The characteristics of high velocity O and B stars which are ejected from supernovae in binary systems

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ABSTRACT

We perform binary population synthesis calculations to study the origin and the characteristics of runaway O and B stars which are ejected by the supernova explosion of the companion star in a binary system. The number of OB runaways can be explained from supernova ejections only if: high mass stars are preferentially formed in binaries, the initial mass ratio distribution is strongly peaked to unity and stars are rejuvenated to zero age upon accretion of mass from a companion star. Taking these requirements into consideration we conclude that at most 30% of the runaway O stars but possibly all runaway B stars obtain high velocities due to supernovae in evolving binaries. Stars which obtain high velocities via supernova ejections have the following characteristics: 1) at least 10% of the high velocity B stars and half the O stars have a mass greater than the turn off mass of the cluster in which they are born and would be observed as blue stragglers in the parent cluster, 2) their equatorial rotational velocities are proportional to their space velocity and 3) between 20% and 40% of the runaways have neutron star companions but less than 1% are visible as radio pulsars in part of the orbit.

Subject headings: binaries: close stars: blue stragglers stars: evolution stars: kinematics stars: early-type supernovae: general

1. Introduction

OB runaways are among the most massive stars with high velocities (\(\gtrsim 25\,\text{km s}^{-1}\)) or are located far (\(\gtrsim 100\,\text{pc}\)) from their estimated birth place compared to other O and B

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stars in the galactic disc (Gies & Bolton 1986; Gies 1987). (The terms OB runaway and runaway O and B stars will be used interchangeably.)

The first discovered OB runaways, the B0V star $\mu$ Col and the O9.5V star AE Au (Blaauw & Morgan 1954) started a half century debate about their characteristics and the origin of the, sometimes inferred, high velocities.

The definition of a runaway varies between researchers. Blaauw (1961) argues that only stars with a velocity in excess of $40 \text{ km s}^{-1}$ should be called runaways, Stone (1991) on the other hand, defines a runaway as a star which belongs to a separate group of stars which follows a Maxwellian velocity distribution with a higher mean. Although Stones’ (1991) definition is theoretically most distinctive, the definition of a velocity cut-off is the most practical. We define a runaway as a star with velocity $v > 25 \text{ km s}^{-1}$, and the specific frequency of runaways $f_{\text{run}}$ as the number of runaways with mass $M$ as fraction of all stars with the same mass.

The specific frequency of runaways among O and B stars decreases steeply from $f_{\text{run}} \approx 20\%$ among the earliest O stars to about 2.5% among early B stars and even smaller frequencies among later B1 to B5 stars (Blaauw 1961). Stetson (1981) found that $>30\%$ of A stars and almost all F stars have high velocities. These velocities may be the result of the heating of the Galactic disc by molecular clouds and Stone (1991) concludes that the fraction of true runaways among A stars is $0.3\%$ (less than 1%).

Many runaways are characterized by high rotational velocities (Conti & Ebbets 1977). Some runaways can be traced back to the association in which they were born. The runaway stars $\zeta$ Oph, AE Aur, $\mu$ Col and 53 Ari were blue stragglers if placed back in the association from which they are ejected (Blaauw 1993; Hoogerwerf et al. 2000). Accurate distances and proper motions of most of the runaway O and B stars may have to wait until the FAME (Full Sky Astrometric Mapping Explorer) mission. This satellite will measure accurate positions and velocities of O and B star to a distance of several kiloparsec.

The observed frequency of single line spectroscopic binaries among OB runaways $\lesssim 19\%$ (Gies 1987) where among other O stars this is between 40% (Garmany & Conti 1980) and 60% (Conti et al. 1977). Sayer et al. (1996, see also Philp et al. 1996) conclude that between 20% and 40% of the OB runaways may have a pulsar companion but most are unobservable.

A number of scenarios have been proposed to explain the origin of OB runaway stars. The following two ejection mechanisms are most promising:

- A star is ejected from a close binary at the moment its companion explodes in a
supernova (Blaauw 1961).

- A star is ejected in a dynamical 3- or 4-body encounter (Poveda et al. 1967).

In this paper we study the first mechanism using binary population synthesis. Previous population synthesis studies claim that all OB runaways are readily explained by the supernova ejection mechanism. Stone (1982, see also Leonard & Dewey 1993; De Donder et al. 1997) conclude that about half the O stars have a high space velocity and that 20% to 40% of these may have a compact binary companion in an eccentric orbit. High rotational velocities and high Helium abundances are generally explained by assuming that the pre-supernova binary has experienced a phase of mass transfer. The star may be rejuvenated during such a phase which may explain why some observed runaways are blue stragglers (Blaauw 1993). The observation of bow shocks around about a dozen Wolf-Rayet stars suggests that their velocities are also high. The recently observed bow shocks around the X-ray binary Vela X-1 (Kaper et al. 1997) and EZ Cma (van Buren et al. 1995) indicates that these binaries have high space motions, which may be obtained in the supernova in which the compact object formed (van Rensbergen et al. 1996).

Opposing these are the claims that OB runaways can be readily explained by dynamical ejection from young and dense star clusters (Aarseth 1974; Gies & Bolton 1986; Leonard and Duncan 1988). The high velocities of some observed runaways can be explained in this process (Conlon et al. 1990; Leonard 1991). And high Helium abundances, rotational velocities and the fact that some are blue stragglers could be explained from star which are ejected in a binary-binary encounter in which the ejected star first merges with one of the other stars (Leonard 1995). The runaway pair $\mu$ Col and AE Aur is most easily explained in this way as $\sim 2.7$ Myaer ago both stars may have been ejected in opposite direction from the association Ori OB1 (Blaauw & Morgan 1954; Hoogerwerf et al. 2000), indicating a dynamical origin rather than a supernova ejection. Other evidence for dynamical ejection is provided by the existence of two double-lined spectroscopic binaries among the sample of known runaways (Gies & Bolton 1986).

Supporters of either mechanism claim to be able to explain the observable characteristics of O and B runaways and their specific frequencies. In this papers I discuss the characteristics of massive stars which obtained a high velocity from a supernova in a close binary system. This paper is organized as follows. Section 2 describes the binary evolution program used for the calculations, the results of the calculations are described in section 3 and we discuss these in section 4. Section 5 sums up.
2. Methods

We use the binary population synthesis code SeBa\(^2\) (Portegies Zwart & Verbunt 1996) with adjustments as in model B from Portegies Zwart & Yungelson (1998).

The binaries are initialized as follows: The mass of the most massive star (primary) is selected from the initial mass function for the Solar neighborhood as described by Scalo (1986; 1998). The masses of the companions are randomly selected between 0.1 M\(_\odot\) and the primary mass. Then the other binary parameters are determined. Binary eccentricities are selected from the thermal distribution between 0 and 1. Orbital separations \(a\) are selected with equal probability in \(\log a\) between 1 R\(_\odot\) (or Roche-lobe contact whichever is larger) and an upper limit of 10\(^6\) R\(_\odot\) (about 0.02 pc). Table\(\[\]\) gives an overview of the various distribution functions from which stars and binaries are initialized. In sect.\(\[\]\) we study the effect of changing these assumptions.

We will only mention some of the model features of SeBa (for details see Portegies Zwart & Verbunt 1996). Single stars between \(\sim 9\) and 25 M\(_\odot\) explode in a supernova to form a neutron star. Less massive and more massive stars become white dwarfs and black holes, respectively. Neutron stars receive a velocity kick upon birth. Following Hartman et al. (1997), we assume the distribution for isotropic kick velocities

\[
P(u)du = \frac{4}{\pi} \cdot \frac{du}{(1 + u^2)^2},
\]

with \(u = v/\sigma\) and \(\sigma = 600\ \text{km s}^{-1}\).

A star which receives mass from its companion in a close binary system may be rejuvenated in the process. The accreting star is rejuvenated with the product of its current age and the fraction of mass gained in the mass transfer process (see Portegies Zwart & Verbunt 1996 for details). Rejuvenation is thus less effective early on in the evolution of the star (near the zero-age main sequence) but becomes more effective when the accretor approaches the terminal-age main sequence.

3. Results

We initialize 10\(^6\) binaries with a primary mass between \(M = 1\ M_\odot\) and 100 M\(_\odot\). Mass transfer and stellar winds may affect the masses of both stars and the binary parameters.

\(^2\)The name SeBa is adopted from the Egyptian word for ‘to teach’, ‘the door to knowledge’ or ‘(multiple) star’. The exact meaning depends on the hieroglyphic spelling.
The binaries are evolved until the first supernova, which is the only way to obtain a velocity \( v > 0 \).

Figure 1 gives, as a function of mass, the number of stars which are ejected in a supernova as a fraction of the initialized primaries with the same mass. The fraction of stars in which the companion experiences a supernova is a steep function of mass (bullets in Figure 1). Binaries with a primary star \( M \lesssim 9 \, M_\odot \) do not produce runaways because the primary is not massive enough to experience a supernova. Runaways with a mass \( m \lesssim 9 \, M_\odot \) can still be produced but only from binaries in which the primary was massive enough to experience supernova. The filled triangles in figure 1 show the specific frequency of runaways (according to our definition: stars which received a velocity in excess of 25 km s\(^{-1}\)). The fraction of runaways is much smaller than the fraction of stars in which the companion experiences a supernova; many supernova explosions occur in rather wide binaries resulting in small ejection velocities.

Runaway stars may obtain high velocities after a complicated evolution as member of a close binary. This initial 'pre runaway' phase lasts until the primary star with mass \( M \) explodes in a supernova: \( t_{sn}(M) \). The runaway has thus spent \( t_{sn}(M) \) as a non-runaway. Before the supernova, however, the binary may have experienced a phase of mass transfer, rejuvenating the accretor with \( dt_{Bss} \), i.e., the time gained on the main sequence due to rejuvenation. The lifetime of the star then becomes \( t_{ms}(m) + dt_{Bss} \) and the total time it spends as a runaway is

\[
t_{run} = t_{ms}(m) - t_{sn}(M) + dt_{Bss}. \tag{2}
\]

All other stars, including the primaries of the binaries which do not gain high velocities because they do not experience a supernova remain visible for \( t_{ms}(M) \). (We neglect the post main-sequence evolution for this population.) The specific frequency of runaways can then be defined by summing over all stars in the denominator and all runaways in the nominator;

\[
f_{run} \equiv \frac{\sum_{run} t_{run}}{\sum_{all} t_{ms}(M) + \sum_{run} dt_{Bss}}. \tag{3}
\]

The extra time gained as a blue straggler appears in the denominator as a correction factor.

The importance of the time lost as a non-runaway and the rejuvenation of the accretor are demonstrated with the open triangles in Fig. 1. The time gained by rejuvenation is not enough to account for the time lost in the pre-supernova binary. Only \( \sim 2\% \) of the stars in the mass range from \( 6 \, M_\odot \) to \( 30 \, M_\odot \) are observable as runaways with velocities \( > 25 \) km s\(^{-1}\). These masses correspond at zero age to spectral type B3V and O6V for the \( 6 \, M_\odot \) and \( 30 \, M_\odot \) star, respectively.

Figure 2 gives, as a function of mass, the fraction of the lifetime that a star with mass
\( m \) spends as a runaway.

\[
\tau_{\text{run}} \equiv \frac{t_{\text{run}}}{t_{\text{ms}}(M) + dt_{\text{Bss}}}. \tag{4}
\]

The width of the distribution reflects the various accretion histories of the stars. Rejuvenation is more effective if more mass is accreted and if that happened later in the evolution of the accretor (near the terminal-age main sequence). High mass stars spend a smaller fraction of their lifetime as runaway.

Figure 3 shows that \( \gtrsim 95\% \) of the runaways (filled triangles) have accreted some mass and are therefore rejuvenated. These stars appear younger than they really are, but his only shows up if the turn-off mass of their parent association drops below the mass of the runaway: if put back in the parent cluster the runaway appears above the turn off as a blue straggler. At any time the fraction of blue straggler among runaway stars is only about 10% for B stars and about 40% for O stars (open triangles). A higher mass star spend a larger fraction of its runaway lifetime as a blue straggler.

Figure 4 shows the probability distribution (by number) as a function of runaway velocity and mass. High mass stars tend to have smaller velocities than low mass stars; which is consistent with observations (see Gies & Bolton 1986).

Non-conservative mass transfer generally results in a shorter binary orbit, since the lost mass carries angular momentum. The runaways produced in such binaries tend to obtain higher speeds after the supernova (see also van den Heuvel et al. 2000). Because the runaway star has accreted less material it is evident that the highest velocity runaways have lower anomalous surface abundances, but higher equatorial rotational velocities. The latter is a result of the tidal locking during a phase of mass transfer.

Figure 5 shows the fraction of binaries that survives the first supernova (bullets) and the binary fraction among runaways (triangles). The binary fraction among runaways is about 20% for late type B stars and increases to \( \sim 40\% \) for earlier spectral types.

Figure 6 shows the probability distribution in orbital period and space velocity of the binaries which survive the supernova. Shorter period binaries often have higher space velocities (see also van den Heuvel et al. 2000).

4. Discussion

We studied the characteristics of high velocity B and O stars using binary population synthesis. The only way in which a star can obtain a high velocity in the model is by the
supernova explosion of the companion star in a binary system. If the binary is dissociated in the supernova a single neutron star (or black hole) and the rejuvenated companion star are ejected, otherwise the runaway star will still be accompanied by the compact object. Independent whether the runaway star is single or the member of a binary system it is likely to be a blue straggler, rapidly rotating and the star may have a funny surface abundance due to its history as an accreting star.

The observed frequency of runaways among O stars is \( \sim 20\% \), much higher than the \( \sim 2\% \) resulting from the model calculations. The \( \sim 2\% \) runaways among B stars from the model is on the low side but not inconsistent with the observations reported by Blaauw (1993) and Stone (1991).

These are serious discrepancies and may in part be solved by invoking various observational selection effects and by adjusting initial conditions and model parameters. We discuss each in turn.

Young O stars remain easily hidden in their parental clouds for a substantial fraction of their lifetime. The stars are born with low velocities and gain speed at later age. This means that for as long as the star resides in the cloud it may be hard to observe. Hiding the youngest –non runaway– O stars enhances the fraction of star with high velocity relative to low velocity objects. Estimates based on the lifetime of dense parental clouds indicates that the most massive O stars spend less than about 1 million years unobservable in the optical. This is not enough to increase the fraction of runaways by more than a few percent and can therefore not be responsible for the order of magnitude discrepancy between the observed and computed frequency of spectral type O runaways.

4.1. Boosting the formation rates of type O runaways

The result of the population synthesis calculations are insensitive to the initial mass function and the eccentricity distribution, but selecting a different mass ratio distribution affects the results more strongly. Observations of high mass binaries favor a mass ratio distribution which is somewhat peaked to unity (Garmany & Conti 1980; Hogeveen 1991).

An initial mass ratio distribution of the from \( P(q) \propto q^3 \) with the same limits as adopted before results in an increase of the fraction of runaway O stars and decreases the fraction of runaways among later spectral types. Figure 7 (circles) shows the results of these calculations with \( 10^6 \) binaries. The fraction for O stars is still too low by at least a factor four, but the observed trend is well explained.
Wide binaries do not contribute to the formation of runaways. Decreasing the maximum orbital separation from $10^6 R_\odot$ to $10^4 R_\odot$ increases the fraction of runaways by roughly 50% over the entire mass range. The increase obtained by this change, indicated by the vertical arrow in fig. 7, is still not sufficient to explain the observed fraction of runaways among O stars.

Finally we may extend the lifetime of the runaway by assuming that mass transfer causes the accretor to rejuvenate to zero age. Combining this with the above discussed alternative mass-ratio distribution results in a specific frequency of runaway stars consistent with the observations (see • in Fig. 7). This indicates, however, that we still under produce runaways by a factor two, as we assumed a binary frequency of 100% where the observations indicate that only $\sim 50\%$ of the O stars reside in binaries (Garmany & Conti 1980; Conti et al. 1977).

We conclude from these arguments that at most 30% of the runaway O stars but most of the B stars can be explained from supernova ejections.

4.2. Hide and seek the pulsar

The binary evolution model predicts a binary fraction among runaways from 20% for late B stars to $\sim 40\%$ among early O stars. These binary frequencies are much higher than the observed $\lesssim 8\%$ (Philp et al 1996; Sayer et al. 1996). The binary fraction among runaways is again presented in Figure 8, but we improved statistics by adding the results of the calculation with the mass ratio distribution peaked to unity from sect. 4.1 to our initial results. (The binary fraction among runaways is rather insensitive to the initial mass ratio distribution.)

All runaway binaries contain a neutron star or a black hole. There are a number of selection effects against finding a radio pulsar as a companion to a massive star. The low mass of a neutron star compared to its accompanying O or B star makes it hard to observe the periodicity in a radial velocity curve. A radio pulsar dies after about 10 Myear. For runaways which remain visible for a shorter time (for $M \gtrsim 15 M_\odot$) this poses no limiting factor. Low mass stars, however, live much longer than the pulsar and the majority of stars with $M \lesssim 8 M_\odot$ are therefore accompanied by an unobservable –dead– pulsar.

The triangles in Fig. 8 show the binary fraction among runaways in which the neutron star is visible as a pulsar. We assumed here that the pulsar lives for 10 Myear and neglected the limited beaming fraction of the pulsar. As expected, low mass runaways are likely to be accompanied by a dead pulsar, where the high mass stars do not suffer from this selection
effect. The chance of catching the neutron star as a pulsar among low mass runaways is small, even though a large fraction of runaways is accompanied by one.

The radio emission from a pulsar is easily absorbed by the mass lost in the stellar wind of the O or B star. The minimum rate of mass loss in the stellar wind required to hide the pulsar can be estimated from the optical depth of the stellar wind for free-free absorption (e.g., Eq. 16 in Illarionov & Sunyaev 1975), we obtain

$$
\dot{M}_{\text{hide}} \gtrsim 5.6 \times 10^{-13} (M + m) [a(1-e)]^{3/2} \ [M_\odot \, \text{yr}^{-1}].
$$

Here \(M\), \(m\), \(a\) and \(e\) are the primary and secondary masses (in \(M_\odot\)), the semi major axis (in \(R_\odot\)) and the orbital eccentricity of the binary. Here it is assumed that the wind of the accompanying star is transparent at \(\lambda = 75\ \text{cm}\) and the temperature of the stellar plasma is \(10^4\ \text{K}\). The estimate for \(\dot{M}_{\text{hide}}\) depends on the eccentricity; substitution of \((1+e)\) for \((1-e)\) in Eq. (5) gives the lower limit for the mass loss rate given that the radio pulsar is only visible at apocenter.

We estimate the mass loss rate for a main sequence star with mass \(M\) (in \(M_\odot\)), luminosity \(L\) (in \(L_\odot\)) and radius \(R\) (in \(R_\odot\)) with (Lamers 1981; Lamers et al. 1993)

$$
\log \dot{M}_{\text{wind}} = -4.83 - 4.58 \log L - 0.87 \log R - 0.49 \log M.
$$

Here \(\dot{M}_{\text{wind}}\) is in \(M_\odot \, \text{yr}^{-1}\). Many of the runaways have experienced a phase of mass transfer and may have enhanced mass loss rates (Snow 1982), which we do not account for. If \(\dot{M}_{\text{wind}}\) exceeds \(\dot{M}_{\text{hide}}\) the pulsar is unobservable. The large circles in Fig. 8 shows the number of binaries in which the pulsar is visible through the stellar wind as fraction of all runaway stars (single and binary). Some pulsar, however, are observable near apocenter but hidden at pericenter (small circles in Fig. 8).

Between 30% and 40% of the high-mass (spectral type O) runaways are accompanied by a radio pulsar, but 2% to 4% of these are visible through the stellar wind of their companion. About 1% of the early type stars will therefore be observable as a radio source. For early spectral type B stars (\(m \gtrsim 7\ M_\odot\)) this fraction increases to about 1.8% mainly due to their lower mass loss rates, which makes it easier for the pulsar to shine through. For later spectral type stars the fraction drops again; mainly caused by the longer lifetime of the lower mass stars, which outlive the pulsar.

These numbers provide upper limits to the fraction of runaways which have a visible pulsar as companion as we did not take the limited beaming of the radio signal into account. The beaming fraction may be about 1/3, decreasing \(f_{\text{run}}\) to \(\lesssim 0.3\%\) for O type runaways and to \(\sim 0.6\%\) for spectral type B stars. Realistically speaking we expect that about one in 350 runaway O stars and one in 200 B stars may be observable through the accompanying
radio pulsar. A considerably larger fraction may be observed as an X-ray source. Runaway binaries in which the pulsar is visible have generally rather large orbital periods to allow the pulsar to shine through the dense wind of the O star. These binaries therefore tend to have relatively small runaway velocity (see Fig. 6).

The high velocity stars of spectral type A (and later) found by Lance (1988a) may in part be explained from binary supernova ejections. Not all their characteristics, however, are satisfactory explained from this model. These stars do not show abnormal high rotational velocities and tend to appear considerably younger than the A stars in the Galactic disc. The latter characteristic indicates that these stars are blue stragglers. This is somewhat unexpected as the later spectral type stars tend to spend less time as blue stragglers (see Fig. 5). Figure 5 shows that the specific frequency of runaways drops for lower masses and we expect that the number of high velocity A stars ejected by supernova explosions is small. A mass ratio distribution which peaks to zero increases the fraction of runaways among later spectral types considerably. Figure 5 on the other hand shows that lower mass stars tend to receive higher runaway velocities, which is consistent with the observations (Lance 1988b). It is, however, arguable that the minority of late type stars obtain their high velocities or large distance from the Galactic disc by supernovae.

5. Conclusions

We perform detailed binary population synthesis calculations to study the origin of runaway O and B stars.

The majority of the OB runaways can be explained with the evolution of binaries if: 1) the mass ratio distribution for binaries with early type primaries strongly peaks towards unity, 2) stars are rejuvenated to zero age by mass accretion from a companion star in a close binary, and 3) the binary fraction among early type stars is close to 100%. Taking these requirements into consideration we conclude that about 30% of the runaway O stars but the majority of runaway B stars may originate from evolving binaries.

Runaway O and B stars which are ejected in the supernova explosion of their binary companions have the following characteristics:

1. Half the type O runaways and at least 10% of the B stars are observable as blue stragglers relative to the association in which they were born.

2. High velocity runaways have higher equatorial rotation and lower surface helium abundances. The runaways in shorter period binaries have higher space velocities.
3. The binary fraction among runaway B stars is about 20% and increases to about 40% for early type O stars.

4. For late type B stars ($m \lesssim 8\,M_\odot$) the accompanying pulsar is most likely dead.

5. The radio signal of most pulsars in runaway binaries are unobservable due to absorption in the stellar wind. For early B stars ($m \lesssim 7\,M_\odot$) only $\lesssim 2\%$ of the pulsars are visible, this fraction drops to $\lesssim 1\%$ for O star runaways ($m \gtrsim 15\,M_\odot$).

Acknowledgements: This work was supported by NASA through Hubble Fellowship grant HF-01112.01-98A awarded by the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., for NASA under contract NAS 5-26555.

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Fig. 1.— Stars and binaries which are ejected upon a supernova as fraction of the primaries initialized with the same mass. The filled symbols give number fractions, open symbols represent observable fractions (see Eq. 3). The latter are corrected for the time that a star spends as a runaway. The fraction for stars which are ejected upon a supernova are identified with •, triangles gives the fraction of runaways among these (stars with $v > 25 \text{ km s}^{-1}$). A Poissonian 1σ error bar is presented at the far right bullet.

Fig. 2.— Fraction of the lifetime that a star spends as a runaway (see Eq. 3). The distribution is broad, bullets give the mean for the specific mass bins, solid lines give the 90% confidence intervals and the error bar to the most right point gives the dispersion of the distribution.

Fig. 3.— Number fraction of blue stragglers among runaways (filled triangle). These fractions do not incorporate the time a runaway spends as a blue straggler. The open triangles correct for this by weighting the time a star spend as a runaway by the time it is observable as a blue straggler.

Fig. 4.— Number of stars and binaries that are ejected upon a supernova (gray shades and contours) as a function of velocity and the mass of the runaway (the visible component in the case of a binary). Gray shades are linear in number density.

Fig. 5.— Binary fraction as a function of the mass of the observable component. The bullets indicate the fraction of binaries which survive the supernova. The triangles give the binary fraction among runaways ($v > 25 \text{ km s}^{-1}$). Error bars are 1σ Poissonian.

Fig. 6.— Probability distribution of runaway velocity as a function of orbital period for binaries with a visible star of $m > 5 \text{ M}_\odot$. 

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Fig. 7.— Specific frequency of runaway stars weighed with lifetime. The dotted line give the results of the standard model (open triangles in Fig. [4]). Circles give the results for a mass ratio distribution which is peaked to unity. The arrow indicates the increase in the fraction of runaways when the maximum semi major axis is reduced by two orders of magnitude to $10^4 R_\odot$. The • show the specific frequency of runaways assuming that an accreting star is rejuvenated to zero age. The error bar to the last ○ shows the 1σ Poissonian error. The other error bars indicate the observed fraction of runaways from Blaauw (1961; 1993).

Fig. 8.— Binary fraction among runaway stars as a function of mass (●, see also fig. [5]). The filled triangles give the fraction of binaries in which the neutron star is active as a radio pulsar (weighted on the lifetime of the runaway star). The small open circles (connected with the dotted line) gives the specific frequency of runaway binaries for which the pulsar is visible through the stellar wind at apocenter, the large circles show the fraction for which the pulsar is visible all the time.
Table 1. Initial conditions for the binaries. The first and second columns give the parameter and the functionality, followed by the adopted lower and upper limits.

| parameter       | function                  | limits       |
|-----------------|---------------------------|--------------|
| mass function   | $P(M) = \text{Scalo (1986)}$ | $1 \, \text{M}_\odot$, $100 \, \text{M}_\odot$ |
| secondary mass  | $P(m) = \text{constant}$  | $0.1 \, \text{M}_\odot$, $M/\text{M}_\odot$         |
| orbital separation | $P(a) = 1/a$            | $1 \, \text{R}_\odot$, $10^6 \, \text{R}_\odot$ |
| eccentricity    | $P(e) = 2e$              | $0$, $1$     |
