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MASSIVE CLOSE BINARIES: OBSERVATIONAL CHARACTERISTICS

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Abstract. Theoretically predicted evolutionary phases of massive close binaries are compared with the observations. For the evolution up to the High-Mass X-ray Binary (HMXB) phase there is fair agreement between theory and observation. Beyond the HMXB phase there is much uncertainty. Notably it is puzzling why we observe so few systems consisting of a helium star and a neutron star (Cygnus X-3 is the only one found so far), and why the incidence of double neutron stars is so low. A better understanding of Common Envelope evolution is required in order to answer these questions. The role of velocity kicks imparted to neutron stars during supernova collapse is discussed. Such kicks might cause many runaway OB stars to be single.

1. Introduction

Figure 1 depicts the subsequent evolutionary stages through which a massive close binary system with a not too small initial mass ratio ($q = M_2/M_1 \geq 0.4$) is, theoretically, expected to pass (see for example Van den Heuvel 1974, 1978, 1983 and 1993 and references therein). For such systems the first phase of mass transfer proceeds more or less "conservatively", i.e.: total mass and orbital angular momentum of the system are expected to be conserved.

The different evolutionary phases and their expected durations are described in the figure and its caption, to which we refer the reader for details.

In this paper we discuss in section 2 the possible identifications with observed types of binary systems of the various evolutionary phases up till the X-ray binary phase. We also discuss in this section the reasons for the differences between the two observed classes of High Mass X-Ray Binaries (HMXB): the 'Standard' HMXBs and the Be/X-Ray Binaries.

In section 3 as an intermezzo we discuss the evidence of kicks imparted to neutron stars at birth, and the possible implications of these kicks for the origins of HMXBs.

In section 4 we discuss the formation of the low-mass X-ray Binaries, since these also are the products of the evolution of high-mass binary systems. This is because, in order to produce a neutron star or a black hole, a star should have an initial mass of $\geq 8M_\odot$ and $\geq 30 - 40M_\odot$ respectively (cf. Van den Heuvel and Habets 1984; De Kool et al. 1987). Hence, the low-mass X-ray binaries, which consist of a neutron star or a black hole together with a low-mass star ($\leq M_\odot$), must also have started out as massive binary systems - in this case with a very small mass ratio (≤ 0.15).

In section 5 we discuss the final evolution of high-mass X-ray binaries and the identification of the expected final evolutionary stages with observed binary systems. Finally, we discuss the loose ends and gaps that exist in our understanding

Fig. 1. Conservative evolution of a close binary system with initial masses of 25 and $10 M_{\odot}$. Each stage is labelled with the approximate age of the system and the orbital period in days. The numbers inside the representation of the stars indicate mass ($M_{\odot}$). The system becomes a wind-powered 'standard' massive X-ray binary for some 10^4 yr in stage e (see text). For the subsequent evolutionary stages f, g and h: see text.

of the evolution of massive binary systems.

2. Evolutionary phases up till the HMXB phase

2.1. A DIFFERENCE IN EVOLUTION BETWEEN THE INTERMEDIATE-MASS AND HIGH-MASS SYSTEMS, AND THE PRODUCTION OF Be-X-RAY BINARIES

The Be/X-ray binaries have systematically lower masses (companion masses $\simeq 8 - 15 M_{\odot}$) and wider orbits ($P \sim 15^d$ to several years) than the "standard" HMXBs. This difference is simply explained by the lower relative mass fraction contained in the helium core produced in lower mass stars as compared to massive stars ($M_{\text{He}} \sim 0.1 M^{1.4}$, where M is the initial main-sequence mass of the star), in combination with the conservation of mass and orbital angular momentum during the first phase of mass transfer, as can be easily verified (see van den Heuvel 1983). Figure 2 depicts as an example the evolution of an intermediate-

Fig. 2. Conservative scenario for the formation of a Be/X-ray binary out of a close pair of early B stars with masses of $13.0 M_{\odot}$ and $6.5 M_{\odot}$. The numbers indicate mass (in units of $M_{\odot}$). After the end of the mass transfer the Be star presumably has a circular disk or shell associated with its rapid rotation (induced by the previous accretion of matter with high angular momentum; from Habets (1985)).

mass close binary (component masses $13+6.5 M_{\odot}$) into a Be/X-ray binary. One notices that during the first phase of mass transfer, its orbital period increases by a much larger factor (i.e.: ~ 8) than for the system of figure 1, also if that system would have had the same initial mass ratio 0.5 (in that case its period would have increased by only a factor 2.0, as one can easily verify). The rapid rotation of the mass-receiving original secondary in the Be system is due to the large amount of mass with angular momentum which this star received (by accretion through a disk). Due to the long orbital periods of the Be systems, tidal forces are insufficient to synchronize the rotation of the stars with their orbital periods. (Binary stars with early type main-sequence components and $P \geq 10^d$ are never synchronized (cf. van den Heuvel 1970)).

This explains why the Be stars in Be/X-ray binaries remained in rapid rotation whereas most of the standard HMXBs (which, with one exception have $P \leq 10^d$), have been tidally synchronized.

2.2. STATISTICAL PROPERTIES OF UNEVOLVED OB-BINARIES

2.2.1. distribution of mass ratios $\phi(q)$

These are subject to large selection effects, favouring the detection of systems with high mass ratios. For a recent discussion we refer to Hogeveen (1991; see also van den Heuvel 1993). It appears likely, from the work of Garmany et al. (1980) that the mass-ratio distribution of O-type binaries can be reasonably well

approximated by a flat distribution, whereas the works of Abt & Levy (1978) and Trimble (1990) yield distributions $\phi(q)$ ranging from approximately flat to $\phi(q) \sim q^{-1}$ (Trimble). Hogeveen (1991) even obtained a distribution as steep as $\phi(q) \sim q^{-2}$ down to $q = 0.3$ to 0.4 and flat below $q = 0.3$.

Within the observational uncertainties the distributions of Trimble and Hogeveen cannot be distinguished from the distribution

$$\phi(q) = 2/(1+q)^2 \quad (1)$$

suggested by Kuiper (1935). This distribution has the advantage that it does not become singular at $q = 0$. Studies of the evolution of synthetic stellar populations

TABLE I

Orbital periods (P^f), eccentricities (e), and system runaway velocities (v_g) that known Wolf-Rayet Binaries will obtain after the supernova explosion of their WR star, assuming a $1.4 M_\odot$ neutron star to be left. It is assumed that the mass of the WR star at the time of the explosion is $10 M_\odot$ (or present WR mass, if this is less than $10 M_\odot$), and that the mass ejection is instantaneous and symmetric. For short-period systems also the period after the tidal circularization of the orbit is given, in parentheses. The last column lists the radial velocity amplitude of the O-star induced by the presence of the neutron star remnant of the WR star.

Name	$P(d)$	$M_{wr} + M_{OB}$ $M_\odot$	$P_f(d)$	e	$V_g(km/s)$	$K(km/s)$
AB 6	6.861	6.4+37	8.99	0.13	43.4	12
AB 8	16.664	13.5 +50	23.66	0.17	45.2	8
γ^2 Vel	78.5	25+35	130.8	0.24	33	5.4
HD94305	18.82	16+35	31.33	0.24	52	9
HD97152	7.886	20+35	13.1	0.24	70	11.6
HDE311884	6.34	50+60	8.5 (8.2)	0.14	57	9.6
HD152270	8.893	20+60	11.9	0.14	51	8.4
HDE320102	8.83	11+35	14.7	0.24	67	11.2
HD168206	29.707	13+25	61.8	0.33	53	8.6
HD186943	9.555	13+25	19.9	0.33	77	12.4
HD190918	112.8	9 +35	176.2	0.21	26	4.9
V444Cyg	4.212	11+30	6.2 (5.9)	0.19	77	13.1
GPCep	6.69	10+45.5	9.9 (9.6)	0.18	65	10.9
CQCep	1.64	23+19.3	4.3 (3.2)	0.41	155	27
CXCep	2.217	11+25.6	4.3 (3.7)	0.32	126	21.6

that contain a certain fraction of close binaries show that the results do not differ dramatically between a flat input distribution for q and that given by eq. (1)

(e.g. see Meurs and van den Heuvel 1989; Tutukov and Yungelson 1993, and references therein).

2.2.2. *the initial distribution of orbital periods*

For O-stars and early B-stars the distributions peak approximately around $P \sim 3^d$ (see the review by Vanbeveren 1991, and references therein). For wider unevolved systems, from $P \sim 10^d$ on, the distribution of $\log P$ (and $\log a$) is approximately flat (cf. Abt 1983) implying $f(P) \propto P^{-1}$ and $g(a) \propto a^{-1}$, where f and g denote the distributions of P and a , respectively.

2.3. SYSTEMS AFTER THE FIRST PHASE OF MASS TRANSFER

The computations predict that these systems consist of a helium star and a massive OB main-sequence star. Systems of this type are well-known only among the highest mass binaries ($M_1 \geq 20M_\odot$): the Wolf-Rayet binaries, as first suggested by Paczynski (1967), see van der Hucht (this volume) and Vanbeveren (this volume). Since no WR-stars with masses smaller than about $5 M_\odot$ are known, apparently helium stars with masses $\leq 5M_\odot$ do not produce the very strong winds and large mass loss which are so characteristic for the WR-stars, and make them observable at optical wavelengths. Due to the absence of such winds, helium stars less massive than about $5M_\odot$ go unnoticed (their energy distribution is expected to peak in the extreme UV). A few Be-binaries such as ϕ Per have been suggested to harbour such lower mass helium stars (cf. Habets 1985).

Table 1 lists a number of representative WR binaries (after Abbott and Conti 1987). The table also lists the orbital periods P^f , eccentricities e and runaway velocities V_g (of the centre of the gravity of the system) which would result if their WR-stars would explode in a spherically symmetric supernova, and leave an $1.4 M_\odot$ star remnant (assuming that the mass of the WR star at the time of the explosion was either $10M_\odot$, or its present mass, if that is smaller). The systems do not become unbound by the explosions, as less than half the system mass is ejected, cf. Blaauw (1961).

2.4. SYSTEMS WITH A YOUNG RAPIDLY SPINNING PULSAR: PSR 1259-63 AND LSI 61° 303

Already from the time of the discovery of the first accreting binary X-ray source Cen X-3, the question came up: why do we not observe young radio pulsars orbiting massive stars (cf. Graham-Smith, 1974)? The answers mostly given were: the wind of the massive companion disperses the pulsar signal beyond recognition, or: the neutron star's spin is braked so rapidly by the accretion of wind matter, that there is very little chance to observe the young pulsar phase. Neither may, however, be true, since it now seems clear that massive binary systems containing young neutron stars have been found, namely PSR 1259-63 and LSI 61° 303 (a third one may be the Small Magellanic Cloud pulsar which describes a very elliptic orbit with $P \sim 50^d$ around a B-type star, Manchester, 1993).

PSR 1259-63 is a 47 *ms* radio pulsar in a 3.5 year very eccentric ($e = 0.87$) orbit around an B-type star. It has a magnetic field strength in the normal range for young pulsars ($3 \cdot 10^{11}$ G), and is eclipsed by the wind of the Be star for several months near periastron. Its spindown age is $\sim 3 \cdot 10^5$ yr, suggesting that it is a normal young radio pulsar (Johnston et al. 1993).

LSI 61° 303 is one of the most peculiar Be/X-ray binaries known: it exhibits strong synchrotron radio outbursts with a period of 26.5^d, which is also the radial velocity and photometric period of its peculiar Be-type companion. It was noticed long ago by Maraschi and Treves (1981) that it is in the error box of a COS-B gamma-ray source, and these authors therefore suggested that we are dealing here with a young Crab-like pulsar moving in an eccentric orbit around the Be star. The radio outbursts in this case would occur near apastron, when the relativistic pulsar wind is able to push aside the wind matter of the Be-star.

Recently, GRO-Comptel observations have provided strong confirmation for this model: it was discovered that the gamma-ray flux from this system varies with a 26.5 day period, in phase with the radio outbursts (Hermesen, 1993). Thus here we have probably a very young pulsar orbiting a Be star.

2.5. SYSTEMS AFTER THE FIRST SN-EXPLOSION: RELATION TO RUNAWAY OB STARS

One notices from table 1 that for a considerable number of systems the runaway velocities expected after the SN-explosion of the WR-stars, are in the 50-170 km/s range i.e. of the order of the highest runaway velocities observed for OB-runaway stars.

Blaauw (1993) in an important recent paper showed that 6 out of 7 well-studied runaway OB stars are rapid rotators and have a higher than normal He-abundance, characteristics just as expected for the post-mass transfer mass-gaining components of massive close binaries (the cause for the rapid rotation of the mass-gainer is that the mass-transfer proceeds through a disk, feeding high angular momentum to the star- just like for Be stars in Be/X-ray systems depicted in figure 2). For the runaway stars ζ Oph, AE Aur, μ Col and 53 Ari the parent association is known (the Sco-Cen association for the case of ζ Oph, and the I Ori association for the other three). Blaauw showed that all these four runaway stars are “blue stragglers” in the HR-diagrams of these associations (they are located to the left of the -already evolved- upper main sequence of these associations). This is exactly what one would expect for the post mass-transfer components of the close binaries, as these stars have been rejuvenated by the large amount of fresh hydrogen which they received during the mass transfer.

All this evidence taken together strongly suggests that 6 out of these 7 “classical” runaway OB stars have been produced by mass-transfer in massive close binaries, in which subsequently the original primary star exploded as a SN.

If the SN-mass-ejection was spherically symmetric, one would expect them to still be accompanied by a neutron star or black hole in a bound orbit.

Searches for X-ray emission (other than coronal emission) from runaway OB stars have always been unsuccessful. However, it should be kept in mind that most of the Be/X-ray binaries are transient X-ray sources which often exhibit no X-ray emission at all between their transient outbursts. These X-ray quiet periods can last up to decades.

If the accretion rate is low, the Alfvén radius R_A is located far from the neutron star, such that the centrifugal barrier produced by the neutron star's rotation is too great to allow matter at the Alfvén surface to enter the magnetosphere and to accrete (cf. Stella, White and Rosner 1986). Therefore no accretion will take place during such phases, and one does not necessarily expect X-ray emission from neutron star companions of runaway OB stars (since, on the main-sequence, the winds of these stars are not very strong, and the accretion rate is expected to be low). Only during the brief period prior to overflowing its Roche lobe such a star may produce an X-ray binary. Thus here, like in so many cases, the absence of evidence is *not* the evidence of absence!

It should furthermore be noticed that the HMXBs are (in most cases: mild) runaway OB stars: as shown by van Oyen (1989) their galactic z -distribution is about twice as wide as that of other unevolved OB stars, and they do not occur in ("avoid") OB-associations, and a few of them (e.g. QV Nor= 1538-52; X Persei; SS433) are genuine extreme runaway OB stars with velocities of order 10^2 km/s .

Thus the runaway OB stars have the characteristics of the mass-gaining components of massive close binaries- and the HMXBs are mostly (mild) runaway OBs. This all suggests that it is likely that many of the runaway OBs have resulted from mass-exchange binaries in which the original primary star has exploded as a supernova. Many of them might well have an unseen compact companion star (see especially also Stone, 1991). Alternatively if large asymmetries in the SN mass ejection occur (see next section), it is also possible that a sizeable fraction of the systems was disrupted in the first SN explosion.

3. The Evolutionary History of Low-Mass X-ray Binaries

Contrary to the formation of High-Mass X-ray Binaries, which represent a normal phase in the evolution of massive close binaries, the formation of LMXBs is an extremely rare event that requires very special initial conditions. This follows immediately from the fact that these systems are very long-lived: their mass transfer phase lasts $\gtrsim 10^8 \text{ yrs}$, while there are only some 10^2 such systems in the Galaxy. Thus their formation rate in the Galaxy is only of order $\sim 10^{-6} \text{ yr}^{-1}$, some 10^4 times lower than the supernova rate. Thus, not more than one out of every 10^4 supernovae produces a progenitor system of an LMXB (cf van den Heuvel 1983).

Since thus the probability for a neutron star (or a black hole) to end up with a low-mass companion star is extremely low, the formation of an LMXB must require a very extraordinary combination of initial system parameters. Space does

not allow us to deal with the various possible models for forming LMXBs (with a neutron star as well as a black hole component). We refer to the excellent review by Webbink (1992); for models for the formation of the LMXBs that contain black holes, of which now definitely four have been identified, we refer to de Kool et al. (1987) and Romani (1992).

The importance of the discovery of these systems is that, despite the extremely low probability of forming them, already four of them have been found in our neighbourhood in the Galaxy (within a few *kpc*). This implies that there must be enormous numbers of stellar black holes in the Galaxy of order 10^8 or more (van den Heuvel 1992b). These must all be remnants of massive stars. We thus are only just beginning to observe the tip of this iceberg of massive-star remnants in the Galaxy.

4. Final Evolution of HMXBs, Cygnus X-3 and the Formation of Double Neutron Stars and Neutron-Star Plus Black Hole Binaries

When we first calculated the final evolution of a HMXB (van den Heuvel and De Loore 1973) we found that due to the great difference in mass between the neutron star and its massive companion the mass transfer by Roche-lobe overflow would make the orbital separation of the system shrink dramatically. This orbital shrinking occurs independently of whether the neutron star can accept all the matter that is transferred to it, or expells it from the system due to radiation pressure. We therefore concluded that the final result will be a helium star with a compact companion in a very narrow orbit, with a period of only a few hours, as depicted in figure 1.

We suggested in 1973 that the very peculiar 4.8 hours orbital period X-ray binary Cygnus X-3 (which is one of the intrinsically brightest X-ray sources in the Galaxy, at a distance of about 10 *kpc*, in the galactic plane; it shows gigantic radio outbursts and has a 4.8 hour infrared period and an X-ray lightcurve suggesting the presence of a strong stellar wind from its companion) is to be identified with such a close helium-star binary.

This suggestion was confirmed in 1991 by the discovery by van Kerkwijk et al (1991) that the infrared spectrum of Cyg X-3 shows very strong emission lines of helium and is identical to that of a nitrogen-type Wolf-Rayet star, i.e.: a massive helium star ($M \geq 5 M_{\odot}$). [Optical observations of Cyg X-3 are impossible as the visual extinction in its direction is $> 20^m$].

Refinements of the calculations of the final evolution of HMXBs were introduced by Taam et al. (1978) using the concept of Common-Envelope (CE) evolution (see also Taam and Bodenheimer 1992). These authors argued that a HMXB system will only survive as a binary if the initial orbit is sufficiently wide. In close systems, (i.e. for $P < 100^d$ if $M_2 = 20 M_{\odot}$) the neutron star will, according to this model, spiral completely into the core of its massive companion star and form a so-called Thorne-Zytkov star: a red super-giant with a neutron star in its

center (Thorne and Zytkov 1977; Biehle 1991, Cannon et al. 1992).

If the concept of CE-evolution is correct, this will happen to all “standard” HMXBs and to more than half (and possibly as much as over $\frac{2}{3}$) of all Be/X-ray binaries. Thus, Cyg X-3 should then have resulted from a wide system like one of the Be/X-ray binaries. We have some doubts about this, however, since, judging from its WN6-7 spectrum the helium star in Cyg X-3 appears to be quite massive, more as what one would expect from a standard HMXB, thus: from a system with a short initial orbital period!

We wish to point out here that if the companion in a HMXB has an initial mass $\geq 30M_{\odot}$ (as is probably the case in 4U 1700-37, Cygnus X-1 and 4U 1223-62) this massive star may never evolve into a red super-giant. Instead, because of the existence of the Humphreys-Davidson limit, it will lose most of its envelope mass as a blue super-giant and then become a WR-star (the LBV scenario for the most massive close binaries, Vanbeveren, 1991). Hence, in this case spiral-in is not required to expell the hydrogen-rich envelope, as the star will do this anyhow on its own accord. In such a situation no complete spiral-in needs to occur and even a close HMXB may still survive as a (very) close binary, as suggested in our 1973 model.

It thus seems quite likely to us that Cyg X-3 has resulted from the evolution of a standard HMXB like 4U 1700-37 (O6f-companion, $P = 3.4$ days). It will be clear that a system like Cyg X-3 is an almost ideal progenitor for close double neutron star systems like the Hulse-Taylor pulsar PSR 1913+16 ($P = 7^h45^m$, $e = 0.615$) and PSR 1534+12, as was pointed out long ago (Flannery and van den Heuvel 1975; De Loore et al. 1975). If the initial system resembles Cygnus X-1, the binary after spiral-in will consist of a helium star and a black hole. Upon exploding, the helium star may leave a neutron star or a black hole. In the first case, an eccentric close binary will result, consisting of a (young) pulsar and a black hole.

Such systems must certainly exist in the Galaxy. We expect them, however, to be difficult to observe as the neutron star is a newborn one, most probably with a strong magnetic field and, therefore, with a short spin-down lifetime (at most a few million years). This is contrary to the PSR 1913+16 and 1534+12 systems where we observe the old recycled neutron star of the two, with a weak magnetic field ($\sim 10^{10}$ G) and, therefore, a long spin-down lifetime of several times 10^8 years. This long lifetime is in fact the reason why we are able to observe such systems, despite their rather low birthrate in the Galaxy which is $< 10^{-5} \text{ yr}^{-1}$ (Phinney 1991; Narayan et al. 1991; van den Heuvel 1992a). The neutron star plus black hole binaries will have an even lower birthrate but are not in this favourable situation of a long lifetime of their pulsars. (The birthrate of systems consisting of a black hole and a recycled neutron star -i.e.: in which the black hole is the second-born compact object in the system- is expected to be extremely low, according to our calculations).

5. Pulsar velocities and their possible origins

5.1. OBSERVED PULSAR VELOCITIES

It is long known that pulsars tend to be runaway objects: this is evidenced by their broad galactic z -distribution (Gunn and Ostriker 1970) and by the measurements of individual proper motions (Lyne et al. 1982). Recently, many new pulsar proper motions were published (Harrison et al. 1993) which brings their number of interferometrically measured proper motions to over 55. Furthermore, several individual young pulsars in SN-remnants were discovered that have excessively large space velocities. The most extreme case is that of PSR 1757-24 in the “Bird-like” SNR G5.4-1.2, which has most likely a transverse velocity of 2300 km/s , and certainly $> 1000 km/s$ (Frail and Kulkarni 1991). Another similar case is that of PSR 2224+65 which has a space velocity $> 800 km/s$, directed along the galactic plane (Cordes et al. 1993).

Correcting for selection effects, the root-mean-square tangential velocity in the sample of Harrison et al. (1993) is 248 km/s , implying a mean excess space velocity (with respect to the local rest frame) of $\sim 300 km/s$, which is of the order of the local escape velocity from the Galaxy. In Harrison et al.’s sample of pulsars, 5 (or: $\sim 10\%$) have tangential velocities ranging from 550 km/s to 2300 km/s .

5.2. POSSIBLE ORIGINS OF PULSAR VELOCITIES

5.2.1. *a binary disruption*

Can these very high velocities have been made by binary disruption (i.e.: without asymmetry-kicks)? The answer is: in theory velocities up to $\sim 1400 km/s$ can be produced by the explosion of massive helium stars ($\sim 10M_{\odot}$) in very close binaries with a neutron star companion (the shortest orbital period around a $10M_{\odot}$ helium star without making this star overflow its Roche lobe is $1 - 2^h$). Although this is a (extreme) possibility for obtaining pulsars with high space velocities, it seems unlikely that as much as 10 percent of all pulsars would result from such systems. This is the more so, since the bulk of the helium star plus neutron star systems will contain helium stars with masses between $\sim 2.5M_{\odot}$ and $4 M_{\odot}$. Such systems will not be disrupted in a symmetric SN-explosion of the helium star. Also, such systems will undergo a second spiral-in, in which their mass is reduced further, before exploding (Phinney 1991; Van den Heuvel 1992a) such that they will finish in very narrow orbits which will never disrupt in a symmetric second supernova explosion either (cf. Van den Heuvel 1992a).

So, these systems might produce binary radio pulsars with extremely short orbital periods, which coalesce by gravitational radiation losses very soon after their formation (van den Heuvel 1992a; Tutukov and Yungelson 1993), which might explain why we have not observed such systems. Or, alternatively, these systems are disrupted in the second supernova explosion, due to an asymmetry-kick that is imparted to the newborn neutron star in the explosion. We will argue,

however, that this is quite unlikely. Dewey and Cordes (1987) have argued that asymmetry-kicks are absolutely required in order to avoid producing too many double neutron star systems like PSR1913+16. However, they did not include the occurrence of the second spiral-in of systems with $M_{He} < 4M_{\odot}$ in their calculation, which will drastically alter their conclusions for the following reasons.

Due to the second spiral-in the orbital velocities of these systems will be $> 500 \text{ km/s}$. So, a randomly directed kick of $\sim 300 \text{ km/s}$ (the average observed in Harrison et al.'s sample) will disrupt less than half these systems, since statistically half of the kicks will be in retrograde directions with respect to the orbital motion. Thus, one still would expect more than half of the systems to remain bound after the second supernova explosion: we thus keep producing large numbers of binary pulsars.

5.2.2. *arguments for kicks intrinsic to the SN-collapse*

These come from three independent sources:

1. Independently of whether or not kicks are required to avoid overproducing double neutron stars, the observed orbital eccentricities of the Be/X-ray binaries (on average: $e \sim 0.5$) are far larger than expected in the case that the helium-star progenitors of their neutron stars had undergone a symmetric supernova explosion (see also figure 2). Average kick velocities of 50-100 km/s (and in some cases $> 250 \text{ km/s}$) are required to explain these orbital eccentricities (Verbunt and van den Heuvel 1994; van den Heuvel 1993).
2. As outlined above, it is highly unlikely that of order ten percent of all pulsars obtained their space velocities $> 550\sqrt{2} \text{ km/s}$ through binary disruption in symmetric SN explosions. The most likely alternative seems therefore to us to be that indeed the large observed space velocities of pulsars are due to "kicks", i.e. due to asymmetries in the mass ejection during the supernova explosion itself.
3. The misalignment of the spinaxis of the binary pulsar PSR1534+12 with the normal to the orbital plane (Wolszczan 1992) is clear evidence for a kick imparted to the last-born neutron star in the system; this is because the observed pulsar is the one which was spun-up by accretion during an X-ray binary phase (cf. Wolszczan 1992), so its spinaxis is expected to be normal to the orbital plane. The misalignment with this normal can only be explained by a kick imparted to this plane in the second supernova.

We thus conclude from the work of Harrison et al. and from the other presented evidence (see in particular also Bailes 1989) that it is most likely that pulsars receive in their supernova explosions asymmetry-kicks that on average are of order 300 km/s , and in 10 percent of the cases are between 550 and 1000 km/s .

5.3. IMPLICATIONS OF KICKS FOR THE FORMATION OF HMXBs, AND THE BINARY ORIGIN OF RUN AWAY OB STARS

An average kick of 300 km/s will, independently of its direction, unbind most high-mass binaries with orbital periods $> 30^d$ during the first supernova explosion; the relative orbital velocity in a system with a total mass of $20 M_\odot$ and $P = 30^d$ is about 180 km/s . So, a random kick of 300 km/s will unbind over $2/3$ of these systems (only kicks with velocity vectors in a rather narrow cone around the direction opposite to the orbital velocity will leave bound systems). Similarly, random kicks of 200 km/s will unbind most systems with orbital periods $> 150 \text{ days}$.

If kicks of this magnitude are included it may well be that more than half of all runaway OB stars are single despite them having originated from supernova explosions in binaries. It will, however, be clear that the highest runaway velocities will come from the closest systems, which are unlikely to be disrupted even by kicks of 300 km/s .

Attempts to calculate the evolution of stellar populations that contain a realistic fraction of binaries produce many helium star plus neutron star systems (of order 10^4 in the Galaxy at any one time, cf. Lipunov 1992, 1993; Tutukov and Yungelson 1993). We see, however, only one Cygnus X-3 system in the Galaxy. Clearly, either the results of the population synthesis models cannot be trusted, or most of the helium star plus neutron star systems do not resemble Cygnus X-3. Indeed, helium stars with $M \lesssim 5 M_\odot$ probably don't have the strong WR-like wind mass loss that the helium stars $> 5 M_\odot$ exhibit. As the bulk of the predicted helium star binaries will have $M_{\text{He}} < 5 M_\odot$, this might be a reason why we don't observe them. An alternative explanation might be that most of the progenitor systems spiral-in completely and produce Thorne-Zytkov objects.

Also, the observed birthrate of double neutron star systems like PSR 1913+16 is much smaller than predicted by the above mentioned population synthesis models. These predict a galactic formation rate of double neutron stars of $\gtrsim 10^{-4} \text{ yr}^{-1}$ (Tutukov and Yungelson 1993). Here the same explanation may apply as for the absence of a large number of helium star plus neutron star systems. Alternatively, if indeed $\sim 10^4$ non-X-ray emitting helium star plus neutron star systems are present in the Galaxy, it may be that most double neutron stars are formed at such short orbital periods (due to the occurrence of the second spiral in phase) that they coalesce quickly (i.e.: within a few million years after they were born), such that they have a very low probability for being observed (Van den Heuvel 1992a; Tutukov and Yungelson 1993).

It will be clear that we will only be able to answer these questions if we have a better understanding of the physics of Common Envelope evolution, a still rather poorly understood process.

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