first phase of mass transfer (Flannery and Ulrich 1977; Kippenhahn and Meyer-Hofmeister 1977). This situation is similar to that for the Algol systems which also must have lost some 50 percent of their angular momentum during the preceding mass transfer (Ziolkowski 1976). The substantial mass loss by stellar wind during Of and WR stages is an important additional factor (cf. Van Beveren, this volume).
The outcome of the evolution with moderate losses of mass and angular momentum (i.e. less than two third of the total) is qualitatively still similar to that of conservative evolution - i.e.: the more evolved component is less massive than the secondary and the binary separation does not differ by more than a factor 2 to 3 from that in the conservative case. We will indicate this type of evolution as "quasi-conservative" (cf. Webbink 1980). Apparently, the existence of WR binaries and massive X-ray binaries can be understood in terms of such evolution.

4.3. Modes of envelope interaction

Quasi-conservative evolution is expected only in case that
(a) the initial mass ratio of the system is not too low, (b) the separation is not too small and (c) the envelope of the mass-losing star is in radiative equilibrium. Although for the conditions (a) and (b) no precise limits can be set, it seems that for $q \gtrsim 0.5$ and orbital periods longer than a few days the quasi-conservative approximation is probably adequate since in that case equation (1) does not induce a drastic reduction of the binary period during the exchange and there will remain enough room in the system to accommodate the rapidly swelling secondary. As in this case the thermal timescales of the two stars are not too much different the rate at which mass is transferred will be roughly similar to the rate at which the secondary can accommodate it.
Condition (c) follows from the fact that mass transfer from a radiative envelope (*Mode II* of binary interaction defined by Webbink 1980) is self-stabilizing, as it induces the envelope to shrink. Consequently,

systems that simultaneously fulfil the conditions (a), (b) and (c) are expected to evolve quasi-conservatively, and to transfer mass at a rate of the order

$$\dot{M}_1 = M_1/\tau_{KH} \simeq -3.10^{-8} M_1^{\ 3} \ (M_\odot/yr) \qquad (2)$$

where M_1 is expressed in solar units (cf. Paczynski 1971).
If conditions (a) and/or (b) are not fulfilled, the secondary will after the onset of the mass transfer rapidly swell to its Roche lobe such that a contact system forms surrounded by a common envelope (*Mode I* of Webbink 1979).
Convective envelopes and degenerate stars have the tendency to expand as a consequence of mass loss. Therefore, mass transfer from a convective envelope (Webbink's *Mode III*) has the tendency to grow catastrophically. The expanding envelope will in this case engulf the companion and again a common-envelope system will be formed.

4.4. Outcome of common-envelope evolution for $M_1 \lesssim 10-12\ M_\odot$

Although no precise calculations exist, nor seem possible at present, observations and speculations suggest that cataclysmic (CV) binaries with P ∿ 0.25 - 0.5 days are the outcome of common-envelope evolution of moderately wide to wide binaries consisting of a (sub)giant with a degenerate core ($M_{giant} \lesssim 10-12\ M_\odot$) together with a main-sequence dwarf (Paczynski 1976; Ostriker 1976; Ritter 1976). A variety of arguments (e.g. cf. Van den Heuvel 1976; Meyer and Meyer-Hofmeister 1979; Webbink 1980) strongly suggest that soon after the formation of the common envelope, rapid mass loss with high specific angular momentum will start. Suggestive trial calculation by Taam et al. (1978), Taam (1979), Meyer and Meyer-Hofmeister (1979) show that in all examined cases the secondary spirals down into the envelope of the primary on a timescale of order 10^3 - 10^4 yrs. The secondary has no time to accrete mass from the common envelope, this envelope is lost, and final binary periods of the order of a fraction of a day are expected. The precise reasons for the termination of the spiral-in are, however, not known. Notably, it is not understood why young post-spiral-in systems are always detached (Paczynski 1980). Examples are V 471 Tau in the Hyades (0.8 $M_\odot$ white dwarf + 0.8 $M_\odot$ K-dwarf, P = 12^h) and several double cores of planetary nebulae (e.g. UU Sge, P ∿ 12^h, Bond et al. 1978).

4.5. Common-envelope evolution in massive systems

We consider systems in which the primary has $M_{core} \geq 3\ M_\odot$. If $q < 0.5$ or if the envelope of the primary is convective, or both, one expects that common envelope evolution will occur, and the two stellar cores will spiral-in on a short timescale (10^3 - 10^4 yrs). The resulting system after spiral-in is - in analogy to the CV binaries - expected to consist of the evolved core of the primary together with the unaltered secondary, in an orbital period of less than one day. Since the precise reasons for the termination of spiral-in are not known, we will tentatively assume that, like in the observed lower-mass post-spiral-in sys-

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tems, the Roche lobe around the non-degenerate component has a radius of between 1 and 2 times the stellar radius. For core masses and companion masses of $\sim$ 3 to 5 $M_\odot$ the resulting post-spiral-in periods then are typically of order 0.5 – 1.0 days. The core will finally explode as a SN. We carried out trial calculations for the effects of the SN explosion on these close systems. We assumed that just the helium core of the primary remained after spiral-in and that for $M_{core} \gtrsim 4$ $M_\odot$ this star underwent no further mass loss before exploding. In the mass range 2.6 – 4 $M_\odot$ the later expansion of the envelopes of helium stars (cf. § 3.2.c) may give rise to further spiral-in and mass loss. In the absence of precise calculations for this case we have tentatively assumed that at the time of the explosion core masses as low as 2.0 and 2.5 $M_\odot$ are possible in some cases and again calculated the SN effects. We assumed the remaining compact remnant to have a mass of 1.4 $M_\odot$, and carried out calculations for SN ejection velocities of 5.10^3 km/sec and 10^4 km/sec. We assumed instantaneous sherically symmetric mass ejection and estimated the impact effects following Wheeler et al. (1975) (but corrected for the overestimate – by a factor of order 5 – of the effects of backward blow-off of matter; cf. Fryxell and Arnett 1978). Table V lists some representative results. Since the systems are close and the companions have masses of the same order of those of the exploding cores, disruption is likely. Systems that remain bound always have high orbital eccentricities and high runaway velocities, of order 10^2 – 2.10^2 km/sec. In view of their short separation at periastron, their orbits will rapidly circularize by tidal forces. Figure 2 schematically illustrates this situation. Table V also lists – for bound systems – the resulting binary period P_t after tidal circularization and synchronization, calculated following Sutantyo (1975).

Intermezzo: Low-mass Population I X-ray binaries and their relation to runaway radio pulsars

Bound systems after tidal circularization always have orbital periods $\sim$ 1-2^d and runaway velocities $\sim 10^2$ – 2.10^2 km/s. As pointed out by Sutantyo (1975; cf. Van den Heuvel 1976) Her X-1 must be the result of such an evolution since its 2 $M_\odot$ companion is clearly a Population I object (age < 10^9 yrs); hence, the system must have originated in the galactic plane, and must have been shot out if this plane with a velocity $\geq$ 125 km/sec to reach its present z-distance of 3 kpc. The same applies to Cygnus X-2, where the luminosity of the F-giant indicates an original mass $\gtrsim$ 2 $M_\odot$, while its z-distance indicates a runaway velocity $\geq$ 100 km/sec. [The present mass of $\sim$ 1 $M_\odot$ of the F-giant suggests that later considerable mass transfer took place; in such a case an original binary period of 1 – 2^d may easily be transformed into a longer period like $\sim 9^d$]. From the fact that low-mass Population I X-ray binaries are very rare, whereas spiral-in evolution must be very common, occurring in at least one third of all massive stars (cf. § 4.7) we conclude that post-spiral-in systems with $M_{core} \gtrsim 3$ $M_\odot$ are practically always disrupted by the supernova explosion. Hence, the vast majority of the remnants of such systems will be runaway (young) neutron stars together with runaway normal stars (mostly with $M \lesssim 4$-5 $M_\odot$), with velocities of

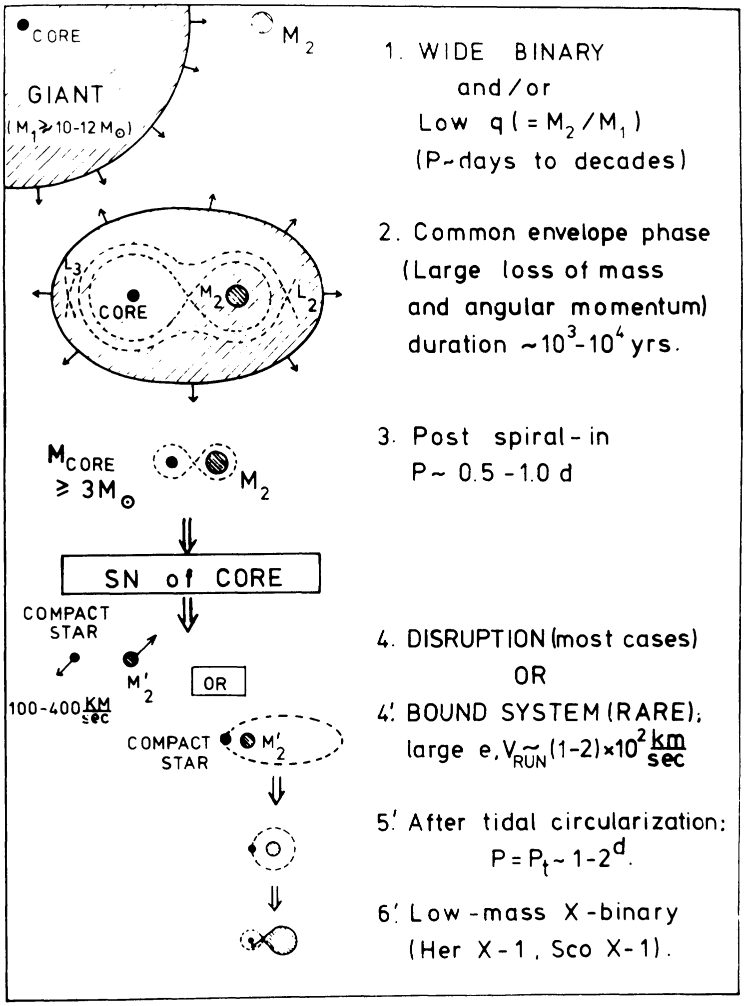

Figure 2. Outline of expected highly non-conservative evolution of massive close binaries with a long orbital period and/or a low initial mass ratio ($q \lesssim 0.5$). Explanation in the text.

order 10^2 - 4.10^2 km/sec. The condition that the bulk of the post-spiral in systems should be disrupted sets a lower limit to the SN ejection velocity. For $M_{core} = 2.5\ M_\odot$, $P_o = 12^h$, the condition that virtually no companions with $M_2 \lesssim 2\ M_\odot$ remain bound requires $V_{SN} \gtrsim 10^4$ km/sec. For $P_o = 24^h$ this limit becomes $\gtrsim 1.4 \times 10^4$ km/sec. Since P_o cannot be much smaller than $\sim 12^h$, we conclude that most probably $V_{SN} \gtrsim 10^4$ km/sec (notice that this ejection velocity of the mantle of a collapsing helium star is not necessarily related to an observable SN; P_o is the post-spiral-in period, before the SN).

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4.6. The final evolution of quasi-conservative systems

Also the massive X-ray binaries will go through a spiral-in phase before terminating their lives (Van den Heuvel and De Loore 1973; Taam et al. 1978; Delgado 1979; cf. Tutukov, this volume), which will result in the formation of a very close system consisting of the compact star and the core of the massive star. Explosion of the stellar core will in most cases lead to disruption of the system, producing two runaway compact stars, one young and one old. The old one will, presumably, have been spun up back to a short rotation period by accretion during the X-ray phase (Smarr and Blandford 1976), so both neutron stars may be observable as radio pulsars. In the rare case that the system is not disrupted in the second SN, a close binary pulsar with a very eccentric orbit will result, resembling PSR 1913 + 16 (Flannery and Van den Heuvel 1975; cf. Tutukov, this volume). In the (probably rare) case that the companion has a helium core mass $\lesssim 3\ M_\odot$, spiral-in may result in a close binary consisting of a white dwarf and an old neutron star. Such a system will have a circular orbit and may, in principle, have any orbital period upwards from about one minute.

4.7. The expected incidence of runaway stars among radio pulsars

Statistical investigations by Abt and Levy (1978) show that over 2/3 of the main-sequence stars in the spectral range B2 - B9 have stellar companions with orbital periods $\lesssim$ 10 yrs. The overall distribution of mass ratios $q = M_2/M_1$ of these systems is roughly represented by $q^{-\frac{1}{4}}$ (down to the completeness limit of $q \simeq 0.2$). At closer scrutiny, the spectroscopic binary mass ratio distribution is double-peaked (Trimble 1974; Tutukov and Yungelson 1980), with one peak near $q = 1$ and the other at low q-values. Systems with short periods ($\lesssim 100^d$) tend to have q-values close to unity (i.e. $\gtrsim 0.5$; cf. Lucy, this volume; Massey and Conti 1980) and produce the peak near $q = 1$. Hence, systems with $q < 0.5$ will preferentially have long periods. These systems will undergo spiral-in evolution. Since, according to Abt and Levy's overall q distribution, systems with $q < 0.5$ represent over 50% of all spectroscopic binaries, one expects that over 1/3 of all stars with $M \gtrsim 10\text{-}12\ M_\odot$ undergo common-envelope evolution and become very short-period binaries before they explode as a SN. Consequently, over 1/3 of all stars with $M \gtrsim 10\text{-}12\ M_\odot$ will produce runaway pulsars with V > 100 km/sec. The other roughly one third (the shorter-period systems with $q \gtrsim 0.5$) will evolve quasi-conservatively and, at the end of their lives, release two runaway compact stars with runaway velocities in the range $10^2 - 10^3$ km/sec (the orbital velocity at periastron of PSR 1913 + 16 is > 500 km/sec). Since quasi-conservatively evolving systems produce *two* runaway pulsars, one expects that some three quarters of all stars with $M \gtrsim 10\text{-}12\ M_\odot$ produce runaway pulsars. Correcting for the fact that also single stars ($\sim$ 1/3 of all) in the mass range 8-12 $M_\odot$ are expected to leave pulsars, one roughly expects some 2/3 of all radio pulsars to be runaways with space velocities > 100 km/sec. This may explain the observed fact that the majority of the radio pulsars have runaway velocities of order 100 - 200 km/sec (Lyne 1980).

5. ACCRETION INDUCED COLLAPSE OF O-Ne-Mg WHITE DWARFS

5.1. Restrictions

In Miyaji et al.'s (1980) calculations a helium accretion rate of 4.10^{-6} $M_\odot$/yr induced core collapse. Such a high rate can only be accommodated in a *wide* binary since for (H) accretion rates $\geq 1.5 \times 10^{-7}$ $M_\odot$/yr a giant envelope forms. In a close system this envelope will be lost immediately along L_2 and L_3. Only if the companion has a mass $M_2 <$ 1.7 $M_\odot$ will the accretion rate, according to eq. (2), be $< 1.5 \times 10^{-7}$ $M_\odot$/yr, and may the binary be close. However, the helium envelope (produced by H-shell burning) expands much during He-shell burning and is probably lost before the core has grown sufficiently to collapse. Hence, in close systems the mass of the O - Ne - Mg white dwarf must already be very close to the Chandrasekhar limit in order to enable collapse to a neutron star. Consequently, only a minor fraction of all O - Ne - Mg white dwarfs in *close* systems is expected to become a SN. No quantitative estimate of this fraction can presently be given.

5.2. Possible relation to the bulge X-ray sources

The amount of mass ejected in the collapse of a white dwarf is not expected exceed a few tenths of a solar mass, and hence is unlikely to cause disruption of the system (cf. Van den Heuvel 1977, and table VI). After the explosion the system will be detached and it may take billions of years before the companion again fills its Roche lobe (either due to gravitational radiation losses or due to its interior evolution), and becomes an X-ray source. If the companion has a mass of 1.0 - 1.2 $M_\odot$ it needs some (5-10) x 10^9 yrs to leave the main-sequence, such that these systems will be very old when they become X-ray sources. A system like Sco X-1 may have formed in this way (its orbital period of $0^d.78$ excludes gravitational radiation from driving the mass transfer). The failure to explain the very high X-ray luminosities (10^{37} - 10^{38} ergs/sec) of the bulge sources in the galaxy and in M31 by gravitational-radiation-induced mass transfer (Li et al. 1979; Ostriker and Zytkov 1979) suggests that also here interior evolution of the companion may play a role.

5.3. Speculations on the origin of binary radio pulsars with circular orbits

In wide binaries (which provide the best seat for accretion-induced collapse) the companion will itself be a giant (presumably with a degenerate core) when the accretion starts. In that case the white dwarf will be engulfed by the giant's envelope and will spiral down into it. Since the white dwarf may collapse at any instant during spiral-in, the resulting neutron-star binary may in principle have any period between a minute and many years. Although the SN will blow off part of the giant's envelope, the remaining part will soon again expand to giant size. Tidal and other friction will rapidly circularize the orbit and spiral-in may or may not resume (depending on the extent of the envelope). When the giant finally ejects its envelope and cools down to a white dwarf a detached star binary with a circular orbit remains. Possibly this was the evolutionary history of PSR 0820 and PSR 0656

(Blandford 1980) although the latter one may also be the product of the scenario depicted in figure 2, in which case its companion would be a main-sequence star. An alternative scenario for PSR 0820 is one which starts from a wide X-ray binary (like G X 1+4) in which the companion to the neutron star has a mass $\lesssim$10-12 $M_\odot$ (cf. §4.6).

6. CONCLUSIONS

(i) It seems likely that the majority of the radio pulsars were formed in binaries that went through a common envelope stage; this explains their high space velocities. Because of its overwhelming importance also among the lower-mass binaries, it seems therefore that common-envelope evolution merits to be a main focus point for future research.

(ii) The evolution of stars in the mass range 8-12 $M_\odot$ (and of helium stars in the range 2.6 to 4 $M_\odot$) should be further explored. Especially the work of Chechetkin et al. (1980) requires further investigation - and some of our conjectures about this mass range may still change considerably.

The reader may judge for himself from the above sections that also on many other points our understanding of the evolution of close binaries is still very poor, and that much further investigation is required.

		$P_o = 0.5^d$ (after spiral-in)		$P_o = 1\overset{d}{.}0$
M_{core}	M_2	$V_{SN} = 10^4$ km/sec	5.10^3 km/sec	$V_{SN} = 10^4$ km/sec
2.5 $M_\odot$	1.2 $M_\odot$	disrupted	$M_2' = 1.1\ M_\odot$ $e = 0.8$, $P_f = 4\overset{d}{.}6$ } $P_t = 23\overset{h}{.}6$ V_{run} = 165 km/sec	Bound (disrupted if $V_{SN} \geq 1.4 \times 10^4$ km/sec)
	2.0 $M_\odot$	$M_2' = 1.69\ M_\odot$ $e = 0.92$, $P_f = 17.3d$ } $P_t = 25\overset{h}{.}9$ V_{run} = 213 km/sec	$M_2' = 1.87\ M_\odot$ $e = 0.65$, $P_f = 2.18d$ } $P_t = 23\overset{h}{.}2$ V_{run} = 161 km/sec	$M_2' = 1.89\ M_\odot$ $e = 0.64$, $P_f = 4\overset{d}{.}16$ } $P_t = 45^h$ V_{run} = 126 km/sec
	4.0 $M_\odot$	$M_2' = 3.74\ M_\odot$ $e = 0.60$, $P_f = 1.56d$ } $P_t = 20\overset{h}{.}0$ V_{run} =196 km/sec	$M_2' = 3.87\ M_\odot$ $e = 0.44$, $P_f = 1\overset{d}{.}05$ } $P_t = 18\overset{h}{.}9$ V_{run} = 153 km/sec	Bound
3.0 $M_\odot$	2.5 $M_\odot$	$M_2' = 2.14\ M_\odot$ disrupted	$M_2' = 2.32\ M_\odot$ $e = 0.76$, $P_f = 3.88d$ } $P_t = 25\overset{h}{.}9$ V_{run} = 196 km/sec	Bound (disrupted if $V_{SN} \geq 1.4 \times 10^4$ km/sec)
4.0 $M_\odot$	2.0 $M_\odot$	$M_2' = 1.44\ M_\odot$ disrupted	$M_2' = 1.74\ M_\odot$ disrupted	$M_2' = 1.78\ M_\odot$ disrupted

Table V. Effect of SN explosions in some representative post-spiral-in systems; V_{SN} is the ejection velocity of the SN shell; the assumed mass of the compact remnant is 1.4 $M_\odot$. P_f, P_t, etc. are defined in figure 2.

Assumed remnant mass	$M_2 = 1.2\ M_\odot$, $P_o = 9\overset{h}{.}2$	$M_2 = M_\odot$, $P_o = 7\overset{h}{.}33$
$M_1' = 1.3\ M_\odot$	$M_2' = 1.18\ M_\odot$, $e = 0.24$ $P_t = 10\overset{h}{.}13$, V_{run}=64km/sec	$M_2' = 0.99\ M_\odot$, $e = 0.25$ $P_t = 8\overset{h}{.}02$, V_{run} = 65 km/sec
$M_1' = 0.9\ M_\odot$	$M_2' = 1.08\ M_\odot$, $e = 0.74$ $P_t = 16^h$, V_{run}=174km/sec	$M_2' = 0.87\ M_\odot$, $e = 0.79$ P_t = 13.7h , V_{run}=183 km/sec

Table VI. Examples of SN effects in two CV binaries with a collapsing O-Ne-Mg white dwarf of mass 1.4 $M_\odot$ (for $V_{SN} = 10^4$ km/sec).

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REFERENCES:

Abt, H.A. and Levy, S.G. 1978, Astrophys. J. Suppl. *36*, 241.
Arnett, W.D. 1978, in: "Physics and Astrophysics of Neutron Stars and Black Holes" (R. Giacconi and R. Ruffini, eds.), North Holl. Publ. Comp., Amsterdam, p. 356.
Blandford, R. 1980, I.A.U. Symp. Nr. 95, "Pulsars" (W. Sieber and R. Wiebelinski, eds.), Reidel, Dordrecht (in press)
Bond, H.E.,Liller, W. and Mannery, E.J. 1978, Astrophys. J. *223*, 252.
Bradt, H.V.,Doxsey, R.E. and Jernigan, J.G. 1978, "Positions and Identifications of Gal. X-ray Sources", MIT preprint CSR-P-78-54, also in: "Advances in Space Exploration, vol. 3 (1979)".
Chechetkin, V.M.,Gershtein, S.S.,Imshennik, V.S., Ivanova, L.N. and Khlopov, M. Yu. 1980, Astrophys. Space Sc. *67*, 61.
Conti, P.S. 1978, Astron Astrophys, *63*, 225.
Cowley, A.P. 1980, Proc. NATO Adv. Study Inst. "Compact Galactic X-ray Sources," (P. Sanford, ed.) Cambridge Univ. Press (in press).
Crampton, D.,Cowley, A.P. and Hutchings, J.B. 1980, Astrophys. J. 235, L. 131.
Davidson, K. and Ostriker, J.P. 1973, Astrophys. J. *179*, 585.
De Cuyper, J.P. 1980, in: "Fundamental Problems in Stellar Evolution" (D. Sugimoto et al., eds.), Reidel, Dordrecht this volume, p. 184.
De Greve, J.P., De Loore, C. and van Dessel Ed. 1978, Astrophys. Sp. Sc. *53*, 105.
Delgado, A. 1979, in: "Mass Loss and Evol. of O-type stars" (P.S. Conti and C. De Loore, eds.), Reidel, Dordrecht, 415.
Delgado, A. and Thomas, H.-C. 1980, preprint Max Planck Institut für Astrophys. Garching b. München.
De Loore, C. and De Greve, J.P. 1976, in: "Structure and Evolution of Close Binary Systems" (P. Eggleton et al., eds.), Reidel, Dordrecht, p. 193.
Flannery, B.P. and Ulrich, R.K. 1977, Astrophys. J. 212, 533.
Fowler, L.A. 1980, (private communication).
Fryxell, B.A. and Arnett, W.D. 1978, Bull. Am. Astron. Soc., *10*, 448.
Gursky, H. 1976, in: " Structure and Evolution of Close Binary Systems" (P. Eggleton et al. eds.), Reidel, Dordrecht. p. 19.
van den Heuvel, E.P.J. 1975, Astrophys. J. *198*, L. 109.
van den Heuvel, E.P.J. 1976, in: "Structure and Evol. of Close Binary systems(P.Eggleton et al.,eds.),Reidel,Dordecht,p.35.
van den Heuvel, E.P.J. 1977, Annals N.Y. Acad. Sciences *302*, 14.
van den Heuvel, E.P.J. 1978, in: " Physics and Astrophys. of Neutron Stars and Black Holes, R. Giacconi and R. Ruffini (editors), North. Holl. Publ. Co. Amsterdam, p. 828.
van den Heuvel, E.P.J. 1980, in "X-Ray Astronomy" (R. Giaconni and G. Setti, eds.) Reidel, Dordrecht, p. 115.

van den Heuvel, E.P.J. and Heise, J. 1972, Nature Phys. Sc. *239*, 67.
van den Heuvel, E.P.J. and De Loore, C. 1973, Astron. Astrophys. *25*, 387.
Hutchings, J.B., Crampton, D., and Cowley, A.P. 1978, Astrophys. J. *225*, 548.
Hutchings, J.B. 1980, in: " Proc. NATO Adv. Study Inst. on Compact Gal. X-ray Sources" (P. Sanford, ed.) Cambridge Univ. Press (in press).
Joss, P.C. and Rappaport S. 1979, Astron. Astrophys. 71, 217.
Kelley, R., Rappaport, S. and Petre, R. 1979, Astrophys. J. (in press).
Kippenhahn, R. and Meyer-Hofmeister, E. 1977, Astron. Astrophys. *54*, 539.
Kippenhahn, R. and Weigert, A. 1967, Zeits. Ap. 65, 251.
Lewin, W.H.G. and Clark, G.W. 1980, in: "Proc. 9th Texas Symp.on Relativ. Astrophys. Ann. New. Y. Acad. Sc. *336*, 451.
Li, F., Rappaport, S., Joss, P.C., McClintock, J.E. and Wright, E. 1980, Astrophys. J. (Lett.), in press.
Manchester, R.N., Newton, L.M., Cooke, D.J. and Lyne, A.G. 1980, Astrophys. J. *236*, L 25.
Massey, P. and Conti, P.S. 1980, Astrophys. J. (in press).
Mc Cray, R. 1979, (priv. communication).
Meyer, F.and Meyer-Hofmeister, E. 1979, Astron. Astrophys. *78*, 167.
Middleditch, J., Mason, K.O., Nelson, J. and White, N. 1980, preprint
Miyaji, S., Nomoto, K., Yokoi, K. and Sugimoto, D. 1980, Publ. Astron. Soc. Japan, 32, 303.
Nomoto, K. 1980, Proc. Workshop on "Type I supernovae", Univ. of Austin, Texas (in press).
Ostriker, J.P. 1976, in: IAU Symp. 73 "Structure and Evolution of Close Binary Systems" (P.Eggleton et al., eds.) Reidel, Dordrecht.
Ostriker, J.P. and Zytkov, A. 1980, In preparation.
Paczynski, B. 1971 a, Ann. Review Astron. Astrophys. 9, 183.
Paczynski, B. 1971 b, Acta Astronomica 21, 1.
Paczynski, B. 1976, in: IAU Symp. 73 "Structure and Evolution of Close Binary Systems" (P.Eggleton et al., eds.) Reidel, Dordrecht, p 75.
Paczynski, B. 1980, Acta Astronomica (in press).
van Paradijs, J. 1978, Nature *274*, 650.
van Paradijs, J. 1980, I.A.U. Circ. No. 3487 (19 june).
Plavec, M. 1968, Advances Astron. Astrophys. *6*, 201.
Ritter, H. 1976, Mon. Notices Roy. Astr. Soc. *175*, 279.
Ritter, H. 1980, ESO Messenger (in press), ESO, Garching b. München.
Savonije, G.J. 1978[1], Astron. Astrophys. *62*, 317.
Savonije, G.J. 1978[2], Ph. D. Thesis, Univ. of Amsterdam.
Savonije, G.J. 1979 , Astron. Astrophys. *71*, 352.
Schwartz, D.A. et al., 1979, Preprint Center for Astrophys. (Harvard Univ.).
Shakura, N.I. and Sunyaev, R.A. 1973, Astron Astrophys *24*, 337.
Smarr, L. L. and Blandford, R. 1976, Astrophys. J. 207, 574.
Sugimoto, D., and Nomoto, K. 1980, Space Sc. Reviews, *25*, 155.
Sutantyo, W. 1974, Astron. Astrophys. *31*, 339.
Sutantyo, W. 1975, Astron. Astrophys. *35*, 251.
Taam, R.E. 1979, Astrophys. Letters *20*, 29.

Taam, R.E. Bodenheimer, P. and Ostriker, J.P. 1979, Astrophys. J. *222*, 269.
Taylor, J.H. 1980, (priv. communication).
Taylor, J. H., Hulse, R.A., Fowler, L.A., Gullahorn, G.E. and Rankin, J.M. 1976, Astrophys. J. 206, L 53.
Thomas, H.-C. 1977, Annual Rev. Astron. Astrophys. *15*, 127.
Trimble, V. 1974, Astron. J. *79*, 967.
Tutukov, A.V. and Yungelson, L.R. 1973, Nautsnie Inform, 27, 58.
Tutukov, A.V. and Yungelson, L.R. 1980, "Close Binary Stars" (editors: M. Plavec et al.) Reidel, Dordrecht, p. 15.
Warner, B. 1974, Mon. N. Roy. Astr. Soc. *167*, 61 p.
Webbink, R.F., 1980, in: I.A.U. Colloq. Nr. 53, "White Dwarfs and Variable Degenerate Stars", Reidel, Dordrecht
Wheeler, J.C., Mc Kee, C.F. and Lecar, M. 1975 Astrophys. J. *200*, 145.
Whelan, J. and Iben, I 1973, Astrophys. J. 186, 1007.
Ziolkowski, J. 1976, in: " Structure and Evol. of Close Binary Systems" (P. Eggleton et al., eds.) Reidel, Dordrecht, p. 321.
Ziolkowski, J. 1977, Annuals N.Y. Acad. Sci. *302*, 47.
Ziolkowski, J. and Paczynski, B. 1980, Acta Astronomica (in press).

DISCUSSION

Sugimoto: I think there are too many ways in that very close binaries containing a compact object can be formed. We do not know how much specific angular momentum is carried away with escaping mass at the time of "shrinkage" of the binary separation or of "spiralling in" of the compact object. Once this is known, it will impose stringent restrictions on the evolution of such binary systems. For example, if we apply the results of calculations of single particle losses from the L_2 point, the separation shrinks so much in most cases that the stars to coalesce. I believe this issue is one of the fundamental problems of binary evolution and I would like to hear your opinion about it.

Van den Heuvel: I am afraid that, in reality, there is no case in which a single cause for "spiralling in" dominates. For example, tidal instability is always expected to occur, either before or after the common envelope is formed (cf. Meyer and Meyer-Hofmeister 1979). As soon as the common envelope forms, there will be a great deal of friction which will accelerate the "spiralling" etc. It would, of course, be nice if one could simply say "mass is lost and carries off a factor $(1+\beta)$ times the specific angular momentum of the system" and if β could then be calculated in some simple way. We could then just introduce the function β into the evolution program, and the calculation of "spiralling in" would be simple. Unfortunately there are, as far as I can see, no such simple ways. One will have to make a combined hydrodynamics plus evolutionary code which also allows for tidal effects, and do a complete calculation. The function β will then follow from such a calculation, but will not be an input parameter. Unfortunately, nature is not always as mathematically simple as one might wish.

Wheeler: Type I supernovae explode at a rate of about 10^{-2} per year in the Galaxy. If they all produce a neutron star in a low-mass binary system, a low-mass binary X-ray source should be created. I have heard it argued that 10^{-2} per year is much greater than the estimated production rate for low-mass X-ray sources. Can you comment on this?

Van den Heuvel: As you saw in my last table, if $\simeq 0.5\ M_\odot$ is ejected in the supernova explosion at a velocity $v_{ej} \sim 10^4$ km/sec, the orbital period (after tidal circularization) is almost doubled, and the system is very detached. If the non-degenerate star has a mass $\leq 1\ M_\odot$, nuclear evolution will not increase its radius to the radius of the Roche lobe for 10^{10} yrs. Also, the timescale for reducing the orbital period enough that the star fills its Roche-lobe is of the same order. Consequently, it may well take more than the age of the galaxy before such a system turns into a low-mass X-ray binary. (All of this depends sensitively, of course, on v_{ej} and on the amount of ejected mass; but for the above parameters, the situation is as I have described it.) Therefore, there may be millions of such detached systems which have not yet become X-ray sources, and the low-mass (bulge) X-ray sources may be just the tip of the iceberg. Under these circumstances, it is not possible to say anything sensible about the formation rate of these objects.

Schatzman: Is it not right that the mass interval within which a white dwarf can become a supernova is very small? In this case, the probability of finding such a white dwarf companion is very small, and would explain the low SN rate.

Van den Heuvel: According to the recent work of Nomoto (preprint 1980), white dwarfs of the required composition may be formed in a fairly broad mass range, between $1.2\ M_\odot$ and $1.4\ M_\odot$ (see also Sugimoto and Nomoto Space Sci. Rev. 25, 155, 1980). Accretion may then bring them to the Chandrasekhar limit. This implies progenitors roughly in the mass range 8-10 $M_\odot$, again a fairly broad region. If one would wish to identify such collapsing white dwarfs with Type I supernovae, one would (because of their frequency) indeed wish them to originate from a fairly broad mass range. Hence, such an identification might well be consistent with Nomoto's results.

Lamb: As you know, there is some controversy about whether Cyg X-2 is a neutron star (Cowley, Crampton, and Hutchings 1979) or a degenerate dwarf (Branduardi *et al*. 1980). Could you elaborate on your mention of an evolutionary scenario by which a neutron star in a binary system with a companion mass $M_\odot \cong 0.5\ M_\odot$ and a period $P \cong 10^d$ could form, and comment on any implications for the nature of Cyg X-2?

Van den Heuvel: There are indeed ways to obtain neutron star X-ray binaries with periods of the order of 10 days and a non-degenerate companion of $\sim 0.5\ M_\odot$. For example, following further the evolution of a system such as Hercules X-1 in the way outlined in my talk, one would rather straightforwardly attain the system parameters of Cygnus X-2. So, even if a low-mass X-ray binary is formed with $P \sim 1$ to 2 days, evolution may considerably change its binary period later on, and there are many possibilities for the final configuration. Of course, this does not at all rule out the possibility that the Cygnus X-2 system contains a white dwarf.

Tayler: I have been surprised not to hear black holes mentioned this afternoon. What is the current view about the probability of black hole formation as a result of close binary evolution?

Van den Heuvel: From the theoretical point of view, I have no clear opinion. Arnett's work on helium stars shows that up to a mass of some 60 $M_\odot$ such stars would always leave neutron stars of roughly a Chandrasekhar mass. Since such helium stars must have been cores of stars more massive than 80 to 100 $M_\odot$, one would need a very massive star in order to terminate with a black hole, and such stars are extremely rare. On the other hand, from the observational point of view, 16 of the 17 known massive X-ray binaries are either pulsing or have mass functions low enough to fit a neutron star. The same holds for the low-mass X-ray binaries and for the bulge sources. For the bursters among the latter sources, independent evidence strongly suggests that we are dealing with neutron stars, and the same holds for the globular cluster X-ray sources (a large fraction of which are also bursters). Therefore, after observing X-ray sources for nearly a decade with more than half a dozen X-ray satellites, we still have only one reasonably strong black hole candidate, namely Cygnus X-1. In my opinion, this seems to tell us that, if stellar-mass black holes exist at all, their formation in close binaries must be extremely rare.