On the origin of high-velocity runaway stars

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Accepted 2009 March 23. Received 2009 March 4

ABSTRACT

We explore the hypothesis that some high-velocity runaway stars attain their peculiar velocities in the course of exchange encounters between hard massive binaries and a very massive star (either an ordinary 50 – 100 M\(_\odot\) star or a more massive one, formed through runaway mergers of ordinary stars in the core of a young massive star cluster). In this process, one of the binary components becomes gravitationally bound to the very massive star, while the second one is ejected, sometimes with a high speed. We performed three-body scattering experiments and found that early B-type stars (the progenitors of the majority of neutron stars) can be ejected with velocities of \(\gtrsim 200 – 400\) km s\(^{-1}\) (typical of pulsars), while 3 – 4 M\(_\odot\) stars can attain velocities of \(\gtrsim 300 – 400\) km s\(^{-1}\) (typical of the bound population of halo late B-type stars). We also found that the ejected stars can occasionally attain velocities exceeding the Milky Way’s escape velocity.

Key words: Stellar dynamics – methods: N-body simulations – binaries: general – stars: neutron – stars: neutron: 1RXS J141256.0+792204 – stars: individual: HD 271791

1 INTRODUCTION

The origin of high-velocity runaway stars can be attributed to two basic processes: (i) disruption of a tight massive binary following the (asymmetric) supernova explosion of one of the binary components (Blaauw 1961; Stone 1991; Leonard & Dewey 1993; Iben & Tutukov 1996) and (ii) dynamical three- or four-body encounters in dense stellar systems (Poveda, Ruiz & Allen 1967; Aarseth 1974; Gies & Bolton 1986; Leonard & Duncan 1990). In the first process, the maximum velocity attained by runaway stars depends on the magnitude of the kick imparted to the stellar supernova remnant [either a neutron star (NS) or a black hole]. For reasonable values of this magnitude, the runaway velocity does not exceed \(\sim 200\) km s\(^{-1}\) (e.g. Leonard & Dewey 1993; Portegies Zwart 2000; see also Gvaramadze 2009). In the second process, the ejection velocity could be higher. One of the most important and best studied channels for producing high-velocity stars is through close encounters between hard (Aarseth & Hills 1972; Hills 1975; Heggie 1975) binary stars (Mikkola 1983; Leonard & Duncan 1990). Numerical simulations by Leonard (1991) showed that the maximum velocity that a runaway star (usually the lightest member of the binaries involved in the interaction) can attain in binary-binary encounters is equal to the escape velocity from the surface of the most massive star in the binaries. For binaries containing upper main-sequence stars, the maximum velocity of runaways could be as large as \(\sim 1400\) km s\(^{-1}\). The result by Leonard (1991) is often invoked to explain the high peculiar velocities measured (or inferred) for some runaway stars (e.g. Heber, Moehler & Groote 1995; Maitzen et al. 1998; Tenjes et al. 2001; Ramspeck, Heber, Moehler 2001; Martin 2006; Gvaramadze 2007; Gvaramadze, Gualandris & Portegies Zwart 2008, hereafter Paper I; Gvaramadze & Bomans 2008a; Gvaramadze 2009).

The recent discovery of the so-called hypervelocity stars (HVSs; Brown et al. 2005; Edelmann et al. 2005; Hirsch et al. 2005) – the ordinary stars moving with velocities exceeding the Milky Way’s escape velocity – attracted attention to dynamical processes involving the supermassive (\(\sim 4 \times 10^6\) M\(_\odot\)) black hole in the Galactic Centre (Gualandris, Portegies Zwart & Sipior 2005; Baumgardt, Gualandris & Portegies Zwart 2006; Levin 2006; Sesana, Haardt & Madau 2006; Ginsburg & Loeb 2006; Bromley et al. 2006; Lu, Yu & Lin 2007; L"ockmann & Baumgardt 2008; Perets 2009). These processes [originally proposed by Hills (1988) and Yu & Tremaine (2003)] can result in ejection velocities of several \(1000\) km s\(^{-1}\). Similar processes but act-
ing in the cores of young massive star clusters (YMSCs) and involving dynamical encounters with intermediate-mass (~100 – 1000 M\(_\odot\)) black holes (IMBHs) were considered in Paper I (see also Gvaramadze 2006) to explain the origin of extremely high-velocity (\(\gtrsim 1000\) km s\(^{-1}\)) NSs (e.g. Chatterjee et al. 2005; Hui & Becker 2006) and HVSSs. Gualandris & Portegies Zwart (2007) proposed that exchange encounters between hard binaries and an IMBH formed in the core of a YMSC in the Large Magellanic Cloud could be responsible for the origin of the HVS HE 0437–5439 (cf. Edelmann et al. 2005; Przybilla et al. 2008a; Bonanos et al. 2008). A strong support to the possibility that at least some HVSSs originate in star clusters rather than in the Galactic Centre comes from the proper motion measurements for the HVS HD 271791, which constrain the birth place of this early B-type star to the outer parts of the Galactic disk (Heber et al. 2008; see also Sect. 5). Another example of an extremely high-velocity (\(\gtrsim 400\) km s\(^{-1}\)) B-type star originated in the Galactic disk is the 5 M\(_\odot\) star HIP 60350 (Maitzen et al. 1998), whose birthplace lies at about 7 kpc from the Galactic Centre (Tenjes et al. 2001).

While the existence of a supermassive black hole in the Galactic Centre is widely accepted, no conclusive evidence has been found for IMBHs. These objects could be the descendants of very massive (\(\gtrsim 1000\) M\(_\odot\)) stars (VMSs), formed in the cores of YMSCs through a runaway sequence of collisions and mergers of ordinary massive stars (e.g. Portegies Zwart & McMillan 2002; Portegies Zwart et al. 2004; see also next Section). Recent numerical studies of the evolution of VMSs, however, indicate that these stars can lose most of their mass due to copious stellar winds and leave behind IMBHs with masses of \(\lesssim 70\) M\(_\odot\) (Belkus, Van Bever & Vanbeveren 2007; Yungelson et al. 2008), which are not large enough to contribute significantly to the production of high-velocity runaway stars (see Paper I).

In this paper, we explore the hypothesis (Gvaramadze 2007) that some high-velocity runaway stars could attain their peculiar velocities in the course of strong dynamical encounters between hard massive binaries and a VMS. In this process, one of the binary components becomes gravitationally bound to the VMS, while the second one is ejected, sometimes with a high velocity. Our goal is to check whether or not this exchange process can produce early B-type stars (the progenitors of the majority of NSs) with velocities of \(\gtrsim 200 – 400\) km s\(^{-1}\) [measured for some massive halo stars (e.g. Carozzi 1974; Tobin & Kaufmann 1984; Keenan et al. 1987; Kilkenny & Stone 1988; Ramspeck et al. 2001; Martin 2006) and typical of pulsars (e.g. Hobbs et al. 2005)] and 3 – 4 M\(_\odot\) stars with velocities \(\gtrsim 300 – 400\) km s\(^{-1}\) (measured for some late B-type halo stars; e.g. Maitzen et al. 1998; Brown et al. 2007). In Section 2, we discuss the existence of VMSs in YMSCs and estimate the number of YMSCs formed in the Galactic disk during a certain interval of time. In Section 3, we estimate the typical ejection velocity produced via exchange encounters between binary stars and a VMS. In Section 4, we compare this estimate with the results from numerical three-body scattering experiments. The discussion is given in Section 5.

## 2 VERY MASSIVE STARS

There is emerging observational evidence that the majority (if not all) of massive stars form in a cluster environment (e.g. Zinnecker & Yorke 2007 and references therein; cf. de Wit et al. 2005; Schilbach & Röser 2008; Gvaramadze & Bonnams 2008b) and that the mass of the most massive star in a cluster is correlated with the mass of the cluster itself (Elmegreen 2000; Weidner & Kroupa 2004, 2006). Observations also suggest that the maximum mass of ordinary stars is saturated at \(\sim 150\) M\(_\odot\) for \(M_d \gtrsim 10^3\) M\(_\odot\), where \(M_d\) is the mass of the cluster (Weidner & Kroupa 2006), a fact which points to the existence of the upper cut-off of stellar masses (Weidner & Kroupa 2004; Figer 2005; Oey & Clarke 2005).

A somewhat higher upper limit on the maximum stellar mass follows from the recent work by Yungelson et al. (2008), who argue that the birth masses of some of the observed stars could be as large as \(\approx 200\) M\(_\odot\) (cf. Oey & Clarke 2005). It is also possible that even more massive stars could originate from the coalescence of binaries whose components have masses close to the upper limit (Yungelson et al. 2008; cf. Leonard 1995). Moreover, numerical simulations of the dynamical evolution of YMSCs show that runaway collisions and mergers of ordinary massive stars can result in the formation of VMSs with masses as large as \(\gtrsim 1000\) M\(_\odot\) (e.g. Portegies Zwart et al. 1999; Portegies Zwart & McMillan 2002; Gürkan, Freitag & Rasio 2004; Freitag, Gürkan & Rasio 2006; see also Suzuki et al. 2007).

Two necessary conditions should be fulfilled for the runaway growth of a VMS. First, the parent cluster should be compact (e.g. Gaborov, Gualandris & Portegies Zwart 2008; Ardi, Baumgardt & Mineshige 2008), i.e. dense enough to ensure that stellar collisions are frequent. Second, the cluster should be massive (\(\sim 10^4 – 10^5\) M\(_\odot\)), i.e. should contain a large number of OB stars – the main building blocks for the VMSs. Let us discuss these conditions in more detail.

It is conceivable that the first condition is fulfilled for the majority of YMSCs since their characteristic radius at birth (i.e. during the embedded phase) is \(\lesssim 1\) pc, independently of their mass (e.g. Kroupa & Boily 2002 and references therein). The high central densities in young clusters could be either primordial (e.g. Murray & Lin 1996; Clarke & Bonnell 2008) or caused by dynamical mass segregation (e.g. Portegies Zwart et al. 1999; Gürkan et al. 2004). The existing observational data on YMSCs do not allow us to discriminate between these two possibilities. The observed top-heavy initial mass functions in the central parts of two of the most massive and dense YMSCs in our Galaxy, NGC 3603 and Arches, could either reflect the initial conditions in the cores of these clusters (e.g. Harayama, Eisenhauer & Mar-

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1 Note that some authors (e.g. Brown, Geller & Kenyon 2009; Tillich et al. 2009) suggest to use the term “hypervelocity” to designate the high-velocity stars ejected solely from the Galactic Centre (i.e. via the dynamical processes involving the supermassive black hole). At present, however, proper motion measurements are available for only one of the known HVSSs (see above) so that it is impossible to unambiguously associate the birthplace of these objects with the Galactic Centre. In the following we will call “hypervelocity” stars all stars with peculiar velocities \(\gtrsim 700\) km s\(^{-1}\).

2 We consider a binary as massive if at least one of its components is more massive than 8 M\(_\odot\).
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3 HIGH-VELOCITY STARS FROM EXCHANGE ENCOUNTERS BETWEEN BINARY STARS AND A VERY MASSIVE STAR

Close dynamical encounters between (hard) binary stars and a VMS can result in the ejection of one of the stars with a high velocity. In this process, one of the binary components is replaced by the VMS, while the second one is ejected (the so-called exchange encounter). For equal mass binary components and zero impact parameter, the typical velocity attained by the escaper is \( \approx 1.8 V_{\text{orb}} \), where \( V_{\text{orb}} \) is the orbital velocity of the ejected star in the original binary (Hills & Fullerton 1980). The ejected star gains its kinetic energy at the expense of the increased binding energy of the post-encounter (newly formed) binary.

The production of high-velocity stars in exchange encounters between binary stars and a VMS is similar to the process of star ejection in the course of close dynamical encounters between binaries and a supermassive black hole (Hills 1988). The main difference is that in the first process the distance of closest approach of the binary to the central massive body is limited by the radius of the VMS, \( R_{\text{VMS}} \), while in the second one it cannot be smaller than the tidal radii of the binary components in the gravitational field of the black hole. Our goal is to check how this distinction affects the typical velocity of ejected stars as well as the fraction of encounters resulting in high-velocity ejections. Below, we use the results of Hills (1988) to estimate the ejection velocity produced in exchange encounters and then in Section 4 we compare this estimate with results from numerical three-body simulations.

In the process of a close encounter between a binary and a VMS, the VMS can be treated as a point mass if its radius is smaller than the binary tidal radius, \( r_t^{\text{lim}} \sim \left( \frac{M_{\text{VMS}}}{m_1 + m_2} \right)^{1/3} a \), where \( M_{\text{VMS}} \), \( m_1 \) and \( m_2 \) are, respectively, the masses of the VMS and the binary components \( (m_1 \geq m_2) \), and \( a \) is the binary semi-major axis. Evolutionary models of VMSs show that these stars develop a core-halo configuration (more pronounced at the upper end of masses), in which most of the mass is concentrated in a dense and compact core while the rest of the mass is spread in an extended tenuous halo (Ishii, Ueno, & Kato 1999; Yungelson et al. 2008). According to Yungelson et al. (2008; also Yungelson, personal communication), 99 per cent of the mass of 500 and 1000 \( M_\odot \) VMSs is confined within a sphere of radius \( \sim 30 \)
and 40 $R_{\odot}$, respectively. (In Section 4 we use these figures as input parameters for our numerical simulations.) For illustrative purposes, we consider exchange encounters between a VMS and a hard binary consisting of main-sequence stars with masses $m_1 = 40 \, M_{\odot}$ and $m_2 = 8 \, M_{\odot}$ and semi-major axis $a \approx 3r_1 \approx 30 \, R_{\odot}$ (typical of tidal binaries; e.g. Lee & Ostriker 1986), where

$$r_1 = 0.8 \left( \frac{m_1}{M_{\odot}} \right)^{0.7} R_{\odot}$$

(2)

is the radius of the primary star (Habets & Heintze 1981). For these parameters, one has from equations (1) and (2) that $r_1^{\text{bin}} \gtrsim 2R_{\text{VMS}}$, so that the VMS can be treated as a point mass.

The typical ejection velocity at infinity attained by the escapers in the course of exchange encounters is (Hills 1988)

$$V_\infty \simeq 640 \, \text{km s}^{-1} \alpha \left( \frac{M_{\text{VMS}}}{100 \, M_{\odot}} \right)^{1/6} \left( \frac{a}{30 \, R_{\odot}} \right)^{-1/2}$$

$$\times \left[ \frac{m_1 + m_2}{(40 + 8) \, M_{\odot}} \right]^{1/3},$$

(3)

where $\alpha$ is a non-monotonic function of the dimensionless closest approach parameter

$$D_\text{min} = 7.9 \frac{R_{\text{min}}}{r_1^{\text{bin}}}$$

(4)

and $R_{\text{min}}$ is the closest approach distance between the binary and the VMS; $\alpha \simeq 1$ for $D_\text{min} \simeq 0$, then it reaches a maximum of $\simeq 1.2$ for $D_\text{min} \simeq 30 - 40$ and then monotonically decreases with increasing $D_\text{min}$. For $R_{\text{min}} \sim R_{\text{VMS}}$ and a VMS of mass $M_{\text{VMS}} = 500$ and 1000 $M_{\odot}$, one has from equation (3) and (4) that $D_\text{min} \simeq 40$ and $V_\infty$ is close to its maximum value of $\approx 1000$ and 1100 km s$^{-1}$, respectively. Note that the weak dependence of $V_\infty$ on $M_{\text{VMS}}$ implies that exchange encounters with ordinary stars of mass of $\sim 100 \, M_{\odot}$ would in principle be sufficient to produce HVs (cf. Section 4).

4 NUMERICAL EXPERIMENTS

In this section, we perform numerical simulations of three-body encounters in order to obtain the velocity distributions for runaway stars produced in the course of exchange interactions between hard binary stars and a massive compact body, either a VMS or an ordinary star of mass of $50 - 100 \, M_{\odot}$. The simulations are carried out using the sigma3 package, which is part of the STARLAB software environment (McMillan & Hut 1996; Portegies Zwart et al. 2001). For a detailed description of the setup of the scattering experiments see Gualandris et al. (2005). During the simulations we allow for physical collisions when the distance between any two stars is smaller than the sum of their radii. For ordinary stars we use the mass-radius relationship given by equation (4), while for the VMSs of mass of 500 $M_{\odot}$ and 1000 $M_{\odot}$ we adopt the radii $R_{\text{VMS}} = 30 \, R_{\odot}$ and 40 $R_{\odot}$, respectively (see Section 3). The initial eccentricity of the stellar binary is randomly drawn from a thermal distribution in the allowed range $(0 - e_{\text{max}})$, where $e_{\text{max}} = 1 - 2(r_1 + r_2)/a$ is chosen as to avoid a collision at the first pericentre passage ($r_2$ is the radius of the secondary star). The relative velocity at infinity between the centre of mass of the binary and the central massive body is set to 5 km s$^{-1}$, in accordance with typical dispersion velocities in YMSC.

4.1 High-velocity early B-type stars

First, we focus on exchange encounters producing high-velocity early B-type stars. From numerical three-body scattering experiments, it is known that the least massive binary component is more likely to be ejected with high velocity if its companion star is much more massive and/or the binary semi-major axis is small (e.g. Gualandris & Portegies Zwart 2007). For illustrative purposes we consider encounters between a binary consisting of two main-sequence stars with masses $m_1 = 40 \, M_{\odot}$ and $m_2 = 8 \, M_{\odot}$ and a (very) massive star with $M_{\text{VMS}}$ ranging from 50 to 1000 $M_{\odot}$. In order to maximize the ejection speed, we assume that the binary system is very tight, e.g. formed by tidal capture. In this case, $\alpha \simeq 3r_1 \simeq 0.15$ AU (see Section 3 and cf. Paper I).

In Fig. 1 we present the probability of different outcomes (branching ratios) as a function of $M_{\text{VMS}}$. For each value of $M_{\text{VMS}}$ we perform a total of 10000 scattering experiments, which result either in a fly-by, an exchange or a merger. Ionizations never take place as the binary is too hard to be dissociated by the VMS. Mergers occur in a large fraction (~65 per cent) of encounters due to the small semi-major axis of the binary and the finite size of the stars. Exchange interactions occur in about 6 per cent of encounters. During these interactions, one of the binary components is captured by the VMS while the other is ejected, sometimes

![Figure 1. Branching ratio for the outcome of encounters between a (40,8) M⊙ binary and a single VMS as a function of the VMS mass. The different outcomes are: merger (circles), fly-by (triangles), ionization (stars) and exchange (squares). The error bars represent the formal (1σ) Poissonian uncertainty of the measurement.](http://www.manybody.org/manybody/starlab.html)
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Figure 2. Velocity distributions at infinity for escaping (8 $M_\odot$) stars in encounters between a binary consisting of a primary star with mass $m_1 = 40 M_\odot$ and a secondary star with mass $m_2 = 8 M_\odot$, and a single VMS of mass $M_{\text{VMS}} = 50 M_\odot$, 100 $M_\odot$, 500 $M_\odot$ and 1000 $M_\odot$ (from left to right). The binary semi-major axis is $a = 0.15$ AU.

with a high velocity. These encounters are the relevant ones for the production of high-velocity runaway stars.

Fig. 2 shows the velocity distribution for 8 $M_\odot$ escapers. As expected, the more massive VMSs are more likely to eject stars with high velocities. Fig. 2 also shows that the typical ejection velocities attained by the escapers are consistent with the predictions derived in Section 3.

In Fig. 3 we show the probability of exchange encounters resulting in ejection of the 8 $M_\odot$ binary component with a velocity from 200 to 700 km s$^{-1}$ (top to bottom). For $M_{\text{VMS}} \gtrsim 100 M_\odot$ about 3 per cent of all encounters produce runaways with peculiar velocities $\geq 400$ km s$^{-1}$. It can be seen (see also Fig. 2) that even an ordinary star of mass of 50 $M_\odot$ can occasionally (in $\sim 1$ per cent of encounters) produce an escape velocity $\geq 400$ km s$^{-1}$. In order to produce escapers with velocities typical of HVSs ($V_\infty \geq 700$ km s$^{-1}$), a VMS of several hundred solar masses is required. In the case of a 200–300 $M_\odot$ VMS, $\gtrsim 2$ per cent of all encounters result in an escape velocity of $\geq 700$ km s$^{-1}$. This fraction gradually increases to $\gtrsim 3$ per cent for the more massive VMSs.

Fig. 4 shows the average recoil velocity, $\langle V_\infty \rangle$, of escapers (8 $M_\odot$ stars; solid symbols) as a function of the binary semi-major axis for four different values of the VMS mass $M_{\text{VMS}} = 50 M_\odot$, 100 $M_\odot$, 500 $M_\odot$ and 1000 $M_\odot$. The empty symbols indicate the velocity $V_{\text{max}}$ for which 1 per cent of the escapers have $V_\infty > V_{\text{max}}$. The average and the maximum velocities increase with the mass of the VMS, as expected from energetic arguments. On the other hand, the fraction of high-velocity escapers decreases rapidly with increasing $a$. For $M_{\text{VMS}} = 50 - 100 M_\odot$, escapers are ejected with velocities $\geq 200 - 400$ km s$^{-1}$ if the binary semi-major axis is in the range $0.15$ AU $< a < 0.6$ AU. The same velocities

Figure 3. The probability of exchange encounters between a (40, 8) $M_\odot$ binary (with $a = 0.15$ AU) and a single VMS resulting in ejection of the 8 $M_\odot$ star with a velocity from 200 to 700 km s$^{-1}$ (top to bottom).

Figure 4. Average recoil velocity of escapers as a function of the initial binary semi-major axis in the interaction of a (40, 8) $M_\odot$ binary star with VMSs of different mass: $M_{\text{VMS}} = 50 M_\odot$ (diamonds), $M_{\text{VMS}} = 100 M_\odot$ (triangles), $M_{\text{VMS}} = 500 M_\odot$ (squares), $M_{\text{VMS}} = 1000 M_\odot$ (circles). Solid symbols represent the average velocity obtained from a set of 10000 scattering experiments while the empty symbols indicate the velocity $V_{\text{max}}$ for which 1 per cent of the escapers have $V_\infty > V_{\text{max}}$. The error bars indicate the $1\sigma$ deviation from the mean. For clarity, we only show them for one data set.
could be achieved with wider binaries (with a up to 1 AU) if \( M_{\text{VMS}} \geq 300 \, M_\odot \). To produce hypervelocity escapers \( M_{\text{VMS}} \) should be \( \gtrsim 500 \, M_\odot \) and the smallest possible semi-major axes are needed \((a \simeq 0.15 - 0.2 \, \text{AU})\). Fig. 4 also shows that even a 100 \( M_\odot \) star can occasionally produce hypervelocity escapers, but the fraction of these events is very small (see also Fig. 3).

Note that the average recoil velocity of escapers produced in exchange encounters with a VMS is somewhat larger than that produced in encounters with an IMBH of the same mass (cf. Fig. 4 with Fig. 4 in Paper I). This seemingly “incorrect” result can be understood if one takes into account that the ejection velocity is a non-monotonic function of the closest approach of the binary to the central massive body (either a VMS or an IMBH) and that for encounters with the VMS \( R_{\text{min}} \) cannot be less than \( R_{\text{VMS}} \), while for encounters with the IMBH \( R_{\text{min}} \) is limited by the tidal radius of the ejected star, \( r_t \sim (M_{\text{IMBH}}/m_1)^{1/3} r_\star \), where \( M_{\text{IMBH}} \) is the mass of the IMBH and \( m_1 \) and \( r_\star \) are the mass and the radius of the star. For the parameters adopted in our simulations, one has from equations (1) and (4) that \( D_{\text{min}} \simeq 40 - 50 \) and \( \simeq 15 \) for encounters with the VMSs and the IMBHs, respectively. Thus, the first process becomes the larger \( V_\infty \), while in the second one the closest possible approach to the black hole does not produce the maximum ejection velocity (see Section 3; see also Fig. 4 in Gualandris & Portegies Zwart 2007)), which in turn results in the smaller \( V_\infty \).

4.2 High-velocity late B-type stars

Now we simulate exchange encounters producing high-velocity late B-type stars. In order to derive the probability of obtaining the largest possible ejection velocities, we consider encounters between a very tight binary \((m_1 = 10 \, M_\odot, m_2 = 4 \, M_\odot \) and \( a \simeq 3 r_\star \simeq 0.06 \, \text{AU} \)) and a (very) massive star of mass \( 50 - 1000 \, M_\odot \). The branching ratio for these encounters (Fig. 5) is almost identical to that given in Fig. 4. The only difference is the somewhat smaller percentage of exchange encounters due to the smaller semi-major axis of the binary.

The velocity distributions for 4 \( M_\odot \) escapers are shown in Fig. 6 for four different values of the VMS mass: \( M_{\text{VMS}} = 50, 100, 500 \) and 1000 \( M_\odot \). The typical ejection velocity obtained for each set of parameters is consistent with the estimates derived from equation (5). Fig. 7 shows that for all values of \( M_{\text{VMS}} \) about 2 per cent of encounters results in peculiar velocities \( \gtrsim 300 - 400 \, \text{km s}^{-1} \) and that about the same percentage of ejected stars attains velocity \( \gtrsim 700 \, \text{km s}^{-1} \) if \( M_{\text{VMS}} \gtrsim 200 \, M_\odot \).

The average recoil velocity of escapers as a function of the binary semi-major axis is shown in Fig. 5. As in the case of encounters between \((40 + 8) \, M_\odot \) binaries and a VMS, the average and the maximum velocities increase with the mass of the VMS. Both velocities, however, can reach somewhat higher values due to the smaller possible semi-major axis of the binary (cf. with Fig. 5). Note also that although \( \langle V_\infty \rangle \) decreases with increase of \( a \), the fraction of escapers with a given velocity \( < \langle V_\infty \rangle \) could be larger for wider binaries (this is because the percentage of encounters resulting in exchanges increases with increase of \( a \); see e.g. Fig. 1 in Gualandris & Portegies Zwart 2007). This effect is illustrated.
Figure 7. The probability of exchange encounters between a (10, 4) $M_{\odot}$ binary (with $a = 0.06$ AU) and a single VMS resulting in ejection of the 4 $M_{\odot}$ star with a velocity from 200 to 700 km s$^{-1}$ (top to bottom).

Figure 8. Average recoil velocity of escapers as a function of the initial binary semi-major axis in the interaction of a (10, 4) $M_{\odot}$ binary star with VMSs of different mass: $M_{\text{VMS}} = 50 M_{\odot}$ (diamonds), $M_{\text{VMS}} = 100 M_{\odot}$ (triangles), $M_{\text{VMS}} = 500 M_{\odot}$ (squares), $M_{\text{VMS}} = 1000 M_{\odot}$ (circles). Solid symbols represent the average velocity obtained from a set of 10000 scattering experiments while the empty symbols indicate the velocity $V_{\text{max}}$ for which 1 per cent of the encounters have $V_{\infty} > V_{\text{max}}$. The error bars indicate the 1$\sigma$ deviation from the mean. For clarity, we only show them for one data set.

Figure 9. The same as Fig. 7 but for binaries with semi-major axis $a = 0.1$ AU.

in Fig. 9 which shows that for binaries with $a = 0.1$ AU the percentage of escapers with $V_{\infty} > 400$ km s$^{-1}$ is about 2.5 times larger as compared to the case of the more tight binaries (cf. Fig. 7).

5 DISCUSSION

We performed numerical simulations of dynamical encounters between hard massive binaries and a VMS, in order to explore the hypothesis that this dynamical process could be responsible for the origin of high-velocity ($\gtrsim 200 - 400$ km s$^{-1}$) runaway stars. In our study we proceeded from the similarity between encounters involving a VMS and those involving an IMBH (the latter process is already known to be able to produce high-velocity runaways; Paper I; Gualandris & Portegies Zwart 2007) and the fact that the radii of VMSs are smaller than the tidal radii of the intruders (the massive binaries), so that the tidal breakup and ejection can occur before the binary components merge with the VMS (Section 3; see also Gvaramadze 2007). Our study was motivated by the recent evolutionary models of VMSs (Belkus et al. 2007; Yungelson et al. 2008), which suggest that VMSs can lose most of their mass via copious winds and leave behind IMBHs with masses of $\lesssim 70 M_{\odot}$, which are not large enough to contribute significantly to the production of high-velocity runaway stars (see Paper I). We therefore explored the possibility that a VMS could produce high-velocity escapers (either early or late B-type stars) before it finished its life in a supernova and formed a black hole. We estimated the typical velocities produced in encounters between very tight massive binaries and VMSs (with $M_{\text{VMS}} \gtrsim 200 M_{\odot}$) and found that about 3 – 4 per cent of all encounters produce velocities of $\gtrsim 400$ km s$^{-1}$, while in about 2 per cent of encounters the escapers attain velocities comparable to those measured for HVSs (i.e. $\gtrsim 700$ km s$^{-1}$). We therefore argue that the origin of high-
velocity ($\gtrsim 200 - 400 \text{ km s}^{-1}$) runaway stars and at least some HVSs could be associated with dynamical encounters between the tightest massive binaries and VMSs formed in the cores of YMSCs. In this connection, it is worthy to note that the theoretical velocity distribution for HVSs produced in the Galactic Centre (i.e. through the dynamical processes involving the supermassive black hole) predicts the existence of a tail of velocities of up to several thousand km s$^{-1}$, while the peculiar velocities observed for all known ($\sim 20$) HVSs do not exceed $\sim 800$ km s$^{-1}$ (e.g. Sesana, Haardt & Madau 2007; L"ockmann & Baumgardt 2008). Interestingly, the latter figure better agrees with the maximum ejection velocity ($\gtrsim 1000 - 1500$ km s$^{-1}$) produced via dynamical three- and four-body encounters in dense star clusters (see Section 3 and Paper I). The future proper motion measurements for HVSs with GAIA will reveal what fraction of these extremely high-velocity stars originated in the Galactic disk.

We also simulated dynamical encounters between tight massive binaries and single $50-100 M_{\odot}$ stars – the most massive ordinary stars formed in clusters with $M_{cl} \approx 10^3 - 10^4 M_{\odot}$ (Weidner & Kroupa 2006). We found that from 1 to $\approx 4$ per cent of these encounters can produce runaway stars with velocities of $\gtrsim 300 - 400$ km s$^{-1}$ (typical of the bound population of high-velocity halo B-type stars) and occasionally (in less than 1 per cent of encounters) produce hyper-velocity ($\gtrsim 700$ km s$^{-1}$) late B-type escapers. Note that the smaller production rate of high-velocity escapers in this case could be compensated by an order of magnitude larger population of clusters containing 50 $M_{\odot}$ stars (see Section 2).

Our explanation for the origin of high-velocity runaway stars requires a very dense stellar environment of the order of $10^6 - 10^7$ stars pc$^{-3}$ (see Paper I). The role of this environment is three-fold. First, it makes possible the runaway merging process, resulting in the formation of VMSs. Second, it provides suitable conditions for production of tight binaries via the tidal capture process and hardens the existing binaries, thereby increasing the probability of energetic three-body encounters. Third, it ensures that the three-body dynamical encounters are frequent, i.e. the production rate of high-velocity escapers could be high. We caution, however, that whether or not such high densities exist in the cores of star clusters remains unclear to date (see Section 2 and cf. Paper I). This and numerous uncertainties about the initial conditions and early evolution of young star clusters precludes us from making any estimates of the production rate of high-velocity escapers (cf. Paper I).

In Paper I, we suggested that some extremely high-velocity NSs could be the remnants of hypervelocity massive stars ejected via strong dynamical three- or four-body interactions in the cores of YMSCs (i.e. the origin of these NSs should not necessarily be connected with asymmetric supernova explosions). Our suggestion was based on the fact that one of the HVSs known at that time, HE 0437$-$5439, is massive enough ($\gtrsim 9 M_{\odot}$; Przybilla et al. 2008a) to explode as a type II supernova and to leave behind a high-velocity NS. It is important to note that the time of flight of this star from the Galactic Centre exceeds the lifetime of the star and therefore the extremely high peculiar velocity of HE 0437$-$5439 cannot be attributed to the dynamical processes involving the supermassive black hole in the Galactic Centre. The most likely birth place of this HVS is one of the YMSCs in the Large Magellanic Cloud (Gualandris & Portegies Zwart 2007; cf. Przybilla et al. 2008a; Bonanos et al. 2008; see however Perets 2008). Recently, an even more massive ($\gtrsim 11 \pm 1 M_{\odot}$) HVS, HD 271791, was discovered (Heber et al. 2008; see also Carozzi 1974; Kilkenny & Stone 1988) whose birth place cannot be associated with the Galactic Centre. HD 271791 is the only HVS with measured proper motion and all measurements indicate that this star originated in the periphery of the Galactic disk (Heber et al. 2008). Thus, the high peculiar velocity of HD 271791 cannot be attributed to the ejection mechanism involving the supermassive black hole in the Galactic Centre. Przybilla et al. (2008b) proposed that HD 271791 was a member of a massive close binary system disrupted in an asymmetric supernova explosion and that the secondary star (HD 271791) was released at its orbital velocity ($\sim 400$ km s$^{-1}$) in the direction of Galactic rotation (which allowed them to explain the Galactic rest-frame velocity of HD 271791, provided that it is on the low end of the observed range 530 – 920 km s$^{-1}$). One can show, however, that to explain the high space velocity of HD 271791 within the framework of the binary-supernova scenario, the stellar remnant of the supernova explosion [a $\gtrsim 10 M_{\odot}$ black hole, according to Przybilla et al. (2008b)] should receive at birth an unrealistically large kick velocity of 750 – 1200 km s$^{-1}$ (Gvaramadze 2009). We therefore believe that the more likely origin of the peculiar velocity of HD 271791 (and other halo early B-type stars; e.g. Rampeck et al. 2001; Martin 2006) is through the dynamical processes discussed in the present paper and in Paper I.

The same dynamical processes could also be responsible for the origin of early B-type stars observed in the halos of nearby galaxies (e.g. Comerón, Gómez & Torra 2003). We speculate that these stars can meet and ionize the cloudlets of cold gas on their way through the halo and suggest that the so-called extraplanar HII regions (e.g. Tüllmann et al. 2003) could be the Strömgren zones produced by high-velocity runaway OB stars (cf. Gvaramadze & Bomans 2008a). Our suggestion could be supported by the fact that the $H_{\alpha}$-luminosities of two extraplanar HII regions in the galaxy NGC 55 (located at $\approx 0.8$ and 1.5 kpc from the galactic plane) are consistent with the possibility that the ionizing sources of these objects are single B0 or O9.5 stars (Tüllmann et al. 2003).

High-velocity early B-type stars ejected at large angles to the Galactic plane end their lives in the halo and thereby contribute to the population of halo NSs. A possible example of a NS formed in the halo is the high Galactic latitude compact X-ray source 1RXS J141256.0+792204. This object has a high X-ray to optical flux ratio ($> 8700$), typical of isolated NSs (Rutledge, Fox & Shevchuk 2008). If 1RXS J141256.0+792204 is indeed an isolated NS, then its distance from the Sun is $\approx 8.4$ kpc, that corresponds to the distance $z \approx 5.1$ kpc from the Galactic plane (Rutledge et al. 2008). The surface temperature of 1RXS J141256.0+792204 (inferred from modelling its spectrum as thermal blackbody) suggests that this NS should be $\gtrsim 10^6$ yr old, provided that its cooling follows the standard cooling curves. If one assumes that the NS was born near the Galactic plane, then its peculiar velocity should be $> 5000$ km s$^{-1}$, which is too high to be realistic. To avoid this problem, Rutledge et al. (2008) suggested that either 1RXS J141256.0+792204 is not an isolated NS (i.e. the object is much closer to the Sun) or its cooling is non-standard (i.e. the NS is much older). In-
Instead, we suggest that 1RXS J141256.0+792204 could be the remnant of a supernova explosion of an early B-type star ejected from a YMSC in the Galactic disk with a velocity of $v_{\perp} \gtrsim 170$ km s$^{-1}$, where $t_{\ast} \lesssim 30$ Myr is the lifetime of the star. It is obvious that even in case of a symmetric supernova explosion the peculiar velocity of the stellar remnant (the NS) will be as large as that of its progenitor star (Paper I). We argue therefore that the proper motion of 1RXS J141256.0+792204 could be as small as $\sim 4$ mas yr$^{-1}$ [i.e. $\sim 20$ times less than that suggested by Rutledge et al. (2008)] or even smaller if the NS is near the apex of its trajectory. In the latter case, the direction of the proper motion of the NS could be arbitrary.

6 ACKNOWLEDGEMENTS

We are grateful to L.R. Yungelson for useful discussions. VVG acknowledges the Deutsche Forschungsgemeinschaft and the Deutscher Akademischer Austausch Dienst for partial financial support. AG is supported by grant NNX07AH15G from NASA. SPZ acknowledges partial financial support. On the origin of high-velocity runaway stars

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