EVOLUTION OF CLOSE BINARIES AND THE FORMATION OF PULSARS

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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 outlined. It is argued that most of the remnants of massive stars ($M_1 \gtrsim 10\ M_\odot$) will be runaway pulsars, with space velocities $\gtrsim$ 100 km/s, i.e.:
(i) semi-conservatively evolving massive close binaries ($\sim$ 1/3 of all massive stars) after the first SN explosion consist of a massive star and a neutron star; subsequently, after a stage of common-envelope evolution and spiral-in most of these systems are disrupted in the second SN, producing *two* runaway pulsars, one young and one old.
(ii) highly non-conservatively evolving systems (with initial mass ratio $q_0 \lesssim 0.5$ and binary periods up to several decades; $\gtrsim$ 1/3 of all massive stars) will spiral-in during the first phase of mass transfer and are disrupted in the first SN explosion, producing *one* young runaway pulsar, together with a runaway star of low or moderate mass.

In the (rare) case that a non-conservatively evolving system is not disrupted in the first SN, it may later on evolve into a low-mass population I X-ray binary with a high space velocity (> 100 km/s) such as Her X-1 and Cyg X-2.

Compact objects may also be formed in binaries in which a white dwarf of suitable chemical composition is driven over the Chandrasekhar limit by accretion. Such systems may later on evolve into low-mass X-ray binaries. Possible scenarios for the formation of the three binary radio pulsars are discussed.

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.

W. Sieber and R. Wielebinski (eds.), Pulsars, 379–396.

TABLE 1. MASSIVE X-RAY BINARIES

a. Examples of persistent strong sources

Source	Type	P_{orb}(d)	P_{pulse}	$m \sin^3 i$	e	Ref.
SMC X-1	B0I	3.9	$0^s.71$	0.8 + 12.5	0.00	(1)
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	(2)
Cyg X-1	09.7Iab	5.6	--	1.5 + 2.4 (i = 30°)	0.00	(1)

b. Examples of weaker or transient pulsating sources

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

TABLE II. LOW-MASS X-RAY BINARIES

Source	Sp. Type	P_{orb}	P_{pulse}	M_{opt}	M_x	z	Ref.
Her X-1	A-F	$1^d.70$	$1^s.2$	2.2	1.3	3 kpc	(4)
Sco X-1	accr. disk	$0^d.787$	--	<1	--	400 pc	(4)
1627-673	accr. disk	41 min	$7^s.7$	0.05	∿1.4(?)	--	(5)
2129+47	G-dwarf(?)	$5^h.2$	--	1(?)	--	--	(4)
Cyg X-2	F-giant	$9^d.843$	--	0.5-1.1	1.3-1.8	1.5 kpc	(4)

TABLE III. BINARY RADIO PULSARS

Name	P_{pulse}	P_{orb}	e	Ref.
PSR 0656+64	$0^s.196$	24^h41^m	0.00	Fowler (1980)
PSR 0820+02	$0^s.865$	3.1 yr	0.00	Manchester et al. (1980)
PSR 1913+16	$0^s.059$	7^h45^m	0.62	Taylor et al. (1976)

(1) Conti (1978) (2) Kelley et al. (1980) (3) Bradt et al. (1978)
(4) Cowley (1980) (5) Middleditch et al. (1981)

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

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 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 light-curve) 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 at least 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 the star is unevolved) binary periods of less than about ten hours. The high X-ray luminosities of these sources (10^{36} - 10^{38} erg/s) 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). Finally, there are the three binary radio pulsars listed in Table III.

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 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 or 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

We refer to earlier reviews (Plavec, 1968; Paczynski, 1971a; Thomas, 1977; van den Heuvel, 1978; Webbink, 1980). In Kippenhahn and Weigert's classification, binaries that are so close that the primary star already overflows its Roche-lobe during core-hydrogen burning are indicated as case A. For $M_1 \sim 10\ M_\odot$ case A occurs only for $P_{orb} \lesssim 2.5$ d. Systems in which the primary fills its Roche-lobe after the star has left the main sequence but before the onset of core helium burning are called case B, and systems in which the lobe is filled still later case C. Systems in case B have periods typically in the range from a few days to $\sim 10^2$ days; in case C from $\sim 10^2$ days to several decades. 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 (1971b), Arnett (1978), Savonije (1978) and Delgado and Thomas (1980) show the following results (cf. especially Sugimoto and Nomoto, 1980):

a. In helium stars with $M \leqq 2\ M_\odot$ 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 and 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 $M \sim 2 - 3\ M_\odot$ 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 collapse, 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. Delgado and Thomas (1980) found that a $4\ M_\odot$ He-star in a $1\overset{d}{.}49$ 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

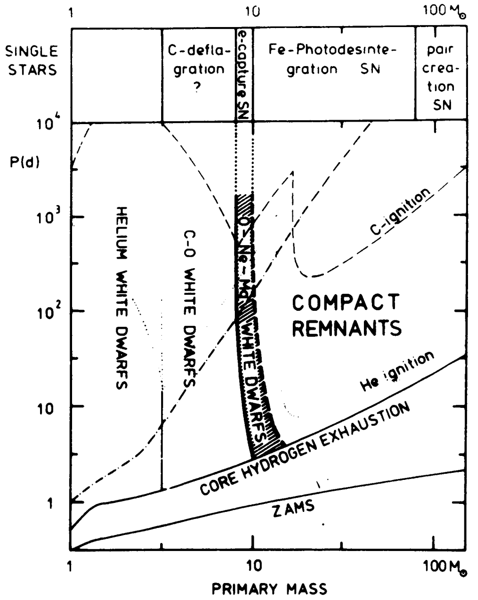

Figure 1: Classification of expected final evolutionary states of primary stars of close binaries as a function of primary mass and orbital period (partly after Webbink, 1980). The orbital periods correspond to binaries in which the primary star just fills its Roche lobe (for mass ratio unity). At the top of the figure the expected final evolutionary states of single stars are indicated.

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 (± 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 shellburning before the onset of mass transfer, the required initial mass is $M_{ms} \gtrsim 10\,(\pm 1)\,M_\odot$. 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 (± 1) $M_\odot$, for long periods about 8 (± 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 and C-O 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 an 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 accretion 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 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 Fig. 1) may (sometimes much) later, during the mass transfer from secondary to primary, undergo an electron-capture SN. Canal and Schatzman (1976) and Canal and Isern (1980) have pointed out that also C-O white dwarfs which were born with a mass close to the Chandrasekhar limit may be induced by accretion to undergo collapse to a neutron star. This process was further studied by Canal et al. (1980). It appears that collapse is favoured by fast accretion ($\sim 10^{-6}$ $M_\odot$/yr), a low central temperature ($\sim 10^7$ K, which would imply that the white dwarf is billions of years old) and a low central C^{12} abundance (cf. Canal, 1980). The collapse is induced by e-captures on O^{16} in the centre; C-ignition takes place off-center and may very well induce non-negligible mass ejection — to an extent not known so far. Since accretion-induced collapse may, if the secondary is a low-mass star, occur billions of years after the formation of the white dwarf, such SNe may also occur in old stellar systems. It seems attractive, therefore, to identify this type of collapse with Type I SNe (Sugimoto and Nomoto, 1980; Nomoto, 1980; Canal, 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 and the C-O 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.

4. THE FATE OF THE ENVELOPE

4.1 Quasi-conservative Evolution: Formation of Massive X-ray Binaries

We consider primary stars which directly evolve to core collapse ($M_{core} \geq 3$ $M_\odot$). 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, 1971a):

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

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 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. 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). De Greve et al. (1978) and Massey (1980) 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. 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 or 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.

4.2 Highly Non-conservative Evolution

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. Condition (c) follows from the fact that mass transfer from a radiative envelope 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

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

where M_1 is expressed in solar units (cf. Paczynski, 1971a).

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. The same holds if condition (c) is not fulfilled, since mass transfer from a convective envelope has the tendency to grow catastrophically.

4.3 Outcome of Common-envelope Evolution for $M_1 \leqq 10 - 12\ M_\odot$

Although no precise calculations exist, observation and speculation suggest that cataclysmic (CV) binaries with $P \sim 0.25 - 0.5$ 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 calculations 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 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, $P \sim 12^h$, Bond et al., 1978).

4.4 Common-envelope Evolution in Massive Systems

We consider systems in which the primary has $M_{core} \gtrsim 3\ M_\odot$. 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 systems, 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 ~ 3 to $5\ M_\odot$ the resulting post-spiral-in periods then are typically of order 0.5 to 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/s and 10^4 km/s. We assumed instantaneous spherically symmetric mass ejection and estimated the impact effects following Wheeler et al. (1975) (but

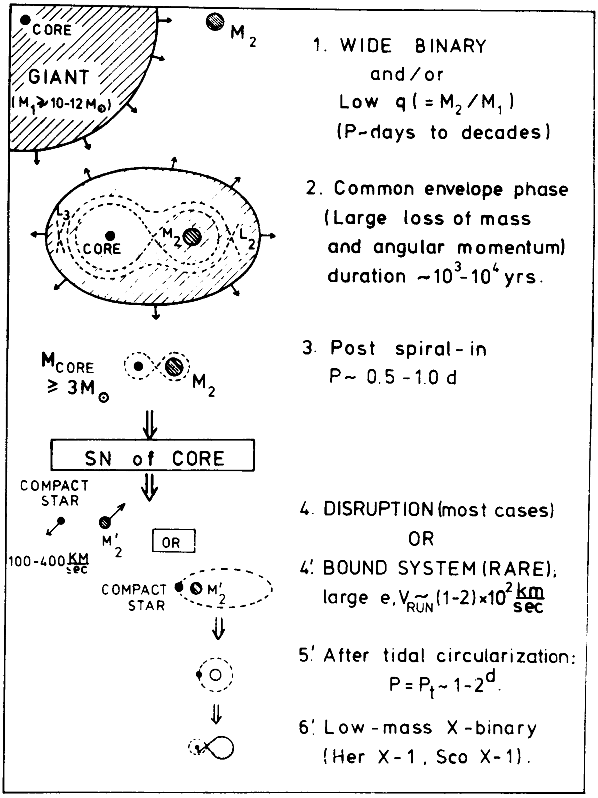

Figure 2: Expected highly non-conservative evolution of massive close binaries with a long P and/or low q (explanation in text)

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

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 IV 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/s. In view of their short separation at periastron, their orbits will rapidly circularize by tidal forces. Figure 2 schematically illustrates this situation. Table IV 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 of the plane with a velocity ≧ 125 km/s 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 ≧ 100 km/s. [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. §4.6), 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 order $10^2 - 2.10^2$ km/s. 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/s. For $P_o = 24^h$ this limit becomes $\geqq 1.4 \times 10^4$ km/s. Since P_o cannot be much smaller than $\sim 12^h$, we conclude that most probably $V_{SN} \gtrsim 10^4$ km/s (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).

4.5 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; Tutukov, 1979), 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

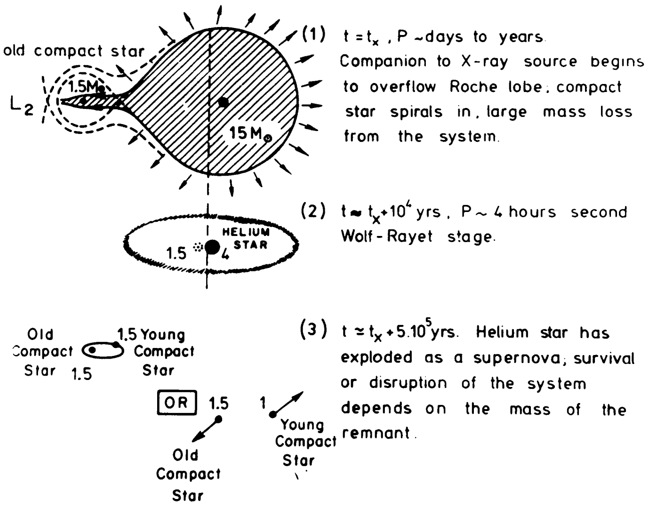

Figure 3: Final evolution of quasi-conservative systems (see text)

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 Ulrich, 1975). 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.

4.6 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 $q^{-1/4}$ (down to the completeness limit of $q \cong 0.2$). 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, 1981; Massey, 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 $M \gtrsim 10 - 12\ M_\odot$ undergo common-envelope evolution and become very short-period binaries before they explode as a SN. Consequently, over 1/3 of all stars with $M \gtrsim 10 - 12\ M_\odot$ will produce runaway pulsars with $V > 100$ km/s. 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/s (the orbital velocity at periastron of PSR 1913+16 is > 500 km/s). Since quasi-conservatively evolving systems produce *two* runaway pulsars, one expects that some three quarters of all stars with $M \gtrsim 10 - 12\ M_\odot$ 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/s. This may explain the observed fact that the majority of the radio pulsars have runaway velocities of order 100 - 200 km/s (Lyne, 1981).

5. ACCRETION-INDUCED COLLAPSE OF WHITE DWARFS

5.1 Restrictions

In Miyaji et al.'s (1980) calculations a helium accretion rate of $4.10^{-6}\ M_\odot$/yr onto an O-Ne-Mg white dwarf 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. Similar considerations hold for the accretion induced collapse of C-O white dwarfs. As an additional constraint these must have had masses close the Chandrasekhar limit already at their formation. The amount of mass ejected in the collapse of a white dwarf does probably not exceed a few tenths of a solar mass, and hence is unlikely to cause disruption of the system (cf. van den Heuvel, 1977, 1981). 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.

5.2 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 may 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 may 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 neutron star binary with a circular orbit remains. Possibly this was the evolutionary history of PSR 0820 and PSR 0656 (Blandford, 1981) 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 GX 1+4) in which the companion to the neutron star has a mass $\leqq 10-12\ M_\odot$ (cf. §4.5) and, consequently, terminates its life as a white dwarf.

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 may explain their generally high space velocities. Non-conservatively evolving systems which survive the SN of the primary star may become short-period binary radio pulsars and may subsequently evolve into low-mass population I X-ray binaries such as Her X-1.

(ii) Accretion-induced collapse of O-Ne-Mg or C-O white dwarfs may occur in young as well as old systems, and may explain the existence of an old population of low-mass X-ray binaries. It also may explain the existence of close as well as wide binary radio pulsars with nearly circular orbits.

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DISCUSSION

HELFAND: Your one third of stars that evolve quasi-conservatively keeps one of the pulsars trapped for a time long compared to what we think of as the β-field decay or adjustment time in pulsars. When these are released at the time of the second SN they may well not be capable of producing radio pulsar emission. Also, since this scenario applies mostly to massive (i.e. rare) stars, I doubt that it will make a significant contribution to the pulsar birthrate.

VAN DEN HEUVEL: To start with your last comment, I am not sure that this is correct, since the entire pulsar birthrate is, as we can see it now from the theoretical point of view, only coupled with stars more massive than about 8 - 10 $M_\odot$. And among these the pulsars released in the second SN make a significant contribution to the birthrate. As to the observability of the spun-up old pulsar as a radio pulsar, this obviously depends on the magnetic field strength. If the field is strong, their periods may be long and they may not be observable. On the other hand if, as in PSR 1913+16, the field is weak, they will have short periods and may be observable.

Y.-M. WANG: I gather from what you said that a binary radio pulsar can live twice, with an X-ray phase in between. During the X-ray stage, the torque exerted by an accretion disc may be able to align the neutron star's spin axis with the orbital axis.

VAN DEN HEUVEL: I agree; this may have interesting observational consequences for PSR 1913+16.

TAYLOR: Do you like the $\sim$ 24-hour orbital period, circularized during spiral-in, as an evolutionary model for the binary pulsar PSR 0656+64?

VAN DEN HEUVEL: It is one of the possibilities. However, as I have pointed out, also a different evolutionary history is possible, which would lead to a white dwarf or a helium star companion. I think that only the (optical) observations can decide which of these possibilities is correct.

BLANDFORD: How do you estimate the duration of the X-ray binary phase, i.e. when the mass transfer rate is low $\lesssim 10^{-8}$ $M_\odot$ yr^{-1}?

VAN DEN HEUVEL: I presume that you are concerned with the Her X-1 like systems? Here the precise evolutionary calculations of Savonije suggest an X-ray lifetime by beginning Roche-lobe overflow of a few times 10^5 yrs up to $\sim 10^6$ yrs, which I adopted here.

CHEVALIER: I have a couple of comments on supernovae. First, you have argued that the rate of "faint" supernovae is about three times the rate of normal type II supernovae. This would give a supernova remnant formation rate three times the rate of type II supernovae. This is contrary to existing evidence but may be within the errors. It is important to study the selection effects that might affect estimates of the rate of supernova remnant formation. Second, observations of normal type II supernovae indicate typical expansion velocities of 4000 - 5000 km s^{-1}. If the envelope of the progenitor is lost, the same energy may be given to a smaller mass, increasing the typical velocities by a factor 1.4 - 1.8. Finally, if low-mass binaries in the bulge and globular clusters are formed from the O-Ne-Mg cores, is there any problem with massive progenitor objects (8 - 10 $M_\odot$) giving rise to an old population?

VAN DEN HEUVEL: Thank you for this comment. To answer your last question: I do not think that this is a serious problem. Also the massive white dwarfs that we observe in some of the cataclysmic binaries (e.g. Z Cam) must have had fairly massive progenitors, i.e. some 5 $M_\odot$ or more. Similar systems can be produced if the red giant was a 8 - 12 $M_\odot$ star which lost its envelope. Of course, these white dwarfs might have been produced billions of years ago, but may just recently have been driven over the Chandrasekhar limit, when their companions overflowed their Roche lobes.