Astron. Astrophys. 318, 812–818 (1997)

ASTRONOMY
AND
ASTROPHYSICS

The number of O-type runaways, the number of O and Wolf-Rayet stars with a compact companion and the formation rate of double pulsars predicted by massive close binary evolution

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Received 19 March 1996 / Accepted 4 June 1996

Abstract. Using a detailed model of massive close binary evolution and accounting properly for the effects of asymmetric supernova explosions (SN) where we use recent observations of pulsar runaway velocities, we determine the theoretically expected number of post-SN O-type stars with and without a compact companion (CC), the number of O-type runaways, the number of WR+CC systems and the formation rate of binary pulsars in our Galaxy. We conclude that

- at least 50% of the O-type runaways are formed through the binary scenario,
- less than 3% of all WR stars may hide a CC,
- the formation rate of binary pulsars in our Galaxy ≈ 0.003-0.01 times the formation rate of massive stars; this corresponds roughly to a binary pulsar formation rate of the order of 10^{-5}/year in agreement with the observations.

Our results reveal a significant fraction of single WR stars but with a binary history. We also predict the existence of 'weird' WR stars, i.e a WR star with a CC in its centre (descendants of Thorne-Żytkow objects).

Key words: stars: evolution; early-type; kinematics – binaries: close: Wolf-Rayet – pulsars

1. Introduction

A star is classified as a runaway star when its peculiar velocity v_{pec} is larger than 30 km/s. With this definition the observations reveal that $\sim$ 10% of all O-type stars are runaways (Gies and Bolton, 1986; Gies, 1987).

We know of two processes able to produce runaway stars: close encounters in dense clusters (Poveda et al., 1967; van Albada, 1968; Aarseth and Lecar, 1975; Lada et al., 1984) and the supernova (SN) explosion in massive close binaries (MCBs) (Blaauw, 1961). Gies and Bolton favored the cluster ejection process, based on the fact that a number of O-type runaways are normal non-evolved close binaries. Furthermore in the '80s it was accepted that the SN ejecta did not deviate much from spherical symmetry, and thus most of the runaways produced by the binary scenario were supposed to have a compact companion. The detailed study of Gies and Bolton did not show any signature of the presence of a compact companion in their remaining set of single line O-type runaways.

Following the qualitative scenario for MCB evolution of van den Heuvel and Heise (1972) and the early ideas on the physics of the SN explosion in MCBs, it was expected that a significant number of WR stars hide a compact companion. However Uhuru did not detect any WR hard-X-ray sources and this was a problem for the evolutionary scenario of MCBs (Vanbeveren et al., 1982).

There are 3 (4) binary pulsars known in the Galaxy where both components are neutron stars or black holes. Accounting for the expected lifetime of such binary pulsars, van den Heuvel (1992) estimated a galactic formation rate for these systems of ≈ 2.4 10^{-5} /year. This value may still be a factor 2 lower (van den Heuvel, 1996, private communication). Again with the early ideas on the SN explosion and its effect on binary parameters, this value was at least a factor 30 smaller than theoretically expected from binary evolution.

Using recent measurements of pulsar proper motions (Harrison et al., 1993) and a new pulsar distance scale (Taylor and Cordes, 1993), Lyne and Lorimer (1994) obtained a 3-D pulsar velocity distribution f(v_p), which can be very well described by the following relation:

$$f(v_p) = 1.96 \cdot 10^{-6} v_p^{3/2} e^{-3v_p/514}\,, \qquad (1)$$

If these velocities reflect the kick velocity a compact star may get as a consequence of an asymmetric SN explosion (notice that this distribution implies an average kick velocity of 450 km/s which is substantially larger than any previous estimate), one might expect that a large number of binaries will become unbound during the SN explosion, contrary to earlier ideas.

In Vanbeveren et al. (1996) (Paper I) we discussed in detail the evolutionary model for MCBs and how to use it in population synthesis. A summary is given in section 2. We will use this model in order to study the effect of the SN explosion, accounting for the distribution of kick velocities given above, on the following questions:

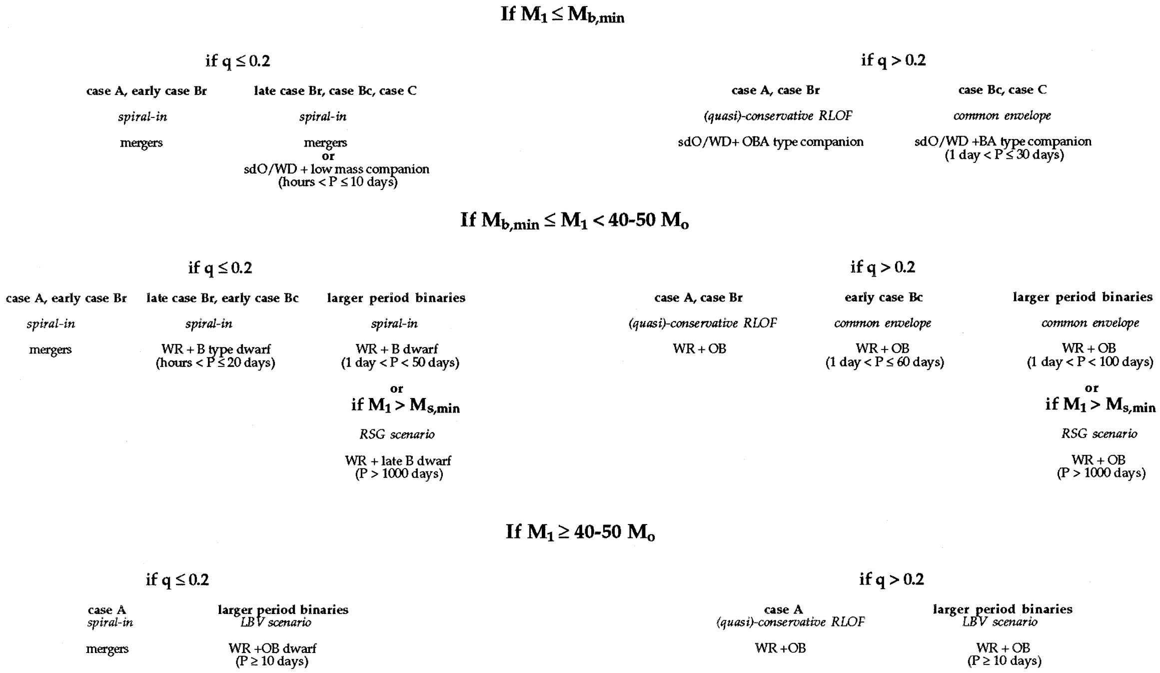

Fig. 1a. The intermediate mass or massive close binary evolutionary model up to the end of core helium burning of the original primary. We consider three mass intervals; M_1 is the initial mass of the primary, $M_{b,min}$ is the minimum initial mass a primary of a close binary must have in order to evolve into a WR star after Roche lobe overflow (RLOF); $M_{s,min}$ is the minimum initial mass of a star above which stellar wind mass loss during the RSG phase is sufficient in order to remove most of the hydrogen rich layers, i.e. for a star to evolve into a WR star without the explicit help of the RLOF process (from Vanbeveren et al., 1996).

How many O-type stars are runaways as a consequence of a previous binary SN explosion and how many of them have a CC?

How many WR stars are expected to have a CC?

What is the expected formation rate of double pulsars in our Galaxy?

2. The population synthesis model

We start with a population consisting of a single star population and a binary population. In order to estimate the number of stars in different evolutionary phases, we need

a. an MCB evolutionary model.
b. a single star evolutionary model.
c. the lifetimes of the different evolutionary phases.
d. star and binary parameter distributions.

We use the MCB evolutionary model which is discussed in detail in Paper I and summarized in figure 1.

The model accounts for the following processes:

- The LBV scenario for binaries with primary masses larger than 40-50 $M_\odot$.

- The RSG scenario for case Bc/case C binaries with $M_{s,min} \le M_1 \le 40\text{-}50\ M_\odot$ (M_1 = primary mass). The value of $M_{s,min}$ ranges between 20 $M_\odot$ and 30 $M_\odot$ and depends on the adopted evolutionary scenario for single stars. For the evolution of massive single stars we use the 'standard single star scenario' and the 'alternative single star scenario' discussed in Paper I.

- MCBs with an initial mass ratio $q < 0.2\text{-}0.3$ do not perform Roche lobe overflow (RLOF) but the low mass secondary is dragged into the envelope of the primary and spirals-in. As was outlined in Paper I, most of them merge. Their further evolution is uncertain. One possibility is that the evolution of the merger resembles the evolution of a star who has accreted an amount of mass (= mass of the low mass component). This model is used here although the final numbers do only marginally depend on this class of MCBs.

- Case Bc and case C binaries evolve through a common envelope phase for which we use the spiral-in prescription of Webbinck (1984). It is characterized by a parameter α_{CE} describing the efficiency by which orbital energy is converted by friction into potential energy of the mass that needs to be removed from the system.

- By far the most important class of MCBs for population synthesis is the case Br class (and to a lesser extend the case A class). When the mass ratio of the binary is larger than some value q_{min}, their evolution is quasi-conservative and we use the parameter prescription of Vanbeveren et al. (1979) characterized by the parameters β (= the fraction of mass lost by the primary due to RLOF which is accreted by the secondary), and the parameter α (= the specific angular momentum removed from the orbit by the mass leaving the binary). If during the RLOF phase significant mass loss from the system occurs on

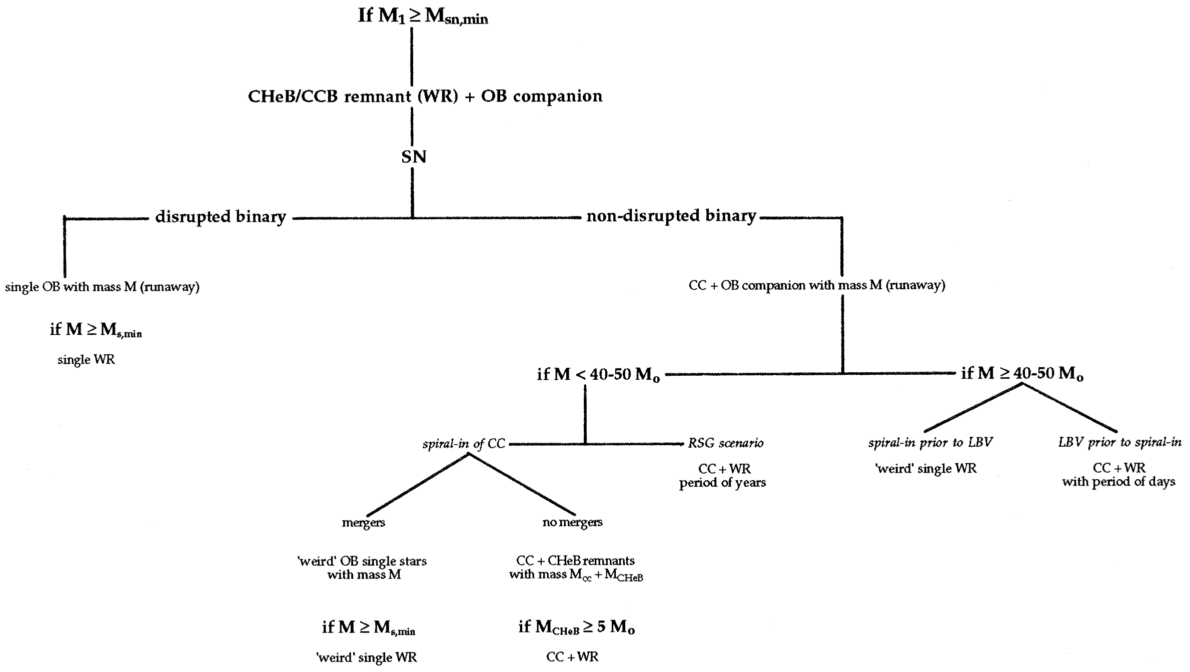

Fig. 1b. The evolutionary model of a massive close binary after the supernova explosion of the original primary; $M_{sn,min}$ is the minimum mass a primary must have in order for a supernova to occur; $M_{s,min}$ has the same meaning as in figure 1a but applied to the rejuvenated mass gainer of the binary; M_{CHeB} is the mass of the hydrogen deficient core helium burning star after the spiral–in phase (from Vanbeveren et al., 1996).

the Kelvin-Helmholtz timescale (= the RLOF timescale), this can to our knowledge only happen if matter leaves the binary through the second Lagrangian point L_2 forming a ring around the binary or if material lost by the primary gains sufficient energy from the orbit by dynamical friction in order to be pushed out of the binary. Both processes imply very large α values, i.e. $\alpha \geq 3 - 6$(Paper I).

• The post-RLOF evolution during core helium burning (CHeB) is determined by WR like stellar wind mass loss rates.

• The evolution of an MCB through the first SN explosion is followed using the presciption of asymmetric SN explosions of Sutantyo (1978). The distribution of kick velocities has been studied by Lyne and Lorimer (1994) and can be very well described by Eq. 1.

• When after the SN explosion the binary was disrupted, the further evolution of the OB single star is followed by using the appropriate single star scenario. When the binary was not disrupted, as the OB star evolves and expands, the CC spirals in possibly removing the outer layers of the OB star. If the CC does not merge, a WR+CC binary can be formed. If the OB+CC system merges, its further evolution is followed using two limiting models (see also Paper I):

a. during the merging process the OB star has lost most of its hydrogen rich layers and thus a WR star is formed with a CC in its centre: we call this a 'weird' WR star. In order to compute their number we adopt the same WR timescales as for ordinary WR stars in close binaries.

b. if the OB+CC binary merges, the evolution of the OB-type star is that of a normal single star which possibly evolves into a WR star after mass loss by an efficient stellar wind during the red supergiant phase. Also in this case the WR star is a 'weird' WR star.

• The evolution of a CHeB star + CC binary is then followed through the second SN explosion, similarly as through the first one, using the distribution of kick velocities given by Eq. 1.

• The runaway velocity of the OB+CC binary (if the SN did not disrupt the binary) or of the OB single star (if the SN did disrupt the binary) after SN, is computed as explained in Paper I.

A population synthesis model contains the following parameters:

• IMF $\propto M^{-\gamma}$ with $\gamma = 2.7$ and $\gamma = 2$,

• The mass ratio distribution of MCBs: we use $\Phi_1(q)$ = flat distribution, $\Phi_2(q)$ = the mass ratio distribution of Hogeveen (1991) or $\Phi_3(q) \propto q^{0.5}$ which peaks moderately towards q = 1.

• The period distribution of MCBs: $\Pi(P) \propto 1/P$.

• The efficiency factor during the different spiral-in phases in MCBs, i.e. α_{CE1} for non-evolved binaries with an initial mass ratio $q \leq 0.2$, α_{CE2} for case Bc and case C binaries and α_{CE3} for OB + CC binaries.

• The value of q_{min} for case A/case Br binaries above which β is assumed to be constant (=β_{max}). To start with, we compute the results with $\beta_{max} = 1$ and $\beta_{max} = 0.5$ independent from the period of the case Br binary. This period independency is probably not very realistic. Once the period of the binary is large enough (P>1000 days) for a system to evolve as a case Bc, $\beta_{max} = 0$. For periods small enough, the gasstream from the first Lagrangian point hits the companion directly. It may therefore be tempting to

Table 1. The fraction, relative to all O-type stars, of O+CC binaries, O+CC runaways, O-type stars resulting from binary evolution which are single because the binary was disrupted during the previous SN explosion (Osb) and Osb runaways. Different values are considered for the parameters entering the population model (see text).

f	q_{min}	β_{max}	α	α_{CE}	γ	$\Phi(q)$	M_{CC}	(O+CC)/O	$(O+CC)_{rw}/O$	O_{sb}/O	$O_{sb,rw}/O$
0.8	0.4	1	3	1	2.7	flat	1.4	0.035	0.018	0.244	0.042
0.8	0.4	0.5	3	1	2.7	flat	1.4	0.028	0.017	0.147	0.040
0.8	0.4	0.5	6	1	2.7	flat	1.4	0.036	0.024	0.122	0.062
0.8	0.4	1	3	1	2.7	Hogeveen	1.4	0.028	0.016	0.154	0.038
0.8	0.4	0.5	3	1	2.7	Hogeveen	1.4	0.018	0.012	0.074	0.026
0.8	0.4	0.5	6	1	2.7	Hogeveen	1.4	0.019	0.014	0.059	0.034
0.8	0.4	1	3	1	2.7	Garmany	1.4	0.037	0.018	0.270	0.041
0.8	0.4	0.5	3	1	2.7	Garmany	1.4	0.032	0.019	0.172	0.043
0.8	0.4	0.5	6	1	2.7	Garmany	1.4	0.041	0.027	0.144	0.071
0.8	0.6	0.5	6	1	2.7	flat	1.4	0.033	0.022	0.114	0.056
1	0.4	0.5	6	1	2.7	flat	1.4	0.042	0.028	0.142	0.072
0.5	0.4	0.5	6	1	2.7	flat	1.4	0.025	0.017	0.085	0.043
0.8	0.4	0.5	6	1	2	flat	1.4	0.032	0.022	0.107	0.054
0.8	0.4	0.5	6	1	2	Hogeveen	1.4	0.019	0.014	0.059	0.032
0.8	0.4	0.5	6	1	2	Garmany	1.4	0.037	0.024	0.125	0.061
0.8	0.4	0.5	6	0.5	2.7	flat	1.4	0.036	0.024	0.122	0.062
0.8	0.4	0.5	6	1	2.7	flat	3	0.036	0.018	0.117	0.058

propose a relation where β_{max} decreases with increasing period, i.e. $\beta_{max} = 1 - 10^{-3}P$ (P in days).

- The angular momentum loss during the non-conservative RLOF of case A and case Br binaries; we use $\alpha = 3$ and $\alpha = 6$.
- The minimum initial mass $M_{s,min}$ for a single star to become a WR star and the corresponding single star evolutionary model.
- The final fate of OB+CC binaries who merge during their ensuing spiral-in phase.
- The fraction f of MCBs with periods up to 10 years in the population. Remember that the period of interacting massive binaries ranges between 1000 and 2000 days so that the fraction of interacting binaries is smaller than f.

3. Results and conclusions

We first recall that a detailed comparison of the O-type and WR sample within 3 kpc from the sun reveals a most probable population model (Paper I). This model assumes an overall MCB fraction (binaries with periods up to 10 years) ≈ 0.8, a non-conservative case Br evolution where on the average 50% of the mass lost by a primary should leave the binary, taking with it a significant fraction of the angular momentum of the system ($\alpha \geq 3-6$) and a flat Φ(q) or a Φ(q) which peaks moderately towards 1. For single stars, the alternative evolutionary scenario of Vanbeveren (1991, 1995, 1996) gives the best correspondence with observations.

3.1. The number of O-type runaways formed through binary evolution

MCBs are a fact, SN explosions in MCBs are a fact and thus runaways formed through the binary scenario are a fact. Table 1 gives the theoretically expected number of post-SN O-type stars for different values of the parameters in our population synthesis model as well as the expected number of O-type runaways (runaway velocity $\geq 30\ km/sec$). We always give the numbers relative to the total number of O-type stars (= the number of single O-type stars + the number of unevolved pre-RLOF O-type primaries of MCBs + the number of O type stars with a post-RLOF CHeB companion + the number of post-SN O-type stars, singles and with a CC).

We conclude:

- Only 16-23% of the MCBs remain bound after the SN explosion of the primary.
- Between 5% and 25% of the O-type stars are post-SN binary components. The majority is single, however remember that they have had a binary history.
- Only 3% (and even less) of all O-type stars are expected to have a CC.
- About 5-8% of the O-type stars are runaways with a runaway velocity $\geq 30\ km/s$. Less than 1/3 of them have a CC.
- Accounting for the observed number of O-type runaways and their observed binary frequency, we conclude that the SN explosion in MCBs is responsible for at least 50% of the observed fraction of O-type runaways.

3.2. The number of WR stars with a compact companion

In order to have an idea of the morphology of post-SN WR stars (i.e. WR + CC binaries or 'weird' WR single stars), we start from the observed WR + OB binaries, listed by Smith and Maeder (1989), and continue their evolution with the MCB model discussed in section 2. We first assume that the WR star is at the beginning of its WR phase (i.e. at the beginning of the WNL phase, resp. the WNE phase, resp. the WC phase, when the WR

Table 2. The further evolution of observed WR+OB binaries for an efficiency factor $\alpha_{CE} = 1/\alpha_{CE} = 0.5$ during spiral-in.

HD /Name	SpT	M_{WR}+M_{OB}	Period days	Prob. survival	Prob. WR+CC	$P_{f,min}$ days	$P_{f,max}$ days	Prob. Weird WR	$V_{rw,min}$ km/s	$V_{rw,max}$ km/s
E320102	WN7+O5/7	11+35	8.83	0.38	0.05/0.02	0.08	0.61/0.22	0.33/0.36	25.29	58.12
				0.40	0.05/0.02	0.08	0.65/0.23	0.34/0.38	26.30	59.12
90657	WN4+O4/6	12+24	8.255	0.31	0.04/0.01	0.07	3.59/1.30	0.26/0.29	30.99	71.34
				0.30	0.03/0.01	0.07	3.56/1.29	0.26/0.29	33.01	73.04
94546	WN4+O8V	7+17	4.831	0.36	0/0	0.05	3.24/1.18	0/0	41.64	105.9
				0.39	0/0	0.05	3.17/1.15	0/0	42.99	107.2
186943	WN4+O9	16+35	9.555	0.36	0.05/0.02	0.08	0.62/0.22	0.30/0.34	30.46	60.84
				0.37	0.06/0.02	0.08	0.55/0.20	0.31/0.35	32.91	63.64
190918	WN4+O9Ib	15+35	112.8	0.10	0.09/0.04	0.09	0.60/0.22	0.02/0.06	13.39	25.98
				0.12	0.11/0.06	0.08	0.67/0.24	0.02/0.07	13.90	27.09
CX Cep	WN5+O8	5+12	2.127	0.40	0/0	0.03	1.80/0.66	0/0	60.02	167.3
				0.46	0/0	0.04	1.94/0.71	0/0	66.92	177
V444 Cyg	WN5+O6	10+26	4.212	0.45	0.02/0.02	0.07	3.07/1.11	0.43/0.43	36.21	85.88
				0.42	0.02/0.02	0.07	3.01/1.09	0.40/0.40	38.15	88.88
197406	WN7+?	60+12.4	4.317	0.09	0/0	0.04	1.84/0.67	0/0	69.88	105.8
				0.11	0/0	0.04	2.08/0.76	0/0	121.5	165.2
CQ Cep	WN7+O	31+26	1.641	0.43	0.02/0.02	0.07	3.14/1.14	0.41/0.41	65.53	118
				0.44	0.02/0.02	0.07	3.02/1.09	0.42/0.42	104.6	160.2
63099	WC5+O7	10+35	14.7	0.30	0.04/0.02	0.08	0.55/0.20	0.26/0.29	21.74	49.32
				0.36	0.06/0.02	0.09	0.62/0.22	0.30/0.34	53.90	83.57
94305	WC6+O6/8	16+35	18.82	0.28	0.07/0.04	0.08	0.61/0.22	0.21/0.24	26.22	50.30
				0.24	0.04/0.02	0.08	0.57/0.20	0.21/0.23	79.84	106.7
97152	WC7+O7V	11+18	7.886	0.30	0.04/0.01	0.05	3.46/1.26	0.25/0.28	36.79	84.93
				0.28	0.04/0.01	0.05	3.49/1.27	0.23/0.26	97.40	151.8
152270	WC7+O5/8	7+18	8.893	0.29	0.04/0.01	0.05	3.29/1.19	0.25/0.27	34.51	84.99
				0.31	0.05/0.02	0.05	3.46/1.26	0.26/0.29	57.50	109.4
68273	WC8+O9I	19+35	78.5	0.143	0.11/0.06	0.08	0.68/0.24	0.03/0.09	18.68	32.69
				0.14	0.08/0.04	0.08	0.67/0.24	0.06/0.10	58.02	74.49
CV Ser	WC8+O8	12+24	29.71	0.17	0.05/0.02	0.07	3.39/1.23	0.12/0.14	21.55	47.60
				0.20	0.06/0.03	0.06	0.79/0.28	0.14/0.17	61.05	90.48

component is a WNL, resp. WNE, resp. WC). Then we assume that the WR star is at the end of its corresponding phase. For each binary we compute the SN survival probability, accounting for the kick velocity distribution discussed earlier. When an OB+CC binary is formed, its further evolution is continued through the spiral-in phase for two values of the efficiency parameter α_{CE} (i.e. $\alpha_{CE} = 1$ and $\alpha_{CE} = 0.5$). When the binary does not merge due to spiral-in, a CHeB+CC binary is formed. When the mass of the CHeB component is larger than 5 $M_\odot$, the star is considered as a WR star and thus a WR+CC binary is formed. The results are given in table 2. For each system we give the survival probability after the SN explosion of the WR star, the probability that a WR+CC binary is formed and the probability that a 'weird' WR star is formed. For each WR+OB system the minimum and maximum period, $P_{f,min}$ and $P_{f,max}$, of the possible CHeB+CC binary after spiral-in and the minimum and maximum runaway velocity, $V_{rw,min}$ and $V_{rw,max}$, of the post-SN system are given. The latter values always correspond to values holding for the bound case. A disrupted OB-type star (thus a disrupted CHeB star) has a runaway velocity in between the minimum and maximum values given in the table.

We conclude:

- The majority ($\sim$ 75 %) of the observed WR + OB binaries will be disrupted as a consequence of the SN explosion of the WR star. The majority of the OB stars of these disrupted binaries will evolve into WR stars, i.e. single WR stars but with a binary history where accretion could have played a major role.

- Less than 2% ($\alpha_{CE} = 0.5$) and 5% ($\alpha_{CE} = 1$) of the observed WR+OB systems will form WR+CC binaries. The periods of these WR+CC binaries range between 0.05-1.3 days ($\alpha_{CE} = 0.5$) and 0.05-3.6 days ($\alpha_{CE} = 1$).

- About 20-30% of the observed WR+OB binaries will produce 'weird' WR stars.

We now start from a sample of unevolved MCBs and single stars satisfying the distributions discussed in section 2. Table 3 gives the number population synthesis results for the WR stars for various values of the parameters in our population model. The following conclusions are based on the numerical results holding for a non-conservative case Br evolutionary model, as suggested at the beginning of this section.

- The expected frequency (relative to all WR stars) of WR+CC binaries is $\leq 2.5\%$ ($\alpha_{CE} = 1$) and $\leq 1\%$ ($\alpha_{CE} = 0.5$), with most of them having periods of the order of hours.

Table 3. Similar as table 1 but for WR stars. We assume that OB+CC mergers loose all their hydrogen rich layers during the merging process and thus a WR star is formed immediately after merging. For a few cases we also made computations with the alternative model i.e the mergers further evolve as single stars.

f	q_{min}	β_{max}	α	α_{CE}	γ	$\Phi(q)$	M_{CC}	(WR+CC)/WR	Weird WR/WR	WR_{sb}/WR
0.8	0.4	1	3	1	2.7	flat	1.4	0.036/0.037	0.075/0.041	0.258/0.268
0.8	0.4	1	3	0.5	2.7	flat	1.4	0.023	0.090	0.260
0.8	0.4	0.5	3	1	2.7	flat	1.4	0.022/0.023	0.079/0.040	0.159/0.166
0.8	0.4	0.5	3	0.5	2.7	flat	1.4	0.013	0.089	0.161
0.8	0.4	0.5	6	1	2.7	flat	1.4	0.019/0.021	0.138/0.070	0.128/0.138
0.8	0.4	0.5	6	0.5	2.7	flat	1.4	0.011	0.148	0.129
0.8	0.4	1	3	1	2.7	Hogeveen	1.4	0.022/0.023	0.057/0.029	0.154/0.159
0.8	0.4	1	3	0.5	2.7	Hogeveen	1.4	0.014	0.068	0.158
0.8	0.4	0.5	3	1	2.7	Hogeveen	1.4	0.012/0.013	0.048/0.023	0.086/0.089
0.8	0.4	0.5	3	0.5	2.7	Hogeveen	1.4	0.007	0.055	0.089
0.8	0.4	0.5	6	1	2.7	Hogeveen	1.4	0.010/0.011	0.082/0.039	0.071/0.074
0.8	0.4	0.5	6	0.5	2.7	Hogeveen	1.4	0.006	0.089	0.072
0.8	0.4	1	3	1	2.7	Garmany	1.4	0.040/0.041	0.080/0.044	0.287/0.298
0.8	0.4	1	3	0.5	2.7	Garmany	1.4	0.025	0.095	0.288
0.8	0.4	0.5	3	1	2.7	Garmany	1.4	0.025/0.027	0.087/0.044	0.181/0.189
0.8	0.4	0.5	3	0.5	2.7	Garmany	1.4	0.015	0.098	0.181
0.8	0.4	0.5	6	1	2.7	Garmany	1.4	0.022/0.024	0.153/0.078	0.145/0.157
0.8	0.4	0.5	6	0.5	2.7	Garmany	1.4	0.012	0.163	0.145
0.8	0.6	0.5	6	1	2.7	flat	1.4	0.018/0.020	0.131/0.066	0.124/0.134
0.8	0.6	0.5	6	0.5	2.7	flat	1.4	0.010	0.141	0.126
1	0.4	0.5	6	1	2.7	flat	1.4	0.021/0.023	0.152/0.077	0.141/0.153
1	0.4	0.5	6	0.5	2.7	flat	1.4	0.012	0.163	0.142
0.5	0.4	0.5	6	1	2.7	flat	1.4	0.015/0.016	0.108/0.053	0.100/0.106
0.5	0.4	0.5	6	0.5	2.7	flat	1.4	0.012	0.163	0.142
0.8	0.4	0.5	6	1	2	flat	1.4	0.019/0.021	0.127/0.067	0.142/0.152
0.8	0.4	0.5	6	0.5	2	flat	1.4	0.012	0.136	0.144
0.8	0.4	0.5	6	1	2	Hogeveen	1.4	0.011/0.012	0.081/0.040	0.087/0.091
0.8	0.4	0.5	6	0.5	2	Hogeveen	1.4	0.007	0.088	0.089
0.8	0.4	0.5	6	1	2	Garmany	1.4	0.022/0.023	0.139/0.075	0.159/0.171
0.8	0.4	0.5	6	0.5	2	Garmany	1.4	0.013	0.148	0.159
0.8	0.4	0.5	6	0.5	2.7	flat	1.4	0.011/0.011	0.148/0.075	0.129/0.140
0.8	0.4	0.5	6	1	2.7	flat	3	0.033/0.035	0.131/0.066	0.124/0.133
0.8	0.4	0.5	6	0.5	2.7	flat	3	0.020	0.146	0.125

- About 10%-18% of all WR stars could be 'weird' WR stars, descendants from Thorne-Żytkow objects.

- About 10-15% of all WR stars are single but with a binary history.

Within 3 kpc from the sun there are ~ 100 WR stars. Accounting for the foregoing conclusions, we predict more than 10 'weird' WR stars, 10-15 single WR stars but with a binary history. We also expect at most 1-3 WR stars with a compact companion orbiting with a period of a few hours.

3.3. The formation of binary pulsars

Similarly as in the previous section we start with a population model and we determine all CHeB+CC binaries. When the mass of the CHeB component is large enough, a second SN explosion occurs. The effect on the binary parameters is again studied using the kick velocity distribution given by Eq. 1. In table 4 we give the formation rate of binary pulsars (neutron star/black hole + neutron star/black hole) for different values of the population model. We conclude (again we only consider the non-conservative case Br models):

- The formation rate of binary pulsars is about 0.003-0.01 times the formation rate of massive stars.

There are about 5000 massive stars within 3 kpc from the Sun (Humphreys and McElroy, 1984). If we assume that this number is representative for our whole galactic disk and that the galactic disk radius is approximately 13 kpc, we expect about 100000 massive stars in the Galaxy. The average lifetime of a massive star is ≈ 24 million years and this gives us a galactic massive star formation rate of ≈ $4.2\ 10^{-3}$ /year. We thus obtain a galactic binary pulsar formation rate ranging from $1.3\ 10^{-5}$ to $4.2\ 10^{-5}$ /year. Accounting for the crudeness of this estimate we consider this as a very good agreement with the value which is of the order of $\sim 10^{-5}$ /year (see section 1) and which is derived from the observed number of binary pulsars in the Galaxy and their expected lifetime.

Table 4. The number of binary pulsars formed per year assuming a massive star formation rate of 1/year. Different values are considered for the parameters entering the population model.

f	β_{max}	α	α_{CE}	γ	$\Phi(q)$	$M_{sn,min}$	M_{CC}	Binary pulsars/yr
0.8	0.5	3	1	2.7	flat	8	1.4	0.0089
0.8	0.5	3	1	2.7	Hogeveen	8	1.4	0.0047
0.8	0.5	3	1	2.7	Garmany	8	1.4	0.0108
0.8	0.5	6	1	2.7	flat	8	1.4	0.0076
0.8	0.5	6	1	2.7	Hogeveen	8	1.4	0.0034
0.8	0.5	6	1	2.7	Garmany	8	1.4	0.0094
0.8	0.5	3	0.5	2.7	flat	8	1.4	0.0049
0.8	0.5	3	0.5	2.7	Hogeveen	8	1.4	0.0025
0.8	0.5	3	0.5	2.7	Garmany	8	1.4	0.0059
0.8	1	3	0.5	2.7	flat	8	1.4	0.0043
0.8	1	3	0.5	2.7	Hogeveen	8	1.4	0.0031
0.8	1	3	0.5	2.7	Garmany	8	1.4	0.0049
0.8	0.5	3	1	2	flat	8	1.4	0.0080
0.8	0.5	3	1	2.7	flat	8	1.4	0.0059
0.8	0.5	3	1	2.7	flat	8	3	0.0254
0.8	0.5	3	1	2.7	flat	10	3	0.0184
0.8	0.5	6	0.5	2	flat	8	1.4	0.0030
0.8	0.5	6	0.5	2.7	flat	10	1.4	0.0024
0.8	0.5	6	0.5	2.7	flat	8	3	0.0133
0.8	0.5	6	0.5	2.7	flat	10	3	0.0101
1	0.5	3	1	2.7	flat	8	1.4	0.0111
0.5	0.5	3	1	2.7	flat	8	1.4	0.0056

4. Conclusions

A detailed population synthesis model including the evolutionary effects of massive close binaries with periods ranging from 1 day to 10 years and the effect of an asymmetric SN explosion of the primary and of the secondary, reveals the following general conclusions:

- At least 50% of the observed O-type runaways are formed through the binary scenario and only 12-17% of the O-type runaways have a compact companion.
- Only 1% - 3% of all WR stars may hide a compact companion.
- We expect a binary pulsar formation rate of the order of 10^{-5} /year, corresponding to the formation rate which is based on the observed number of binary pulsars and their expected lifetime.

Acknowledgements. The authors thank the referee Ralph Wijers for his valuable remarks in the paper. Part of this research was carried out in the framework of the project Service Centres and Research Network initiated and financed by the Belgian Federal Scientific Services (DWTC/SSTC)

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