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Hyperfast pulsars as the remnants of massive stars ejected from young star clusters

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ABSTRACT

Recent proper motion and parallax measurements for the pulsar PSR B1508+55 indicate a transverse velocity of $\sim 1\,100\,\mathrm{km\,s^{-1}}$, which exceeds earlier measurements for any neutron star. The spin-down characteristics of PSR B1508+55 are typical for a non-recycled pulsar, which implies that the velocity of the pulsar cannot have originated from the second supernova disruption of a massive binary system. The high velocity of PSR B1508+55 can be accounted for by assuming that it received a kick at birth or that the neutron star was accelerated after its formation in the supernova explosion. We propose an explanation for the origin of hyperfast neutron stars based on the hypothesis that they could be the remnants of a symmetric supernova explosion of a high-velocity massive star which attained its peculiar velocity (similar to that of the pulsar) in the course of a strong dynamical three- or four-body encounter in the core of dense young star cluster. To check this hypothesis we investigated three dynamical processes involving close encounters between: (i) two hard massive binaries, (ii) a hard binary and an intermediate-mass black hole, and (iii) a single star and a hard binary intermediate-mass black hole. We find that main-sequence O-type stars cannot be ejected from young massive star clusters with peculiar velocities high enough to explain the origin of hyperfast neutron stars, but lower mass main-sequence stars or the stripped helium cores of massive stars could be accelerated to hypervelocities. Our explanation for the origin of hyperfast pulsars requires a very dense stellar environment of the order of $10^6 - 10^7\,\mathrm{stars\,pc^{-3}}$). Although such high densities may exist during the core collapse of young massive star clusters, we caution that they have never been observed.

Key words: stellar dynamics – methods: N-body simulations – stars: individual: RX J0822-4300 – stars: neutron – pulsars: general – pulsars: individual: B1508+55.

1 INTRODUCTION

It has been known for a long time that the typical peculiar space velocities of pulsars are an order of magnitude larger that those of their progenitors – the massive stars (e.g. Gott, Gunn & Ostriker 1970). Subsequent proper motion measurements for pulsars suggested that some of them could be very fast objects, with peculiar speeds of up to $\sim 1\,000\,\mathrm{km\,s^{-1}}$ (e.g. Chatterjee & Cordes 2004; Hobbs et al. 2005). Two mechanisms have been proposed for the origin of high-velocity pulsars. The first one involves the disruption of tight (semidetached) massive binary systems following the second (symmetric) supernova explosion (e.g. Blaauw 1961; Iben & Tutukov 1996). This mechanism, however, cannot produce velocities in excess of $\sim 700\,\mathrm{km\,s^{-1}}$ (Portegies Zwart & van den Heuvel 1999). Moreover, the high-velocity pulsars formed in this way are the remnants of the first supernova explosion and therefore should be *recycled*, i.e. their spin characteristics should be significantly affected by the stellar wind of the companion star – the progenitor of the second supernova (cf. Chatterjee et al. 2005). The second mechanism relies on a natal kick (caused by the asymmetry of the supernova explosion; e.g. Shklovskii 1970; Dewey & Cordes 1987) or on a post-natal acceleration (caused by the asymmetric electromagnetic or neutrino emission from the

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newborn pulsar; e.g. Tademaru & Harrison 1975; Chugai 1984). In principle, this mechanism can produce solitary high-velocity pulsars with ordinary spin-down characteristics, i.e. non-recycled pulsars (e.g. Scheck et al. 2006). Thus, detection of non-recycled pulsars moving with a velocity $\gtrsim 1\,000\,\mathrm{km\,s^{-1}}$ would suggest that the mechanism involving the binary disruption by the supernova explosion does not apply to all cases. In the following we refer to pulsars (neutron stars) moving with velocities of $\gtrsim 1\,000\,\mathrm{km\,s^{-1}}$ as 'hyperfast pulsars' (a term introduced by Chatterjee et al. 2005).

Until recently the best candidates for hyperfast pulsars were PSR B2224+65 (associated with the well-known Guitar Nebula; Chatterjee & Cordes 2004) and PSR B2011+38 (see Hobbs et al. 2005 and references therein), whose peculiar velocities (both $\sim 1\,500\,\mathrm{km\,s^{-1}}$) were inferred on the basis of proper motion measurements and dispersion measure distance estimates. The uncertainties associated with the distance estimates, however, leave a possibility that these velocities are overestimated. Recent proper motion and parallax measurements for the pulsar PSR B1508+55 gave the first example of a high velocity ($1\,083^{+103}_{-90}\,\mathrm{km\,s^{-1}}$) directly measured for a (non-recycled) pulsar (Chatterjee et al. 2005). This result proved the existence of a population of hyperfast neutron stars, and implies that the peculiar velocity of PSR B1508+55 cannot be solely due to the disruption of a tight massive binary system. A possible way to account for the high velocity is to assume that at least part of this velocity is due to a natal kick or a post-natal acceleration (Chatterjee et al. 2005).

In this paper, we propose an alternative explanation for the origin of hyperfast pulsars (cf. Gvaramadze 2007). We suggest that PSR B1508+55 (as well as other hyperfast neutron stars[1]) could be the remnant of a symmetric supernova explosion of a high-velocity massive star (or its helium core) which attained its peculiar velocity (similar to that of the pulsar) in the course of a strong three- or four-body dynamical encounter in the core of the parent young massive star cluster (YMSC).

Our suggestion is based on the fact that massive ($\geqslant 10^4\,\mathrm{M_\odot}$) star clusters are still forming in the disk of the Milky Way (see Sect. 3) and on the hypothesis that the cores of some YMSCs harbour intermediate-mass black holes (IMBHs), i.e. black holes (BHs) with masses ranging from ~ 100 to $\sim 10^4\,\mathrm{M_\odot}$ (see Sect. 3). Our suggestion also requires the existence of very dense stellar environment ($\sim 10^6 - 10^7\,\mathrm{pc^{-3}}$) to ensure that three- or four-body dynamical encounters are frequent (see Sect. 4). Although such high densities may exist during the core collapse of YMSCs, we caution that they have never been observed (we discuss this problem in Sect. 3). In Sect. 2, we briefly discuss the mechanisms for the origin of hypervelocity stars, the recently discovered class of stars moving with a speed of $\sim 1\,000\,\mathrm{km\,s^{-1}}$, and suggest that similar mechanisms (although acting in a different environment) could be responsible for the origin of some of the hyperfast neutron stars. In Sect. 4, we estimate the maximum possible velocities of high-velocity escapers produced by various dynamical processes in the cores of YMSCs. In Sect. 5, we compare these estimates with results from numerical simulations while in Sect. 6 we discuss the ability of these processes to explain the origin of hyperfast pulsars.

2 HYPERVELOCITY STARS AND MECHANISMS FOR THEIR PRODUCTION

The discovery of high velocity pulsar PSR B1508+55 (Chatterjee et al. 2005) coincided with the discovery of the hypervelocity stars[2] (Brown et al. 2005; Edelmann et al 2005; Hirsch et al. 2005). The existence of the latter was predicted by Hills (1988), who showed that a close encounter between a tight binary system and the supermassive BH in the Galactic centre (e.g. Ghez et al. 2003; Schödel et al. 2003) could be responsible for the ejection of one of the binary components with a velocity of up to several $1\,000\,\mathrm{km\,s^{-1}}$ (see also Hills 1991). Yu & Tremaine (2003) proposed two additional possible mechanisms for the production of hypervelocity stars. The first one involves close encounters between two single stars in the vicinity of a supermassive BH (the probability of this process, however, is very low and we will not discuss it further) while the second one is based on the interaction between a single star and a putative binary BH in the Galactic centre (e.g. Hansen & Milosavljević 2003).

The discovery of hypervelocity stars (Brown et al. 2005; Edelmann et al. 2005; Hirsch et al. 2005; Brown et al. 2006) provides support for models of ejection mechanisms involving dynamical processes in the vicinity of the supermassive BH (Gualandris, Portegies Zwart & Sipior 2005; Baumgardt, Gualandris & Portegies Zwart 2006; Bromley et al. 2006), and now it is widely believed that these high-velocity objects originate in the Galactic Centre (see, however, Edelmann et al. 2005; see also Sect. 6). It is, therefore, possible that some hyperfast pulsars (or their progenitor stars) were also ejected from the Galactic Centre. For example, one of the hypervelocity stars is a early B-type star of mass $\sim 8\,\mathrm{M_\odot}$ (Edelmann et al. 2005), so that this star will end its evolution in a Type II supernova leading to the production of a hyperfast neutron star. The proper motion measured for PSR B1508+55, however, indicates that this pulsar was born in the Galactic disk near the Cyg OB associations (Chatterjee et al. 2005), i.e. its origin cannot be associated with the Galactic Centre[3]. The proper motions of PSR B2224+65 and PSR B2011+38 also suggest that these pulsars were born far from the Galactic Centre. Therefore, one should look for other places in our Galaxy where one can find a sufficiently massive BH and where the number density of the local stellar population is high enough to ensure that close encounters between stars and the BH are frequent. Note that the characteristic

[1] Another example of a hyperfast neutron star was recently reported by Hui & Becker (2006) and Winkler & Petre (2007). Their proper motion measurements for the central compact object RX J0822-4300 in the supernova remnant (SNR) Puppis A suggest that the peculiar velocity of this neutron star could be as large as $\sim 1\,000 - 1\,500\,\mathrm{km\,s^{-1}}$, provided that the distance to these objects is ~ 2 kpc.

[2] In the following we use the term 'hypervelocity' [introduced by Hills (1988)] to designate the ordinary stars moving with a peculiar speed of $\gtrsim 1\,000\,\mathrm{km\,s^{-1}}$ while for neutron stars we reserve the term 'hyperfast' (see Sect. 1).

[3] For a nice picture illustrating the trajectory of the pulsar on the sky see `http://www.jb.man.ac.uk/news/fastestpulsar.html`

age of the above mentioned pulsars (ranging from ~ 0.4 to ~ 2.3 Myr) implies that at least these three pulsars were not ejected from the dense cores of globular clusters (whose typical age is $\gtrsim$ Gyr) and point to the more plausible cites of their origin – the YMSCs.

We note that with the YMSCs could be associated another important channel for production of high-velocity stars, namely through close dynamical encounters between stars in their cores. This process constitutes the base of the dynamical-ejection scenario proposed by Poveda, Ruiz & Allen (1967) to explain the origin of runaway OB stars. The most effective path for production of high-velocity stars by stellar encounters is through interaction between two hard binaries (e.g. Mikkola 1983; Leonard & Duncan 1988, 1990). This process and processes involving dynamical encounters with IMBHs are discussed in detail in Sect. 4.

3 YOUNG MASSIVE STAR CLUSTERS

Recent discovery of young ($\leqslant 10^7$ yr) and massive ($\geqslant 10^4\,\mathrm{M}_\odot$) star clusters (Borissova et al. 2006; Figer et al. 2006; Davies et al. 2007) accompanied by upward revision of masses of the already known star clusters (Knödlseder 2000; Clark et al. 2005; Homeier & Alves 2005; Santos, Bonatto & Bica 2005; Ascenso et al. 2007; Wolff et al. 2007; Harayama, Eisenhauer & Martins 2008) increased the number of YMSCs in the Galactic disk to $\gtrsim 10$. All but one of these YMSCs are located on the near side of the Galaxy. Taken together these facts suggest that YMSCs are more numerous than it was known hitherto and that many of them are still hidden from observers by the obscuring material in the Galactic plane (Knödlseder et al. 2002; Hanson 2003).

Let us estimate the number of YMSCs formed in the Galactic disk during the last 3×10^7 yr (the lifetime of a star with mass of 8 $\mathrm{M}_\odot$ – the minimum mass of single stars producing neutron stars). We choose this time-span since we assume that the currently observed hyperfast neutron stars could be the descendants of either a 8 $\mathrm{M}_\odot$ hypervelocity star, ejected at the very beginning of its life, or a stripped helium core of the more massive star, attained its peculiar velocity only recently (see Sect. 4). Assuming that the star formation rate (SFR) of $\sim 7-10\times10^{-4}\ \mathrm{M}_\odot\,\mathrm{yr}^{-1}\mathrm{kpc}^{-2}$, derived by Lada & Lada (2003) for embedded star clusters in the solar neighbourhood, is representative for the Galactic disk as a whole (cf. Larsen 2006), one has that $\simeq 6.6-9.4\times10^6\ \mathrm{M}_\odot$ were formed within a circle of 10 kpc. For a power-law cluster initial mass function with a slope =2 (e.g. Lada & Lada 2003) and 50 $\mathrm{M}_\odot < \mathrm{M}_{\rm cl} < 10^6\ \mathrm{M}_\odot$, one has $\sim 70-100$ YMSCs with a mass $M_{\rm cl}\geqslant 10^4\,M_\odot$. This estimate is in good agreement with that derived by Knödlseder et al. (2002) using different arguments (see also Madhusudhan et al. 2007), and exceeds by a factor of 2-3 the figures derived by Larsen (2006). The discrepancy with Larsen (2006) originates due to the somewhat different input parameters adopted in his paper. For example, he uses a factor of 1.3-1.9 smaller SFR, derived by Lamers et al. (2006) for *bound* star clusters in the solar neighbourhood, and assumes a larger upper cut-off of cluster masses, $M_{\rm cl} < 10^7\ \mathrm{M}_\odot$. We prefere to use the SFR given in Lada & Lada (2003) to account for the fact that many embedded star clusters independently of their mass became dissolved within the first $\sim 10^7$ yr of their evolution (a possible example of such a stellar system is the Cyg OB2 association).

To the YMSCs resided in the disk one should add the ones formed in the central part of the Galaxy. Theoretical models of evolution and observability of star clusters within 200 pc of the Galactic Centre suggest that this region could easily harbour ~ 50 YMSCs with properties similar to those of the well-known Arches and Quintuplet systems (Portegies Zwart et al. 2001a, 2002). Recent discovery with 2MASS of a large number of cluster candidates in direction to the Galactic Centre (Dutra et al. 2003, and references therein) supports this suggestion, although follow-up work is required to confirm the nature of these objects.

The dynamical evolution of YMSCs is dominated by massive stars, which sink to the cluster centre on a time scale $t_{\rm cc}\sim 0.1-0.2\,t_{\rm rh}$, which typically is smaller than the main-sequence lifetime of these stars. Interestingly, the dynamical friction time-scale is independent of cluster mass, its size and density profile (e.g. Portegies Zwart & McMillan 2002; Gürkan, Freitag & Rasio 2004), where $t_{\rm rh}$ is the half-mass relaxation time-scale given by (Spitzer 1987)

$$t_{\rm rh}\simeq\frac{0.14M_{\rm cl}^{1/2}r_{\rm h}^{3/2}}{G^{1/2}\langle m\rangle\ln\Lambda}\,. \quad (1)$$

Here, $M_{\rm cl}$ and $r_{\rm h}$ are the total mass and the characteristic (half-mass) radius of the cluster, G is the gravitational constant, $\langle m\rangle = M_{\rm cl}/N_{\rm cl}$ is the mean stellar mass, $N_{\rm cl}$ is the number of stars in the cluster and $\ln\Lambda\simeq 10$ is the Coulomb logarithm. For $t_{\rm cc}=0.15\,t_{\rm rh}$ and using Eq. (1), one has

$$t_{\rm cc}\simeq 3\times10^6\,{\rm yr}\left(\frac{M_{\rm cl}}{10^4\,\mathrm{M}_\odot}\right)^{1/2}\left(\frac{r_{\rm h}}{1\,{\rm pc}}\right)^{3/2} \times\left(\frac{\langle m\rangle}{\mathrm{M}_\odot}\right)^{-1}\left(\frac{\ln\Lambda}{10}\right)^{-1}. \quad (2)$$

As a result, mass segregation drives YMSCs to core collapse. The consequential increase in the central density may results in runaway stellar collisions during which a massive star continues to grow in mass due to repeated bombardment to a very massive star (VMS) (Portegies Zwart et al. 1999; Portegies Zwart & McMillan 2002; Gürkan et al. 2004), provided that core collapse is completed before the most massive stars in the cluster explode as supernovae, i.e. $t_{\rm cc}\lesssim 3\times10^6$ yr. On this time-scale essentially all massive ($\gtrsim 20\,\mathrm{M}_\odot$) stars in YMSCs segregate to the cluster core. For $M_{\rm cl} = 10^4-10^5\,\mathrm{M}_\odot$ and assuming a $0.2-120\,\mathrm{M}_\odot$ Salpeter initial mass function (in this case $\langle m\rangle\simeq 0.7\,\mathrm{M}_\odot$ and $N_{\rm cl}\simeq 1.5\times10^4-10^5$), one has from Eq. (2) that the runaway process occurs in YMSCs with $r_{\rm h}\lesssim 0.3-0.8\,$pc. The majority of young and massive stars appear to reside in dense embedded clusters with a characteristic radius of $\lesssim 1$ pc, which is independent of mass (Kroupa & Boily 2002). It is therefore not unconceivable that an appreciable fraction of YMSCs evolve through a collisional stage. The maximum observed density in the cores of YMSCs [e.g. NGC 3603 (Harayama et al. 2007), Arches (Figer et al. 1999)] is smaller than that required for runaway collisions to occur[4]. Whether

[4] Note, however, that the Arches cluster is not in a state of core collapse, but rather on its way towards this (Portegies Zwart et al. 2007).

or not the discrepancy between the observations and the theory is the result of the small number of known YMSCs remains unclear to date. The consequences of the collisional stage are profound, and we assume here that it may exist at least in some YMSCs.

The VMS formed through runaway collisions will ultimately collapse to a BH. One of the main questions here is wheather or not the BH will be massive or not. The mass of the IMBH formed in this way could be as large as $\sim 1\,000\,\mathrm{M}_\odot$ for $M_{\rm cl} \sim 10^5\,\mathrm{M}_\odot$ (Portegies Zwart et al. 2004), but if the mass loss in the collision product is as high as argued in some calculations (Belkus, Van Bever & Vanbeveren, 2007; Yungelson 2007; Yungelson et al 2008) the final BH may be $\lesssim 100\,\mathrm{M}_\odot$.

It is also possible that IMBHs of mass $\sim 10^3 - 10^4\,\mathrm{M}_\odot$ are the descendants of old globular clusters disrupted by the tidal field of the Galactic disk or that they are formed from the core collapse of massive population III stars. Later they could be captured gravitationally by molecular clouds or by the already existing young star clusters. In the first case, the IMBH initiates star formation in the cloud and, therefore, resides at the centre of the newly formed star cluster (Miller & Hamilton 2002), while in the second case the IMBH rapidly sinks to the centre of the cluster due to the dynamical friction (Miller & Colbert 2004).

4 ORIGIN OF HYPERFAST PULSARS

We now consider the possibility that dynamical processes in the cores of YMSCs could be responsible for ejection of hypervelocity massive stars or their helium cores, whose subsequent collapse and (symmetric) supernova explosion result in the origin of hyperfast neutron stars (pulsars). In the following subsections, we estimate the upper limits for the ejection speed produced by encounters involving: (i) two hard binaries, (ii) a hard binary and an IMBH and (iii) a single star and a hard binary IMBH.

4.1 Binary-binary encounters

In Sect. 2, we mentioned that the most effective path for production of high-velocity stars by stellar encounters is through interaction between two hard binaries, either the tidally captured or the primordial ones. Note that the tidal binaries are very hard by definition since the semimajor axes of their circularized orbits are at most a few stellar radii (e.g. Lee & Ostriker 1986; McMillan, McDermott & Taam 1987). Therefore, it is likely that collisions involving tidal binaries play a dominant role in production of the fastest runaway stars. It is also important to note that due to the mass segregation, the cores of YMSCs are over-represented by massive stars, so that most of tidally captured binaries should be the massive ones. Moreover, one can expect that almost all tidal binaries would be massive if the most massive stars are formed near the centres of their parent clusters (e.g. Bonnell, Bate & Zinnicker 1998; cf. Kroupa 2001).

Numerical simulations by Leonard & Duncan (1988, 1990) showed that the typical velocities at infinity (i.e. well after ejection) of runaway stars (produced in the course of binary-binary collisions) are similar to the orbital velocities of the binary components while the velocities of some escapers can be twice as large. Moreover, the maximum possible velocity attained by the lightest member of the binaries involved in the interaction (e.g. the helium core of a massive star or a early-type B star) can be as large as the escape velocity from the surface of the most massive star in the binaries (Leonard 1991). For the upper main-sequence stars with the mass-radius relationship (Habets & Heintze 1981)

$$r_{\rm MS} = 0.8 \left(\frac{m_{\rm MS}}{\mathrm{M}_\odot}\right)^{0.7} \mathrm{R}_\odot \,, \tag{3}$$

where $r_{\rm MS}$ and $m_{\rm MS}$ are the stellar radius and mass, the maximum possible velocity at infinity of ejected stars is a weak function of $m_{\rm MS}$, $V_{\infty,\rm MS}^{\rm max} \simeq 700\,{\rm km\,s}^{-1}(m_{\rm MS}/\,\mathrm{M}_\odot)^{0.15}$ and could be as large as $\sim 1\,400\,{\rm km\,s}^{-1}$ (cf. Leonard 1991). The ejection velocity could be even larger if the binaries involved in the interaction are already evolved through a common-envelope phase and consist of two helium cores. In this case,

$$r_{\rm He} \simeq 0.2 \left(\frac{m_{\rm He}}{\mathrm{M}_\odot}\right)^{0.65} \mathrm{R}_\odot \,, \tag{4}$$

where $r_{\rm He}$ and $m_{\rm He}$ are the radius and the mass of a helium core (Tauris & van den Heuvel 2006), so that $V_{\infty,\rm He}^{\rm max} \simeq 1\,400\,{\rm km\,s}^{-1}(m_{\rm He}/\,\mathrm{M}_\odot)^{0.175} \sim 2\,300\,{\rm km\,s}^{-1}$.

Scattering experiments by Leonard (1991) showed that only a small fraction (less than 1 per cent) of runaway stars released in the course of binary-binary collisions can attain the maximum possible velocity. So that, to produce at least one hypervelocity (massive) star during the first several Myr of cluster evolution, the collisional time-scale for binaries in the cluster core should be $\lesssim 10^4$ yr. The total rate of binary-binary encounters in the core of radius $r_{\rm c}$ is

$$\Gamma \sim \frac{1}{2} N_{\rm b} n_{\rm b} S_{\rm bb} V_{\rm rel} \,, \tag{5}$$

where $N_{\rm b} \simeq (4\pi/3) r_{\rm c}^3 n_{\rm b}$, $n_{\rm b}$ is the number density of binaries, $V_{\rm rel}$ is the relative velocity of approach of the binaries at infinity,

$$S_{\rm bb} \sim \frac{2\pi G(m_1+m_2)a}{V_{\rm rel}^2} \tag{6}$$

is the gravitationally focused cross section (Leonard 1989), and a is the binary semimajor axis. For the sake of simplicity, we consider the equal-mass and equal-energy binaries, and assume that one of the binary components is a 40 $\mathrm{M}_\odot$ main-sequence star while its companion is a He core of mass of 5 $\mathrm{M}_\odot$. From Eqs. (5) and (6), one has the mean time between binary-binary collisions (cf. Leonard 1989)

$$t_{\rm bb} \sim 8\times 10^3\,{\rm yr} \left(\frac{r_{\rm c}}{0.01\,{\rm pc}}\right)^{-3} \left(\frac{n_{\rm b}}{10^7\,{\rm pc}^{-3}}\right)^{-2} \times \left(\frac{V_{\rm rel}}{5\,{\rm km\,s}^{-1}}\right) \left(\frac{m_1}{40\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{a}{50\,\mathrm{R}_\odot}\right)^{-1} . \tag{7}$$

It follows from Eq. (7) that the collisional time-scale is short enough (i.e. $\lesssim 10^4$ yr) if more than 10 massive binaries exist in the core of radius ~ 0.01 pc. Assuming that almost all stars more massive than $\sim 20\,\mathrm{M}_\odot$ are segregated to the cluster core and exchanged in binaries, one has the minimum mass of the YMSC of $\sim 10^4\,\mathrm{M}_\odot$.

The recent discovery (Muno et al. 2006) of an anomalous X-ray pulsar in the $(4 \pm 1) \times 10^6$-yr old massive ($\gtrsim 10^5\,\mathrm{M}_\odot$) Galactic star cluster Westerlund 1 (Clark et al. 2005) implies that the progenitor of this neutron star was a star with a zero-age main-sequence mass $\gtrsim 40\,\mathrm{M}_\odot$ (cf. Vanbeveren, Van Rensbergen & De Loore 1998). Therefore, one can expect that the hypervelocity helium cores of massive stars ejected from the cores of YMSCs during the first several Myr of cluster evolution will end their lives as hyperfast neutron stars (pulsars).

4.2 Exchange encounters between binary stars and an IMBH

Let us assume that the core of a YMSC harbours an IMBH of mass $M_{\rm BH} = 100 - 1\,000\,\mathrm{M}_\odot$, formed either through a runaway sequence of mergers or from the core collapse of a massive population III star (see Sect. 3).

A close encounter with the IMBH results in the tidal breakup of the binary, after which one of the binary components becomes bound to the IMBH while the second one (usually the least massive star) is ejected with a high speed, given by (Hills 1988; Yu & Tremaine 2003):

$$V_\infty \sim \left(\frac{GM_{\rm BH}}{r_{\rm t}}\right)^{1/4} \left[\frac{4Gm_1^2}{a(m_1+m_2)}\right]^{1/4}, \quad (8)$$

where

$$r_{\rm t} \sim \left(\frac{M_{\rm BH}}{m_1+m_2}\right)^{1/3} a \quad (9)$$

is the tidal radius and m_1 and m_2 are, respectively, the masses of the bound and ejected stars ($m_1 > m_2$). The fastest stars produced in this exchange process come from encounters involving the tightest binary systems (e.g. tidal binaries), since the tighter the binary the closer it can approach to the IMBH before tidal breakup. Combining Eqs. (8) and (9), one has

$$V_\infty \sim \left(\frac{M_{\rm BH}}{m_1+m_2}\right)^{1/6} \left(\frac{2Gm_1}{a}\right)^{1/2}. \quad (10)$$

For a binary having a massive main-sequence component of mass $m_1 \gg m_2$ and $a \simeq 2.5 r_{1,\rm MS}$ (cf. Statler, Ostriker & Cohn 1987), one has from Eqs. (10) and (3)

$$V_\infty \sim 440\,{\rm km\,s^{-1}} \left(\frac{M_{\rm BH}}{\mathrm{M}_\odot}\right)^{1/6} \left(\frac{m_1}{\mathrm{M}_\odot}\right)^{-1/60}. \quad (11)$$

For $M_{\rm BH} = 100 - 1\,000\,\mathrm{M}_\odot$ and $m_1 = 40 - 100\,\mathrm{M}_\odot$, one has from Eq. (11) that the low-mass binary component (e.g. the helium core of a massive star or a B star) can be ejected with a speed $V_\infty \sim 900 - 1\,300\,{\rm km\,s^{-1}}$. The ejection velocity could be somewhat higher if the binary involved in the encounter consists of two helium cores (cf. Sect. 4.1). For example, assuming that $m_{1,\rm He} = 10\,\mathrm{M}_\odot$ and $m_{2,\rm He} = 5\,\mathrm{M}_\odot$, and $a \simeq 5 - 10\,\mathrm{R}_\odot$, one has $v_\infty \simeq 850 - 1\,760\,{\rm km\,s^{-1}}$. Note that the weak dependence of V_∞ on $M_{\rm BH}$ implies that the hypervelocity helium cores can be produced by exchange encounters with stellar mass (i.e. $\sim 20\,\mathrm{M}_\odot$) BHs.

The mean collision time between binary stars and an IMBH is (e.g. Binney & Tremaine 1987)

$$t_{\rm coll} \sim 2\times 10^5\,{\rm yr} \left(\frac{n_{\rm b}}{10^7\,{\rm pc^{-3}}}\right)^{-1} \left(\frac{V_{\rm rel}}{5\,{\rm km\,s^{-1}}}\right) \times \left(\frac{M_{\rm BH}}{100\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{a}{30\,\mathrm{R}_\odot}\right)^{-1}. \quad (12)$$

It follows from Eq. (12) that during the several Myr of cluster evolution one can expect at least a dozen of close encounters involving binaries with $a \geqslant 30\,\mathrm{R}_\odot$. Here, we assume a central density in the cluster which exceeds the observed values. Although such high density may exist during core collapse, we note that the well-studied YMSCs in the Galaxy are not in this stage of their evolution.

4.3 Encounters between single stars and a binary IMBH

Numerical simulations by Gürkan, Fregeau & Rasio (2006) showed that runaway collisions and mergers of massive stars in YMSCs with initial binary fraction larger than ~ 10 per cent could result in the origin of two VMSs. The subsequent supernova explosions of these VMSs produce two IMBH, which ultimately exchange into a binary (Gürkan et al. 2006; cf. Fregeau et al. 2006).

The IMBH binary (IMBHB) gradually hardens due to the interaction with stars in the cluster's core. When the binary separation reduces to $a \lesssim a_{\rm h} \simeq G\mu/4\sigma^2$, where $\mu = M_1 M_2/(M_1+M_2)$ and M_1 and M_2 are the component masses of the IMBHB ($M_1 > M_2$), most of stars passing in the vicinity ($\sim a$) of the IMBHB are expelled from the core at high velocity. The average ejection speed attained by the escapers is (Yu & Tremaine 2003)

$$\langle V_\infty \rangle \sim \sqrt{\frac{3.2 G M_1 M_2}{(M_1+M_2)a}}. \quad (13)$$

Some escapers, however, can reach much higher velocities. For an IMBHB with mass ratio of ~ 1 the maximum ejection velocity is

$$V_\infty^{\max} \sim 1.5\, V_{\rm bin}, \quad (14)$$

where $V_{\rm bin} = [G(M_1+M_2)/a]^{1/2}$ is the relative velocity of the binary components if their orbits are circular (Tutukov & Fedorova 2005). It is clear that the smaller a the larger $\langle V_\infty \rangle$ and $V_\infty^{\max}$. There are, however, two constraints on the minimum value of a, which limit the maximum possible ejection velocity.

First, a should be sufficiently large to prevent the tidal breakup of stars passing through the IMBHB, i.e. $a \gtrsim [(M_1/m)^{1/3} + (M_2/m)^{1/3}]r$, where r is the radius of the star. For r given by Eq. (3), one has

$$a \gtrsim 0.8 \left[\left(\frac{M_1}{\mathrm{M}_\odot}\right)^{1/3} + \left(\frac{M_2}{\mathrm{M}_\odot}\right)^{1/3}\right] \left(\frac{m}{\mathrm{M}_\odot}\right)^{11/30} \mathrm{R}_\odot \quad (15)$$

(for the sake of simplicity we assume a circular binary orbit). It follows from Eqs. (13)-(15) that the smaller the mass of the star the larger velocity it, in principle, can attain; note also that inequality (15) sets an upper limit on the mass of a main-sequence star that can be ejected by a shrinking IMBHB. For a main-sequence star of mass $m = 8\,\mathrm{M}_\odot$ (the minimum mass of single stars producing neutron stars) and assuming that $M_1 = 500\,\mathrm{M}_\odot$ and $M_2 = 300\,\mathrm{M}_\odot$, one has from Eqs. (15), (13) and (14) that

$a \gtrsim 30\,\mathrm{R}_\odot$, $\langle V_\infty \rangle \sim 1950\,\mathrm{km\,s^{-1}}$ and

$$V_\infty^{\max} \simeq 3\,380\,\mathrm{km\,s^{-1}} \left(\frac{\nu}{0.625}\right)^{-1/2} \left(\frac{M_1}{500\,\mathrm{M}_\odot}\right)^{1/2} \times \left(\frac{a}{30\,\mathrm{R}_\odot}\right)^{-1/2}, \qquad (16)$$

where $\nu = M_1/(M_1+M_2)$.

The maximum ejection velocity could be somewhat higher if one considers encounters involving massive post-main-sequence stars, either a blue supergiant or a bare helium core. In this case, a massive star can approach the IMBHB much closer than a main-sequence star. Although the blue supergiant star will lose its hydrogen envelope due to the tidal stripping, its helium core can pass within several $\mathrm{R}_\odot$ from one of the binary components without being disintegrated by the tidal force. To estimate the maximum possible velocity attained by the helium core, one should consider the second constraint on the binary separation. It follows from the requirement that the gravitational radiation time-scale of the shrinking IMBHB (Peter 1964),

$$t_{\rm GWR} \simeq 1\times 10^6\,\mathrm{yr} \left(\frac{\nu}{0.625}\right) \left(\frac{M_1}{500\,\mathrm{M}_\odot}\right)^{-2} \times \left(\frac{M_2}{300\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{a}{30\,\mathrm{R}_\odot}\right)^{4}, \qquad (17)$$

should be larger than the mean collision time,

$$t_{\rm coll} \sim 2.5\times 10^4\,\mathrm{yr} \left(\frac{n}{10^7\,\mathrm{pc^{-3}}}\right)^{-1} \left(\frac{V_{\rm rel}}{5\,\mathrm{km\,s^{-1}}}\right) \times \left(\frac{M_1+M_2}{800\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{a}{30\,\mathrm{R}_\odot}\right)^{-1}, \qquad (18)$$

that is, $a \gtrsim 15\,\mathrm{R}_\odot$. From Eq. (16), one has that a helium core passing through the IMBHB just before the latter merges due to the gravitational emission can attain a speed as large as $\sim 4\,780\,\mathrm{km\,s^{-1}}$.

5 N-BODY SIMULATIONS OF HYPERVELOCITY STARS

In this section, we perform numerical simulations of three-body scatterings with IMBHs, both single and in binaries, in order to obtain the velocity distributions for the ejected stars for the mechanisms described in Sects. 4.2 and 4.3. The simulations are carried out using the `sigma3` package, which is part of the STARLAB[5] software environment (McMillan & Hut 1996; Portegies Zwart et al. 2001b). For a detailed description of the set up of the scattering experiments see Gualandris et al. (2005).

5.1 Exchange encounters between binary stars and an IMBH

First, we focus on interactions in which a binary consisting of two $8\,\mathrm{M}_\odot$ main-sequence stars [with radii of $3.5\,\mathrm{R}_\odot$, see Eq. (3)] encounters a single IMBH of mass in the range

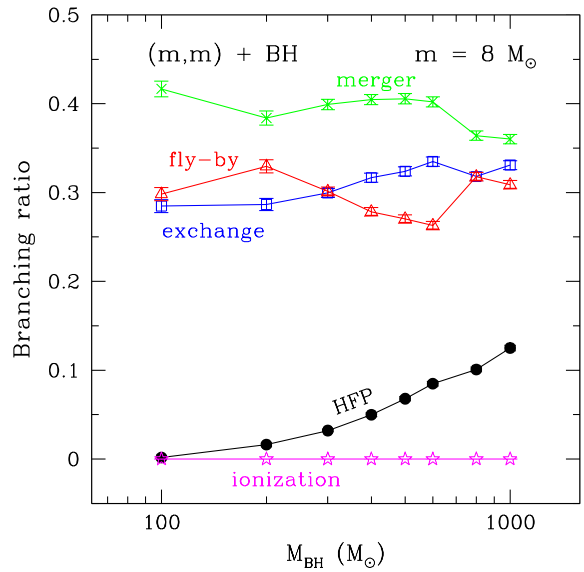

Figure 1. Branching ratio for the outcome of encounters between a binary star and a single IMBH as a function of the IMBH mass. The two binary components are assumed to be $8\,\mathrm{M}_\odot$ main-sequence stars and the semimajor axis is $a = 0.1$ au. The different outcomes are: merger (crosses), fly-bys (triangles), ionization (stars), exchange (squares) and the subset of exchange results with a high-velocity escaper ($V_\infty \geqslant 700\,\mathrm{km\,s^{-1}}$) (bullets). The error bars represent the formal (1σ) Poissonian uncertainty of the measurement.

$100 - 1\,000\,\mathrm{M}_\odot$. The relative velocity at infinity between the IMBH and the centre of mass of the binary is set to $5\,\mathrm{km\,s^{-1}}$, in accordance with typical dispersion velocities in YMSCs. The semimajor axis is $a = 0.1$ au to represent the case of the tightest binaries. In Fig. 1, we present the probability of different outcomes (branching ratios) as a function of the IMBH mass $M_{\rm BH}$. For each value of the IMBH mass, we perform a total of 2 000 scattering experiments, which result either in a fly-by, an exchange, or a merger of the components of the binary. Ionizations never take place as the binary is too hard to be dissociated by the IMBH (Heggie 1975). Mergers occur in a large fraction (∼40 per cent) of encounters due to the small orbital period of the binary star and mostly involve collisions between the binary components caused by perturbations from the IMBH. Exchange interactions occur in about 30 per cent of encounters, with a probability increasing with the IMBH mass. Since the binary components have equal masses, the probability of ejection for the two stars is equal in exchange encounters. During such encounters, one of the main-sequence stars is captured by the IMBH while the other star is ejected, possibly with high velocity. These encounters are the relevant ones for the production of hypervelocity stars. If the velocity of the ejected star exceeds $700\,\mathrm{km\,s^{-1}}$, we regard the star as a possible progenitor of a hyperfast pulsar (indicated with HFP in the figure). The figure shows that more massive IMBHs are more likely to eject stars with hypervelocities.

The distributions of velocities at infinity for the escaping stars are shown in Fig. 2 for three different values of the IMBH mass: $M_{\rm BH} = 100\,\mathrm{M}_\odot, 500\,\mathrm{M}_\odot$ and $1\,000\,\mathrm{M}_\odot$. In

[5] `http://www.manybody.org/manybody/starlab.html`

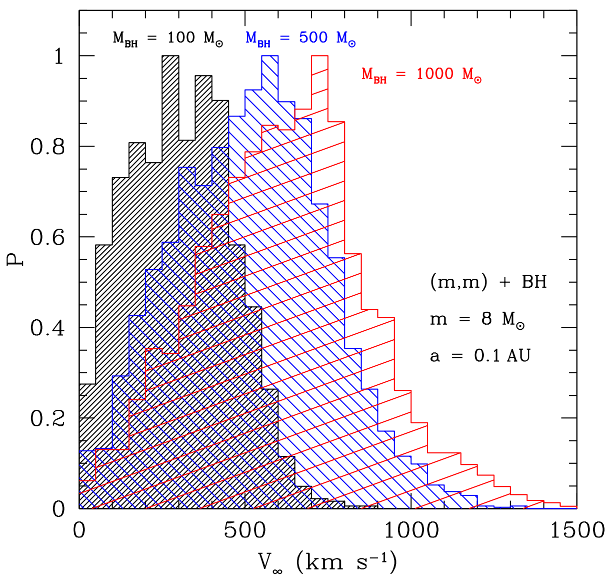

Figure 2. Velocity distributions at infinity for escaping stars in encounters between an equal mass ($m = 8\,\mathrm{M}_\odot$) binary star and a single IMBH for different values of the IMBH mass: $M_{\rm BH} = 100\,\mathrm{M}_\odot$ (left-hand panel), $500\,\mathrm{M}_\odot$ (middle panel), $1\,000\,\mathrm{M}_\odot$ (right-hand panel). The binary semimajor axis is $a = 0.1$ au.

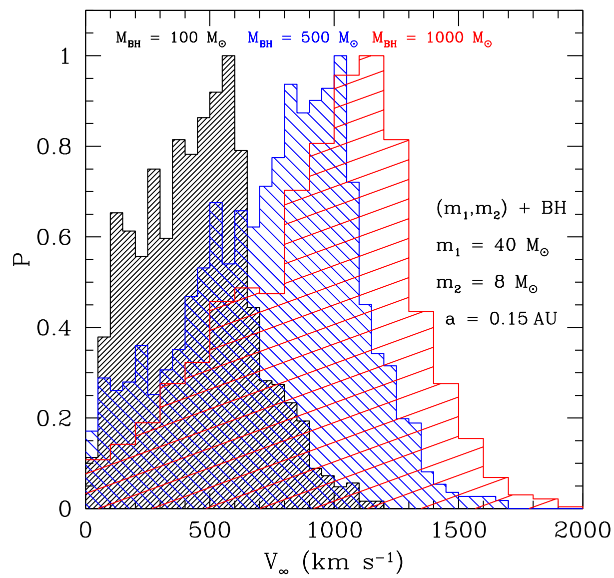

Figure 3. Velocity distributions at infinity for escaping stars in encounters between a binary consisting of a primary star with mass $m_1 = 40\,\mathrm{M}_\odot$ and a secondary star with mass $m_2 = 8\,\mathrm{M}_\odot$, and a single IMBH of mass $M_{\rm BH} = 100\,\mathrm{M}_\odot$ (left-hand panel), $500\,\mathrm{M}_\odot$ (middle panel), $1\,000\,\mathrm{M}_\odot$ (right-hand panel). For this case of unequal-mass binaries, we consider as escapers only the least massive stars (m_2). The binary semimajor axis is $a = 0.15$ au.

order to obtain stars with velocities $V_\infty \gtrsim 700\,\mathrm{km\,s^{-1}}$, an IMBH more massive than a few hundred solar masses is required. In the case of a $500\,\mathrm{M}_\odot$ IMBH, about 20 per cent of all exchanges result in an escape velocity $\geqslant 700\,\mathrm{km\,s^{-1}}$. The fraction increases to 40 per cent for the $1\,000\,\mathrm{M}_\odot$ IMBH. We note that even an IMBH of mass $M_{\rm BH} = 100\,\mathrm{M}_\odot$ can occasionally (in about 1 per cent of all exchanges) produce an escape velocity $\geqslant 700\,\mathrm{km\,s^{-1}}$.

In order to derive the probability of obtaining the largest possible recoil velocities (see Sect. 4.2), we perform additional scattering experiments with the following parameters: $m_1 = 40\,\mathrm{M}_\odot$, $m_2 = 8\,\mathrm{M}_\odot$ and $a = 0.15$ au. The velocity distributions for escapers are shown in Fig. 3 for three different values of the IMBH mass: $M_{\rm BH} = 100\,\mathrm{M}_\odot, 500\,\mathrm{M}_\odot$ and $1\,000\,\mathrm{M}_\odot$. The maximum velocity obtained for each set of parameters is consistent with the predictions derived in Sect. 4.2. The fraction of encounters resulting in velocities larger than $700\,\mathrm{km\,s^{-1}}$ increases from about 7 per cent for $M_{\rm BH} = 100\,\mathrm{M}_\odot$ to about 70 per cent for $M_{\rm BH} = 1\,000\,\mathrm{M}_\odot$.

The average velocity of escapers scales as $a^{-1/2}$, as can be seen in Fig. 4 and as is expected from Eq. (10). The figure shows the average recoil velocity of escapers (solid symbols) as a function of the initial binary semimajor axis for three different values of the IMBH mass $M_{\rm BH} = 100\,\mathrm{M}_\odot, 500\,\mathrm{M}_\odot$ and $1\,000\,\mathrm{M}_\odot$. The empty symbols indicate the velocity $V_{\rm max}$ for which 1 per cent of the encounters have $V_\infty > V_{\rm max}$. The average and the maximum velocities increase with the mass of the IMBH, as expected from energetic arguments.

In our systematic study of the effect of the initial semimajor axis of the interacting binary, we performed further scattering experiments adopting a homogeneous sampling in $\log a$. If the distribution of orbital separations in a star cluster is flat in $\log a$, like in the case of young star clusters

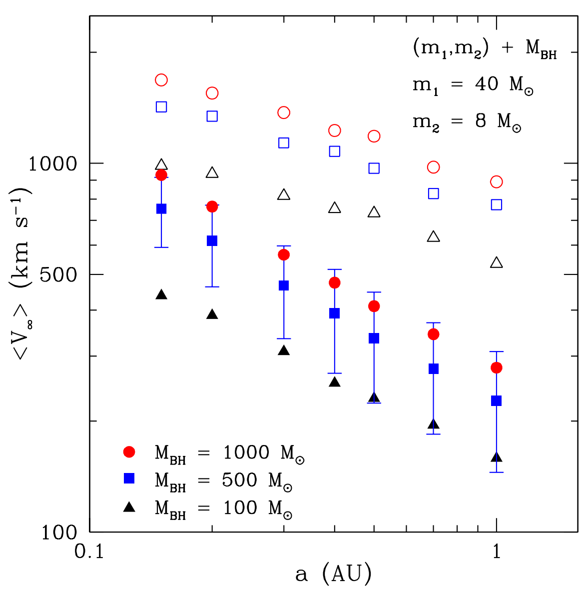

Figure 4. Average recoil velocity of escapers as a function of the initial binary semimajor axis in the interaction of a binary star with IMBHs of different mass: $M_{\rm BH} = 100\,\mathrm{M}_\odot$ (triangles), $M_{\rm BH} = 500\,\mathrm{M}_\odot$ (squares), $M_{\rm BH} = 1\,000\,\mathrm{M}_\odot$ (circles). Solid symbols represent the average velocity obtained from a set of 2000 scattering experiments while the empty symbols indicate the velocity $V_{\rm max}$ for which 1 per cent of the encounters have $V_\infty > V_{\rm max}$. The errorbars indicate the 1σ deviation from the mean. For clarity, we only show them for one data set.

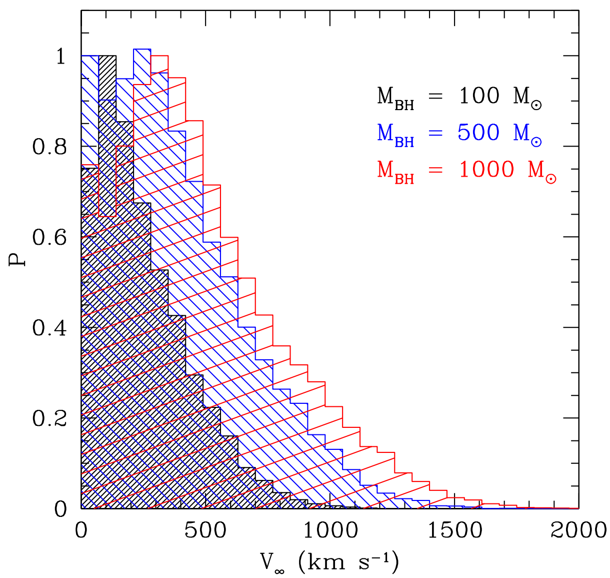

Figure 5. Velocity distributions at infinity for ejected stars after an interaction between a $(40, 8)\,\mathrm{M}_\odot$ binary and an IMBH of mass $M_{\rm BH} = 100\,\mathrm{M}_\odot$ (left-hand panel), $500\,\mathrm{M}_\odot$ (middle panel) and $1\,000\,\mathrm{M}_\odot$ (right-hand panel). These velocity distributions are integrated over the entire range of orbital separations for the initial binary. Only secondary stars ($m_2 = 8\,\mathrm{M}_\odot$) are considered as escapers in this figure.

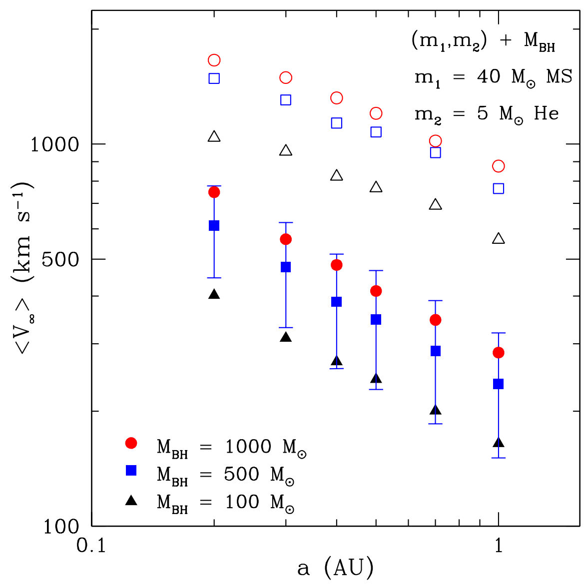

Figure 6. Average recoil velocity of escapers as a function of the initial binary semimajor axis in the interaction between a binary consisting of a main sequence star with mass $m_1 = 40\,\mathrm{M}_\odot$ and a He core with mass $m_2 = 5\,\mathrm{M}_\odot$, and a single IMBH of mass $M_{\rm BH} = 100\,\mathrm{M}_\odot$ (triangles), $500\,\mathrm{M}_\odot$ (squares), $1\,000\,\mathrm{M}_\odot$ (circles). We consider as escapers only the least massive stars, i.e. the He cores. Solid symbols represent the average velocity obtained from a set of 2 000 scattering experimens while the empty symbols indicate the velocity $V_{\rm max}$ for which 1 per cent of the encounters have $V_\infty > V_{\rm max}$. The errorbars indicate the 1σ deviation from the mean. For clarity, we only show them for one data set.

(Kouwenhoven et al. 2005), we can superpose the results of these experiments in order to obtain the total velocity distributions of escapers. The resulting distributions for three different values of the IMBH mass are presented in Fig. 5. The average and the maximum recoil velocities increase with the IMBH mass, as in previous cases. The distributions appear much broader than those in Fig. 3, as a result of the sampling in the semimajor axis.

In order to validate the theoretical predictions in Sect. 4.2, we simulated encounters between an IMBH and binaries consisting of a main-sequence star and a He core. We considered main-sequence stars of mass $m_1 = 40\,\mathrm{M}_\odot$ and radius $r_1 = 11\,\mathrm{R}_\odot$ and He cores of mass $m_2 = 5\,\mathrm{M}_\odot$ and radius $r_2 = 0.6\,\mathrm{R}_\odot$ [see Eq. (4)] in binaries of semimajor axis in the range $0.15 - 1.0$ au. Fig. 6 shows the average recoil velocity of escapers (solid symbols) as a function of the initial binary semimajor axis for three different values of the IMBH mass $M_{\rm BH} = 100\,\mathrm{M}_\odot, 500\,\mathrm{M}_\odot$, and $1\,000\,\mathrm{M}_\odot$. The empty symbols indicate the velocity $V_{\rm max}$ for which 1 per cent of the encounters have $V_\infty > V_{\rm max}$. As in the case of encounters between binary stars and a single IMBH, the average and the maximum velocities increase with the mass of the IMBH. Maximum velocities are somewhat higher compared to the case of two main-sequence stars (see Fig. 4). This is due to the fact that, for a fixed initial semimajor axis, a He star can get much closer to a BH than a main-sequence star. The fraction of very close encounters, however, is small and the average velocity of escapers is not substantially higher than in the case of main-sequence binaries.

5.2 Encounters between single stars and an IMBHB

Another exciting possibility, discussed in Sect. 4.3, is mediated by an encounter between a single star and an IMBHB. We simulate these encounters by considering a single star with a mass of $8\,\mathrm{M}_\odot$ and a radius of $3.5\,\mathrm{R}_\odot$ and binary components with masses in the range $100 - 500\,\mathrm{M}_\odot$, both in equal- and unequal-mass binaries. The semimajor axis is fixed to $a = 30\,\mathrm{R}_\odot \sim 0.14$ au in all cases and the relative velocity at infinity between the single star and the centre of mass of the IMBHB is set to $5\,\mathrm{km\,s^{-1}}$, as in the previous case. We perform 5 000 scattering experiments for each set of parameters. Except for a few mergers (about 1-2 per cent of all cases), the vast majority of the encounters result in a fly-by. With the random choice of impact parameter adopted in the code (see McMillan & Hut 1996; Portegies Zwart 2001a), typical recoil velocities in such large distance encounters are modest. The distribution of recoil velocities is strongly peaked at small velocities ($V_\infty < 100\,\mathrm{km\,s^{-1}}$) but shows a long tail towards large velocities ($V_\infty > 700\,\mathrm{km\,s^{-1}}$). The ejection velocities of escapers depend sensitively on how close the single star approaches the IMBHB during the encounter. High-velocity ejections are realized only if the star approaches the binary within a distance comparable to the binary separation. The maximum ejection velocity for this scenario is achieved when the incoming star passes through the binary system, very close to one of the BHs. The distance of closest approach is limited only by the tidal radius

Table 1. List of BH masses adopted in the scattering experiments with zero impact parameter, followed by the average velocity at infinity for escapers, the velocity $V_{\max}$ for which 1 per cent of the encounters have $V_\infty > V_{\max}$ and the percentage of encounters for which the escapers achieve a recoil velocity larger than $700\,\mathrm{km\,s^{-1}}$. The maximum velocities should be considered as lower limits, as the actual value depends on the random sampling of the initial conditions in the scattering experiments.

M_1 ($\mathrm{M_\odot}$)	M_2 ($\mathrm{M_\odot}$)	$\langle V_\infty \rangle$ ($\mathrm{km\,s^{-1}}$)	$V_{\max}$(1 per cent) ($\mathrm{km\,s^{-1}}$)	# (per cent)
100	100	820	2175	53
200	100	950	2380	66
200	200	1130	3070	75
300	200	1260	3230	80
300	300	1430	3875	83
500	300	1610	4170	87
500	500	1845	4800	91

in the gravitational field of the black hole, which is roughly given by $r_t = (M_{\mathrm{BH}}/m)^{1/3} r$. The fraction of encounters resulting in velocities larger than $700\,\mathrm{km\,s^{-1}}$ increases from about 8 per cent for BHs of $100\,\mathrm{M_\odot}$ to 20 per cent for BHs of $500\,\mathrm{M_\odot}$.

In order to prove the critical dependance of the ejection velocity at infinity of escapers on the distance of closest approach to the IMBHB, we perform another set of simulations with zero impact parameter. The values of the BH masses adopted in each set of simulations are reported in Table 1, followed by the average velocity at infinity for escapers, the velocity $V_{\max}$ for which 1 per cent of the encounters have $V_\infty > V_{\max}$ and the percentage of encounters for which the escapers achieve a recoil velocity larger than $700\,\mathrm{km\,s^{-1}}$ computed over 5 000 scattering experiments for each set of parameters. The results shown in Table 1 show that very large velocities can be achieved in close encounters between a single star and a massive BH binary. Encounters with impact parameters close to zero are, none the less, very rare and we conclude that interactions between a stellar binary and a single massive BH are more likely to result in the ejection of an hypervelocity star.

6 DISCUSSION

In this paper, we explored the hypothesis that the hyperfast pulsars could be the remnants of a symmetric supernova explosion of a high-velocity massive star which attained its peculiar velocity (similar to that of the pulsar) in the course of strong dynamical three- or four-body encounters in the cores of YMSCs. We estimated the maximum velocities obtainable in these encounters and found that they are comparable to those measured for hypervelocity stars. We therefore argue that the origin of hypervelocity stars could be associated with dynamical processes in the cores of YMSCs. Such star clusters are expected to be much more common than hitherto assumed (see Sect 3).

Hypervelocity stars could also originate from other star-forming galaxies. The position in the sky, the age and the observed velocity of the hypervelocity star HE 0437−5439 suggests that it was ejected from the Large Magellanic Cloud (LMC) rather than from the Milky-way Galaxy (Edelmann et al. 2005). Recently, Gualandris & Portegies Zwart (2007) investigated this hypothesis by simulating interactions between a binary and an IMBH in a young star cluster in the LMC and found that the hypervelocity star HE 0437−5439 could have been accelerated by one of the young star clusters in the LMC, but this would require an IMBH of $\gtrsim 1\,000\,\mathrm{M_\odot}$.

The cores of globular clusters may also give rise to ejecting stars and millisecond pulsars with high speed, in particular, those globular clusters which have a high central density and are rich in recycled pulsars. Some globular clusters may even harbour an IMBH, which are known to be able to produce hypervelocity stars, and those clusters form a natural channel for production of solitary millisecond pulsars, whose velocities, in principle, can reach very high values.

In Sect. 4 and Sect. 5, we show that main-sequence O-type stars cannot be ejected from YMSCs with a peculiar velocity sufficiently high to explain the origin of hyperfast neutron stars (unless a $\gtrsim 1\,000\ \mathrm{M_\odot}$ IMBH is present in the cluster center), but lower mass main-sequence stars or stripped helium cores could be accelerated to hypervelocities. We find also that dynamical processes in the cores of YMSCs can produce stars moving with velocities of $\sim 200-400\ \mathrm{km\,s^{-1}}$, which are typical of pulsars (e.g. Hobbs et al. 2005) and the bound population of halo B-type stars (Ramspeck, Heber & Moehler 2001; Brown et al. 2007), and therefore can contribute to the origin of pulsar velocities in addition to asymmetric supernova explosions and disruption of binaries following supernova explosions). But even in these cases the cross-section for producing such high speeds is small and we expect that only a fraction of high-velocity runaways have been accelerated by this mechanism. Nevertheless, some of velocities observed for pulsars may be explained by the proposed scenario. Even though we present the cross-sections for scattering processes discussed in Sect. 4 and Sect. 5, it is still hard to estimate the production rate for the proposed mechanism. The main uncertainty at the moment is in the number and characteristics of the population of young and massive star clusters.

We argue also that some fast moving neutron stars could be the descendants of hypervelocity helium cores, which due to their short lifetimes ($\lesssim 10^6$ yr) can only have been ejected quite recently. As a consequence, the neutron star should not have had time to travel a long distance from its parent star cluster. If we assume that the ~ 2 Myr old pulsar PSR B1508+55 is indeed the remnant of a hypervelocity star, then the pulsar separation from the Galactic plane of ~ 2.5 kpc implies that its progenitor was a helium core (cf. Gvaramadze 2007). The hypervelocity main-sequence stars of mass $\gtrsim 8\ \mathrm{M_\odot}$ ejected at large angles to the Galactic plane end their lives at distances > 10 kpc and thereby contribute to a population of halo and intergalactic supernovae.

The proper motion vectors of several pulsars located in the high-pressure interiors of their associated SNRs show a trend (Ng & Romani 2004) toward alignment with the pulsar rotation axes (inferred from the symmetry of toroidal nebulae surrounding the pulsars). This trend could be understood if pulsars receive at birth a kick directed along their rotation axes. The observed alignment, however, is not perfect.

It is clearly pronounced only for the Vela pulsar[6]. A natural explanation of the misalignment (if one adopts that *all* neutron stars are kicked along their rotation axes) is that the supernova progenitor star had an arbitrarily oriented peculiar velocity, comparable with or larger than the kick velocity received by its descendant at birth. One possibility is that the supernova progenitor was a member of a binary system and that the pulsar peculiar velocity is in part due to the recoil received by the system after the first supernova explosion. Another possibility is that the progenitor star was ejected from the parent YMSC due to the processes discussed in Sect. 4. Thus, the hyperfast pulsars produced by supernova explosion of hypervelocity stars should not show any alignment between their spin axes and proper motion vectors. This inference, however, would be difficult to prove since the hyperfast pulsars leave rapidly from the confines of their parent SNRs [on a time-scale of $\sim 1.4\times 10^4\, v_{1\,000}^{-5/3}(E_{51}/n_{\rm ISM})^{1/3}$ yr, where $v_{1\,000}$ is the pulsar peculiar velocity in units of $1\,000\ {\rm km\,s^{-1}}$, E_{51} is the supernova energy in units of 10^{51} erg, and $n_{\rm ISM}$ is the number density of the ambient interstellar medium]. The only known hyperfast neutron star associated with a SNR (RX J0822−4300 in Puppis A; Hui & Becker 2006; Winkler & Petre 2007) is a radio-quiet object (Gaensler, Bock & Stappers 2000) that makes it impossible to infer the direction of its rotation axis. One can also infer the orientation of the pulsar rotation axis using the radio polarization measurements (e.g. Deshpande, Ramachandran & Radhakrishnan 1999; Johnston et al. 2005). As expected, the proper motion of the hyperfast pulsar PSR B1508+55 shows a large misalignment of $\sim 71^\circ$ (or $\sim 19^\circ$, depending on whether or not the linear polarization of the pulsar radio emission is parallel or orthogonal to magnetic field; see Chatterjee et al. 2005).

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REFERENCES

Ascenso, J., Alves, J., Beletsky, Y., Lago, M.T.V.T., 2007, A&A, 466, 137
Baumgardt, H., Gualandris, A., Portegies Zwart, S., 2006, MNRAS, 372, 174
Belkus, H., Van Bever, J., Vanbeveren, D., 2007, ApJ, 659, 1576
Binney, J., Tremaine, S, 1987, Galactic Dynamics. Princeton Univ. Press, Princeton, NJ
Blaauw, A. 1961, Bull. Astron. Inst. Netherlands, 15, 265

[6] For an alternative explanation of this alignment see Radhakrishnan & Deshpande (2001) and Deshpande & Radhakrishnan (2007).

Bonnell, I.A., Bate, M.R., Zinnicker, H., 1998, MNRAS, 298, 93
Borissova, J., Ivanov, V.D., Minniti, D., Ceisler, D., 2006, A&A, 455, 923
Bromley, B.C., Kenyon, S.J., Geller, M.J., Barcikowski, E., Brown, W.R., Kurtz, M.J., 2006, ApJ, 653, 1194
Brown, W.R., Geller, M.J., Kenyon, S.J., Kurtz, M.J., 2005, ApJ, 622, L33
Brown, W.R., Geller, M.J., Kenyon, S.J., Kurtz, M.J., 2006, ApJ, 640, L35
Brown, W.R., Geller, M.J., Kenyon, S.J., Kurtz, M.J., Bromley, B.C., 2007, ApJ, 660, 311
Chatterjee, S., Cordes, J.M., 2004, ApJ, 600, L51
Chatterjee, S. et al., 2005, ApJ, 630, L61
Chugai, N.N., 1984, Sov. Astron. Lett., 10, 87
Clark, J.S., Negueruela, I., Crowther, P.A., Goodwin, S.P., 2005, A&A, 434, 949
Davies, B., Figer, D.F., Kudritzki, R.-P., MacKenty, J., Najarro, F., Herrero, A., 2007, ApJ, 671, 781
Deshpande, A.A., Radhakrishnan, V., 2007, ApJ, 656, 1038
Deshpande, A.A., Ramachandran, R., Radhakrishnan, V., 1999, A&A, 351, 195
Dewey, R.J., Cordes, J.M., 1987, ApJ, 321, 780
Dutra, C.M., Ortolani, S., Bica, E., Barbuy, B., Zoccali, M., Momany, Y., 2003, A&A, 408, 127
Edelmann, H., Napiwotzki, R., Heber, U., Christlieb, N., Reimers, D., 2005, ApJ, 634, L181
Figer, D.F., Kim, S.S., Morris, M., Serabyn, E., Rich, R.M., McLeanet, I.S., 1999, ApJ, 525, 750
Figer, D.F., MacKenty, J., Robberto, M., Smith, K., Najarro, F., Kudritzki, R.P., Herrero, A., 2006, ApJ, 643, 1166
Fregeau, J.M., Larson, S.L., Miller, M.C., O'Shaughnessy, R., Rasio, F.A., 2006, ApJ, 646, L135
Gaensler, B.M., Bock, D.C.-J., Stappers, B.W., 2000, ApJ, 537, L35
Ghez, A.M. et al., 2003, ApJ, 586, L127
Gott, J.R., Gunn, J.E., Ostriker, J.P., 1970, ApJ, 160, L91
Gualandris, A., Portegies Zwart, S., 2007, MNRAS, 376, L29
Gualandris, A., Portegies Zwart, S., Sipior, M.S., 2005, MNRAS, 363, 223
Gürkan, M.A., Freitag, M., Rasio, F.A., 2004, ApJ, 604, 632
Gürkan, M.A., Fregeau, J.M., Rasio, F.A., 2006, ApJ, 640, L39
Gvaramadze, V.V., 2007, A&A, 470, L9
Habets, G.M.H.J., Heintze, J.R.W., 1981, A&AS, 46, 193
Hansen, B.M.S., Milosavljević, M., 2003, ApJ, 593, L77
Hanson, M.M., 2003, ApJ, 597, 957
Harayama, Y., Eisenhauer, F., Martins, F., 2007, ApJ, in press (astro-ph/0710.2882)
Heggie, D.C., 1975, MNRAS, 173, 729
Hills, J.G., 1988, Nat, 331, 687
Hills, J.G., 1991, AJ, 102, 704
Hirsch, H.A., Heber, U., O'Toole, S. J., Bresolin, F., 2005, A&A, 444, L61
Hobbs, G., Lorimer, D.R., Lyne, A.G., Kramer, M., 2005, MNRAS, 360, 974
Homeier, N., Alves, J., 2005, A&A, 430, 481
Hui, C.Y, Becker, W., 2006, A&A, 457, L33
Iben, I., Jr., Tutukov, A.V., 1996, ApJ, 456, 738
Johnston, S., Hobbs, G., Vigeland, S., Kramer, M., Weisberg, J.M., Lyne, A.G., 2005, MNRAS, 364, 1397
Kouwenhoven, M.B.N., Brown, A.G.A., Zinnecker, H., Kaper, L., Portegies Zwart, S.F., 2005, A&A, 430, 137
Knödlseder, J., 2000, A&A, 360, 539
Knödlseder, J., Cerviño, M., Le Duigou, J.-M., Meynet, G., Schaere, D., von Ballmoos, P., 2002, A&A, 390, 945
Kroupa, P., 2001, in Zinnicker H., Mathieu R., eds, Proc. IAU Symp. 200, The Formation of Binary Stars. Astron. Soc. Pac., San Francisco, p. 199
Kroupa, P., Boily, C.M., 2002, MNRAS, 336, 1188

Lada, C.J., Lada, E.A., 2003, ARA&A, 41, 57
Lamers, H.J.G.L.M., Gieles, M., Bastian, N., Baumgardt, H., Kharchenko, N.V., Portegies Zwart, S., 2006, A&A, 441, 117
Larsen, S.S., 2006, preprint (astro-ph/0606625)
Lee, H.M., Ostriker, J.P., 1986, ApJ, 310, 176
Leonard, P.J.T, 1989, AJ, 98, 217
Leonard, P.J.T, 1991, AJ, 101, 562
Leonard, P.J.T, Duncan, M.J., 1988, AJ, 96, 222
Leonard, P.J.T, Duncan, M.J., 1990, AJ, 99, 608
Madhusudhan, N., Rappaport, S., Podsiadlowski, Ph., Nelson, L., 2007, ApJ, submitted (astro-ph/0710.3854)
McMillan, S.L.W., Hut, P., 1996, ApJ, 467, 348
McMillan, S.L.W., McDermott, P.N., Taam, R.E., 1987, ApJ, 318, 261
Mikkola, S., 1983, MNRAS, 203, 1107
Miller, M.C., Hamilton, D.P., 2002, MNRAS, 330, 232
Miller, M.C., Colbert, E.J.M., 2004, Int.J.Mod.Phys., D13, 1
Muno, M.P. et al, 2006, ApJ, 636, L41
Ng, C.-Y., Romani, R.W., 2004, ApJ, 601, 479
Peter, P.C., 1964, Phys. Rev. B, 136, 1224
Portegies Zwart, S.F., van den Heuvel, E.P.J., 1999, NewA, 4, 355
Portegies Zwart, S. F., Makino, J., McMillan, S. L. W., Hut, P., 1999, A&A 348, 117
Portegies Zwart, S.F., McMillan, S.L.W., 2002, ApJ, 576, 899
Portegies Zwart, S., Gaburov, E., Chen, H.-C., Gürkan, M.A., 2007, MNRAS, 378, L29
Portegies Zwart, S.F., Makino, J., McMillan, S.L.W., & Hut, P., 2001a, ApJ, 546, L101
Portegies Zwart, S.F., McMillan, S.L.W., Hut, P., Makino, J. 2001b, MNRAS, 321, 199
Portegies Zwart, S.F., Makino, J., McMillan, S.L.W., & Hut, P., 2002, ApJ, 565, 265
Portegies Zwart, S.F., Baumgardt, H., Hut, P., Makino, J., McMillan, S.L.W., 2004, Nat, 428, 724
Poveda, A., Ruiz, J., Allen, C., 1967, Bol. Obs. Tonantzintla Tacubaya, 4, 86
Radhakrishnan, V., Deshpande, A.A., 2001, A&A, 379, 551
Ramspeck, M., Heber, U., Moehler, S., 2001, A&A, 378, 907
Santos, J.F.C., Bonatto, C., Bica, E., 2005, A&A, 442, 201
Scheck, L., Kifonidis, K., Janka, H.T., Müller, E., 2006, A&A, 457, 963
Schödel, R., Ott, T., Genzel, R., Eckart, A., Mouawad, N., Alexander, T., 2003, ApJ, 596, 1015
Shklovskii, I.S., 1970, Soviet Astron., 13, 562
Spitzer, L., 1987, Dynamical Evolution of Globular Clusters. Princeton Univ. Press, Princeton, NJ
Statler, T.S., Ostriker, J.P., Cohn, H.N., 1987, ApJ, 316, 626
Tademaru, E., Harrison, E.R., 1975, Nat, 254, 676
Tauris, T.M., van den Heuvel, E.P.J., 2006, in Lewin, W., van der Klis M., eds, Cambridge Astrophysics Ser. 39, Compact Stellar X-Ray Sources. Cambridge Univ. Press, Cambridge, p. 623
Tutukov, A.V., Fedorova, A.V., 2005, Astron. Rep., 49, 678
Vanbeveren, D., Van Rensbergen, W., De Loore, C., 1998, The Brightest Binaries. Kluwer Academic Publishers, Boston
Winkler, P.F., Petre, R., 2007, ApJ, 670, 635
Wolff, S.C., Strom, S.E., Dror, D., & Venn, K., 2007, AJ, 133, 1092
Yu, Q., Tremaine, S., 2003, ApJ, 599, 1129
Yungelson, L., 2007, Highlights Astron., 14, 210
Yungelson, L. R., van den Heuvel, E. P. J., Vink, J.S., Portegies Zwart, S. F., de Koter, A., 2008, A&A, 477, 223