Ejection of hypervelocity binary stars by a black hole of intermediate mass orbiting Sgr A*

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ABSTRACT

The discovery of hypervelocity binary stars (HVBs) in the Galactic halo would provide definite evidence of the existence of a massive black hole companion to Sgr A*. Here, we use a hybrid approach to compute the rate of ejection and the total number of HVBs produced by a hypothetical intermediate-mass black hole (IMBH, $M_2 < 10^5\,\mathrm{M}_\odot$) orbiting Sgr A*. Depending on the mass of M_2 and on the properties of binary stars in the central parsec of the Milky Way, we show that the number of undisrupted HVBs expected to be expelled from the Galactic Centre before binary black hole coalescence ranges from zero to a few dozen at most. Therefore, the non-detection of stellar binaries in a complete survey of hypervelocity stars would not rule out the occurrence of an IMBH–Sgr A* in-spiralling event within the last few $\times 10^8$ yr.

Key words: black hole physics – stellar dynamics – Galaxy: centre.

1 INTRODUCTION

Hypervelocity stars (HVSs) are a natural consequence of the presence of a massive black hole (MBH) in the Galactic Centre (GC). At present, several HVSs are known to travel in the halo of the Milky Way (MW) with Galactic rest-frame velocities between +400 and +750 km s^{-1} (Brown et al. 2005, 2006, 2007). Only the tidal disruption of a tight stellar binary by a single MBH in Sgr A* or the scattering of a single star by a hypothetical MBH binary (MBHB) can kick a 3–4 $\mathrm{M}_\odot$ star to such extreme velocities (e.g. Hills 1988; Yu & Tremaine 2003, hereafter Y03). Direct observational evidence for a secondary intermediate-mass black hole (IMBH) closely orbiting Sgr A* is difficult to establish, however. In Sesana, Haardt & Madau (2007), we showed that the observed velocity distribution of HVSs appears to marginally disfavour the MBHB ejection mechanism, though the statistics are still rather poor. Lu, Yu & Lin (2007, hereafter L07) showed that tight binary stars can be ejected by a MBHB without being tidally torn apart: the discovery of just one *hypervelocity binary star* (HVB) in forthcoming deep stellar surveys could then provide evidence of the existence of a massive or IMBH companion to Sgr A*. [Perets (2008b) proposed an alternative scenario for generating *massive* HVBs by tidal disruption of hierarchical triplets; however the efficiency of this process may be extremely low.]

The analysis of L07 is the starting point of this Letter. Our goal is to provide an estimate of the number of HVBs expected to be produced by the in-spiral of an IMBH on to Sgr A*, using the results of scattering experiments between a MBHB and a bound stellar cusp discussed in Sesana, Haardt & Madau (2008, hereafter S08). We will show that a short burst of HVSs accompanied by a few HVBs would be an incontrovertible signature of a recent in-spiral. By contrast, depending on the properties of the population of binary stars in the GC, it is possible that a fast binary black hole in-spiral and coalescence may occur without the ejection of a single HVB in the Galactic halo.

2 MBHB–STAR INTERACTIONS

Consider a star of mass m_* orbiting the primary hole M_1, and assume, for simplicity, that the secondary hole M_2 ($m_* \ll M_2 \ll M_1$) is in a circular orbit of radius a around M_1. When the star experiences a close encounter with M_2, its velocity is of the order of the MBHB circular velocity, $v_* \sim V_\mathrm{c} = (GM_1/a)^{1/2}$. A star having closest approach distance to M_2 equal to $r_{\mathrm{min},2} \ll a$ will be subject to a velocity variation $\Delta v_* \sim (GM_2/r_{\mathrm{min},2})^{1/2}$ as a result of a (specific) force $\sim GM_2/r^2_{\mathrm{min},2}$ applied for an encounter time-scale $\sim(r^3_{\mathrm{min},2}/GM_2)^{1/2}$ (Quinlan 1996; Y03). This leads to

$$\frac{\Delta v_*}{V_\mathrm{c}} \sim \left(\frac{aM_2}{r_{\mathrm{min},2}M_1}\right)^{1/2} \equiv \sqrt{q/x}, \tag{1}$$

where $x \equiv r_{\mathrm{min},2}/a$ and $q \equiv M_2/M_1$. Since in the limit of close energetic encounters, the ejection velocity of the star is, to first order, $v_\mathrm{ej} \propto \Delta v_*$, equation (1) shows two important scalings: (i) v_ej is inversely proportional to the square root of the closest approach distance to M_2 during the interaction; and (ii) the closest approach distance required to eject a star above a given speed (in units of V_c)

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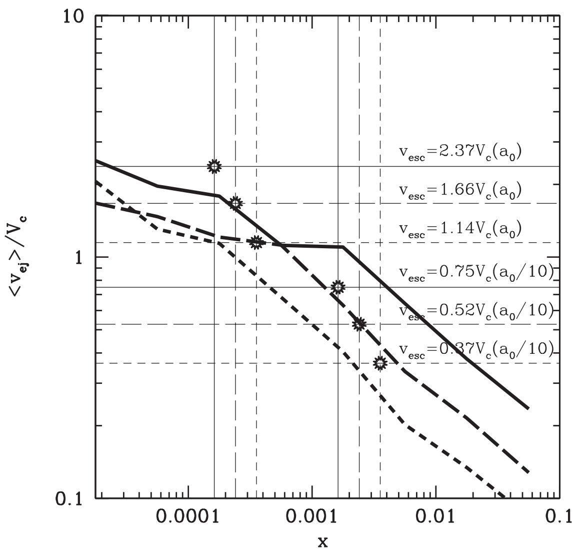

Figure 1. Thick curves: mean stellar ejection velocity (in units of V_c) as a function of the dimensionless minimum distance of approach to M_2, $x = r_{\mathrm{min},2}/a$. The MBHB has an eccentricity of $e = 0.1$ and a mass ratio $q = 1/81$ (solid line), $q = 1/243$ (long-dashed line) and $q = 1/729$ (short-dashed line). The horizontal lines mark the escape velocity $v_{\mathrm{esc}} = 850\,\mathrm{km\,s^{-1}}$ in units of $V_c(a)$ for $a = a_0$, $a = 0.1\,a_0$, and different mass ratios (using the same line styles as above). Similarly, the vertical lines mark the tidal disruption ratio $r_{\mathrm{T},2}/a$ for an equal-mass binary with $m_b = 2\,\mathrm{M_\odot}$ and $a_b = 0.1$ au (leftmost three lines for $a = a_0$, rightmost three for $a = 0.1\,a_0$). Dots mark the intersection of corresponding horizontal and vertical lines dividing the $\langle v_{\mathrm{ej}}\rangle/V_c$–$x$ plane into four quadrants. To produce an HVB, a thick curve must lie in the corresponding upper right quadrant, where $v_{\mathrm{ej}} > v_{\mathrm{esc}}$ and $r_{\mathrm{min},2} > r_{\mathrm{T},2}$. Note how, on average, these stellar binaries tend to be disrupted and do not become HVBs.

scales with the MBHB mass ratio q. To verify these simple analytical estimates, we have performed 15 sets of three-body scattering experiments, using the setup described in S08, for mass ratios $q = 1/81$, $1/243$, $1/729$, and eccentricities $e = 0$, 0.1, 0.3, 0.6, 0.9. In each set, we integrated 5000 orbits drawn from an isotropic distribution of stars bound to M_1, and recorded v_{ej}, $r_{\mathrm{min},2}$ and $r_{\mathrm{min},1}$ (the closest approach distance to M_1). The stellar semimajor axis a_* is randomly sampled from 50 logarithmic bins spanning the range $0.03a < a_* < 10a$. The stellar specific angular momentum L_* is sampled in the interval $[0, L^2_{*,\mathrm{max}}]$, according to an equal probability distribution in L^2_*, where $L_{*,\mathrm{max}} = \sqrt{GM_1 a_*}$ is the specific angular momentum of a circular orbit of radius a_*. A population of stars with such distribution in L^2_* has mean eccentricity $\langle e\rangle = 0.66$, corresponding to an isotropic stellar distribution (e.g. Quinlan, Hernquist & Sigurdsson 1995). We stress that, on average, the ejection velocity does not depend on the details of the initial Keplerian orbit of the star around M_1, but only on $r_{\mathrm{min},2}$. Results are plotted in Fig. 1 for an assumed MBHB eccentricity $e = 0.1$. The scaling $v_{\mathrm{ej}} \propto x^{-1/2}$ breaks down for encounters closer than $x \sim 0.1\,q$: the ejection velocity tends to $\langle v_{\mathrm{ej}}\rangle \sim 3V_c$, the maximum ejection speed at infinity predicted by simple arguments on elastic scattering. We checked that the precise value of e does not play a significant role on determining $\langle v_{\mathrm{ej}}\rangle$.

The third body in our experiments can be thought of either as a single star or as a stellar binary. A binary star of mass $m_b = m_{*,1} + m_{*,2}$ and semimajor axis a_b is broken apart by tidal forces if its centre of mass approaches a compact object of mass M within the distance (e.g. Miller et al. 2005)

$$
\begin{aligned}
r_{\mathrm{T}} &\simeq \left(3\frac{M}{m_b}\right)^{1/3} a_b \\
&\simeq 1.5 \times 10^{-5}\,\mathrm{pc}\left(\frac{M}{10^4\,\mathrm{M_\odot}}\frac{\mathrm{M_\odot}}{m_b}\right)^{1/3}\left(\frac{a_b}{0.1\,\mathrm{au}}\right). \qquad (2)
\end{aligned}
$$

Such a ‘breakup’ radius must be compared with the closest approach distance $r_{\mathrm{min},2}$ required for a hypervelocity ejection. If $r_{\mathrm{T}} < r_{\mathrm{min},2}$, a stellar binary may be kicked to high speeds while preserving its integrity (L07).

Our three-body approximation does not account for the internal degrees of freedom of the stellar binary. In particular, a strong interaction with the MBHB can result in the merger of the two stars. Simulations of stellar binary–binary interaction in the context of star cluster dynamics show that a merger event is a quite common dynamical outcome (Fregeau et al. 2004). However, the dynamical regime we consider is different. The stellar binary experiences a complex weak dynamical interaction with the MBHB (that is unlikely to affect the binary internal structure). Ejection or breakup is caused instead by an instantaneous strong encounter with one of the two MBHs. Simulations of strong three-body encounters involving a stellar binary and a single MBH (with parameters similar to those considered here; Ginsburg & Loeb 2007) show that the merger of the two stars happens at most in ∼10 per cent of the cases.

To make definite predictions, the results of our scattering experiments must be scaled to the GC. The main parameters of our MW models are summarized in Table 1 (see Sesana et al. 2007 and S08 for details). The reservoir of stars in the central parsec of the MW is well described by a power-law density profile, $\rho(r) = \rho_0(r/r_0)^{-\gamma}$, around a $3.5 \times 10^6\,\mathrm{M_\odot}$ MBH. Here, r_0 is the characteristic radius within which the total stellar mass is $2M_1$ (the ‘radius of influence’ of Sgr A*). As the hypothetical secondary hole M_2 sinks in, it starts ejecting background stars when the total stellar mass enclosed in its orbit is $M_*({<}a) \simeq M_2$ (Matsubayashi, Makino & Ebisuzaki 2007). Following S08, we set the MBHB at initial separation a_0 such that $M_*({<}a_0) = 2M_2$. From γ, ρ_0, r_0 and q, we can derive the parameters a_0, $V_{\mathrm{c},0}$, and the period $P(a_0) \equiv P_0$. We take a velocity threshold for escaping the MW potential of $v_{\mathrm{esc}} = 850\,\mathrm{km\,s^{-1}}$ at r_0 (e.g. Smith et al. 2007). The horizontal lines in Fig. 1 depict the quantity v_{esc}/V_c at orbital separation $a = a_0$ and $a = a_0/10$, while vertical lines mark the tidal disruption radius $r_{\mathrm{T},2}$ in units of a for the same two MBHB separations. An equal-mass stellar binary with $m_b = 2\,\mathrm{M_\odot}$ and $a_b = 0.1$ au was assumed. The figure shows that, on average, stars must approach M_2 within a distance $x < r_{\mathrm{T},2}/a$ in order to be ejected. Most binary stars will then be tidally disrupted during the strong interaction with M_2, and only a few tight binaries with $a_b \lesssim 0.1$ au may survive intact and become HVBs. Note that, while stellar binaries can be also broken apart by M_1 ($r_{\mathrm{T},1} \gg r_{\mathrm{T},2}$), it is the secondary hole M_2 that is largely responsible for dissociating candidate HVBs. This is because there is no connection between tidal dissociation by

Table 1. Parameters of the different models. The quantities γ, r_0, ρ_0, q, a_0, P_0, and $V_{\mathrm{c},0}$ are, respectively, the stellar cusp slope, the influence radius of Sgr A*, the stellar density at r_0, the MBHB mass ratio, its separation when ejections start, the MBHB orbital period and circular velocity at a_0.

γ	r_0 (pc)	ρ_0 ($\mathrm{M_\odot\,pc^{-3}}$)	q	a_0 (pc)	P_0 (yr)	$V_{\mathrm{c},0}$ ($\mathrm{km\,s^{-1}}$)
1.5	2.25	7.1×10^4	1/81	0.12	4032	355
			1/243	5.8×10^{-2}	1344	510
			1/729	2.8×10^{-2}	448	735

M_1 and hypervelocity kicks, while a close approach to M_2, required to gain hypervelocity, can break up the binary.

3 HYPERVELOCITY STELLAR BINARIES

To quantify the fraction of binary stars that are not disrupted by M_2 (and M_1), we need to specify their mass and semimajor distributions. In our *default model*, we assume a logflat distribution of semimajor axis,

$$p(a_\mathrm{b})\mathrm{d}a_\mathrm{b} = \mathrm{d}a_\mathrm{b}/a_\mathrm{b}, \tag{3}$$

in the range $10^{-2} < a_\mathrm{b} < 1$ au (Heacox 1998). The lower limit is set by the contact separation of two solar-mass stars, while the upper limit considers that the binaries with $a_\mathrm{b} > 1$au are unlikely to survive in the dense stellar environment of the GC (e.g. Y03). We have also run a case with the distribution of semimajor axis arising from a lognormal distribution of binary periods P_b:

$$p(\log P_\mathrm{b}) = C\exp\left[\frac{-(\log P_\mathrm{b} - \langle \log P_\mathrm{b}\rangle)^2}{2\sigma^2_{\log P_\mathrm{b}}}\right]. \tag{4}$$

Here, $C = 0.18$ is a normalization constant, $\langle \log P_\mathrm{b}\rangle = 4.8$, $\sigma^2_{\log P_\mathrm{b}} = 2.3$ and the period P_b is measured in days (Duquennoy & Mayor 1991). The above semimajor axis distributions are coupled to two different choices of the stellar binary member's mass function (for a total of four different models). We assume all binaries either to be composed of two equal solar-mass stars ($m_\mathrm{b} = 2\,\mathrm{M}_\odot$, *default model*) or to follow a Salpeter initial mass function (IMF) in the range 1–15 $\mathrm{M}_\odot$ for $m_{*,1}$ while $m_{*,2}$ is randomly chosen in the mass range $1\,\mathrm{M}_\odot$–$m_{*,1}$. We will discuss later the effect of these different assumptions on our results.

To estimate the fraction of stellar binaries that survive the interaction with the binary black hole and are ejected intact as HVBs, we proceed as follows. For fixed q and e, we consider orbital separations in the range 0.1–1 a_0, select from our 5000 simulated orbits those resulting in an ejection with $v_\mathrm{ej} > v_\mathrm{esc}$, and denote their number with $N_\mathrm{ej}(a)$. We then assume that each of these 'ejection orbits' is followed by a binary stellar system with parameters (a_b, $m_{*,1}$, $m_{*,2}$) drawn from the distributions described above, and calculate the radii $r_{\mathrm{T},2}$ and $r_{\mathrm{T},1}$ using equation (2). Finally, if during the chaotic interaction with the MBH pair it is $r_{\mathrm{min},2} < r_{\mathrm{T},2}$ or $r_{\mathrm{min},1} < r_{\mathrm{T},1}$, the stellar binary is counted as 'disrupted before ejection', and added to $N_\mathrm{TD}(a)$. The fraction of HVBs as a function of a is then

$$f_\mathrm{HVB} = \frac{N_\mathrm{ej}(a) - N_\mathrm{TD}(a)}{N_\mathrm{ej}(a)}. \tag{5}$$

Results are shown in Fig. 2 for our default model with MBHB eccentricity $e = 0.6$. The fraction of undisrupted HVBs is of the order of 20–40 per cent, dropping to 5–20 per cent if the distribution of semimajor axis is derived from equation (4); similar fractions are obtained for all the eccentricity values we sampled. Surviving hypervelocity binaries have $\langle a_\mathrm{b}\rangle \lesssim 0.1$ au, i.e. only tight binary stars can be ejected undisrupted. It is clear from the figure that f_HVB and $\langle a_\mathrm{b}\rangle$ do not significantly change as the MBHB shrinks. We can understand this result by noting that $\langle v_\mathrm{ej}\rangle/V_\mathrm{c} \propto \sqrt{a/r_{\mathrm{min},2}}$, i.e. $v_\mathrm{ej} \propto r_{\mathrm{min},2}^{-1/2}$. The ejection velocity (in physical units) does not depend then on MBHB separation, but only on the minimum approach distance to M_2. Fig. 2 also shows that the quantities f_HVB and $\langle a_\mathrm{b}\rangle$ decrease slightly with decreasing black hole mass ratios q. This occurs because $r_{\mathrm{T},2} \propto M_2^{1/3} \propto q^{1/3}$, while $r_{\mathrm{min},2} \propto q$, i.e. the more massive the secondary hole the weaker the interaction required to kick a star above a given speed. If q is (say) three times smaller, a binary star must approach M_2 at a distance three times smaller to be ejected. But as the breakup radius $r_{\mathrm{T},2}$ decreases by just a factor of $3^{1/3}$, fewer tighter stellar binaries can survive undisrupted the tidal field of M_2.

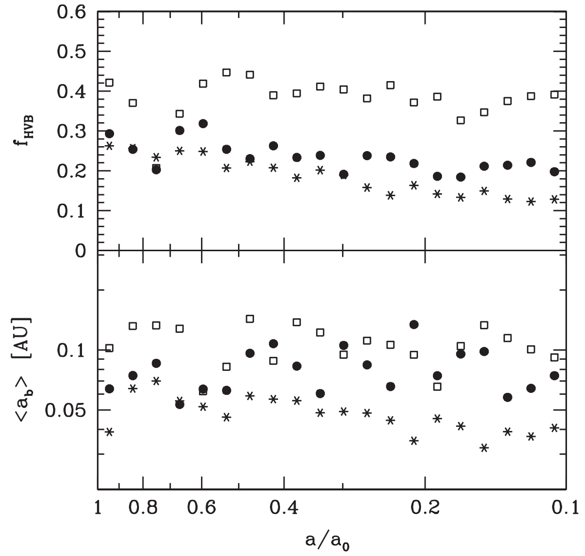

Figure 2. Upper panel: fraction of binaries that survive the interaction with the MBHB and are ejected intact with $v_\mathrm{ej} > v_\mathrm{esc}$, as a function of MBHB separation. Open squares: $q = 1/81$. Filled circles: $q = 1/243$. Stars: $q = 1/729$. Lower panel: mean semimajor axis a_b of undisrupted HVBs. Equal-mass binaries with a logflat distribution in a_b (default model) have been assumed, and the MBHB eccentricity is set to $e = 0.6$.

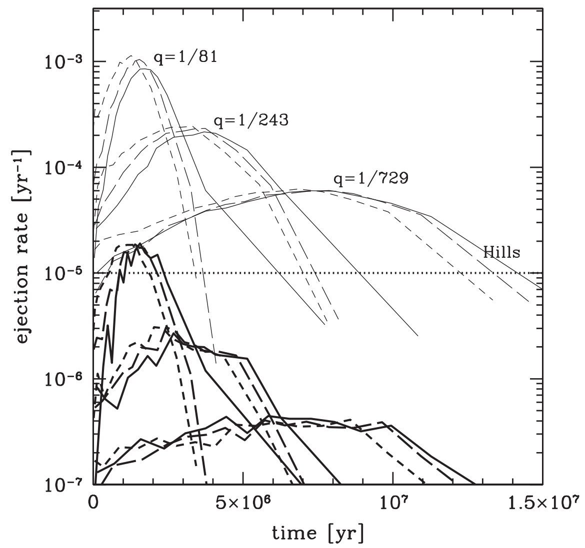

Figure 3. Ejection rates of HVSs calculated in S08 (thin curves) versus the ejection rates of HVBs (thick curves) calculated in this work for the default model and $f_\mathrm{b} = 0.1$. Solid lines: $e_i = 0.1$. Long-dashed lines: $e_i = 0.5$. Short-dashed lines: $e_i = 0.9$. The three sets of curves refer, as labelled, to mass ratios $q = 1/81, 1/243, 1/729$. The dotted horizontal line marks the ejection rate predicted by Hills' mechanism (Y03).

4 EJECTION RATES AND DETECTABILITY

We can now estimate the rate at which binary stars would be ejected into the MW halo by an IMBH spiralling into Sgr A*. In S08, we self-consistently computed the orbital evolution of such an IMBH in terms of $a(t)$ and $e(t)$ (see fig. 8 in S08), and estimated the stellar mass ejection rate $\mathrm{d}m_{\mathrm{ej}}/\mathrm{d}t$. Here, we assume that a fraction f_{b} of scattered stars are binaries, and account for the evolving MBHB eccentricity during orbital decay by linearly interpolating the fraction $f_{\mathrm{HVB}}(a, e)$ along the correct $e(a)$ curve. The ejection rate of HVBs can be written as

$$R_{\mathrm{HVB}} = \frac{1}{\langle m_* \rangle} \frac{\mathrm{d}m_{\mathrm{ej}}}{\mathrm{d}t} \frac{f_{\mathrm{b}}}{2} f_{\mathrm{HVB}}, \tag{6}$$

where $\langle m_* \rangle$ is the mean stellar mass. Results are shown in Fig. 3 for our default model and $f_{\mathrm{b}} = 0.1$. The HVB ejection rate peaks between 5×10^{-7} and $2 \times 10^{-5}\ \mathrm{yr}^{-1}$ over a time-scale of 10^6–10^7 yr, depending on q. For comparison, we also plot the ejection rate of HVSs by the in-spiralling IMBH (S08), as well as the rate of HVSs produced by the tidal disruption of a tight stellar binary by a single MBH in Sgr A* (Hills' mechanism), as estimated by Y03. In all the cases studied, the total number of HVBs, N_{HVB}, is small compared to the expected number of HVSs. We find $N_{\mathrm{HVB}} = 28, 9$ and 4 for $q = 1/81, 1/243$ and $1/729$, respectively. If the a_{b} distribution is lognormal (equation 4), the fraction of tight binaries is reduced and the number of HVBs drops by about a factor of 2. Moreover, in the case of a Salpeter IMF, $\langle m_* \rangle \simeq 2.5\,\mathrm{M}_\odot$ and R_{HVB} is further reduced by the same factor (see equation 6). The number of HVBs would trivially increase linearly with f_{b}. The number of ejected hypervelocity binaries is well approximated by

$$N_{\mathrm{HVB}} \approx 280\ (170)\ f_{\mathrm{b},<1} \frac{\mathrm{M}_\odot}{\langle m_* \rangle} \frac{M_2}{5 \times 10^4\,\mathrm{M}_\odot}, \tag{7}$$

where $f_{\mathrm{b},<1}$ is the fraction of stars in binaries with $a_{\mathrm{b}} < 1$ au, and 280 (170) is the normalization constant appropriate for a logflat (lognormal) a_{b} distribution.

It should be noted that our approach does not account for the binary stars that are not initially bound to the MBHB and populate its loss cone because of two-body relaxation processes. L07 estimated an HVB ejection rate for such an unbound population of few $\times 10^{-6}\ \mathrm{yr}^{-1}$ in the case of a MBHB with $q = 0.01$ and $a = 0.0005$ pc. Such a pair is expected to have a large eccentricity (e.g. Matsubayashi et al. 2007) and a coalescence time-scale of only $\sim 10^5$ yr. For larger orbital separations, the loss cone is larger but the mean ejection velocity is accordingly smaller, leading to lower ejection rates. Such rates are 1 dex smaller than those we derived for bound stars and $q = 1/81$.

5 SUMMARY

We have applied the hybrid approach described in S08 to compute the rate of ejection and the total number of HVBs produced by a hypothetical IMBH orbiting Sgr A*. Depending on the mass of M_2 and on the properties of binary stars in the central parsec of the MW, we have shown that the number of undisrupted HVBs expelled before coalescence ranges from zero to a few dozens at most. In particular, we have found that the rapid in-spiral of a $5 \times 10^4\,\mathrm{M}_\odot$ IMBH would generate $\sim$40 HVBs, assuming a stellar binary fraction of 0.1, $m_* = 1\,\mathrm{M}_\odot$ and a logflat distribution of stellar semimajor axis a_{b}. A 10 per cent binary stellar fraction with $a_{\mathrm{b}} <$ few au is suggested by numerical simulations of dense stellar clusters (e.g. Shara & Hurley 2006; Portegies-Zwart, McMillan & Makino 2007). The number of HVBs is proportional to the mass of the IMBH and inversely proportional to m_*, so in the case of a top-heavy stellar mass function (Schodel et al. 2007) the expected number of HVBs would be lower. Moreover, if the distribution of stellar binary semimajor axis is lognormal instead of logflat, the number of tight binaries that can survive a strong interaction with the MBH pair is smaller. The combination of these factors, combined with the potentially short survival time of these systems in the dense environment of the Galactic Centre (Perets 2008a), can potentially decrease the number of expected HVBs to zero.

To conclude, while the observation of even a single HVB in the Galactic halo would be a decisive proof of the recent in-spiralling of an IMBH into Sgr A*, it is likely that such an event would give origin to at most a handful of HVBs. Therefore, the non-detection of stellar binaries in a complete survey of HVSs may not be used to rule out the existence of an IMBH–Sgr A* pair in the GC.

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REFERENCES

Brown W. R., Geller M. J., Kenyon S. J., Kurtz M. J., 2005, ApJ, 622, 33
Brown W. R., Geller M. J., Kenyon S. J., Kurtz M. J., 2006, ApJ, 640, 35
Brown W. R., Geller M. J., Kenyon S. J., Kurtz M. J., Bromley B. C., 2007, ApJ, 660, 311
Duquennoy A., Mayor M., 1991, A&A, 248, 485
Fregeau J. M., Cheung P., Portegies Zwart S. F., Rasio F. A., 2004, MNRAS, 352, 1
Ginsburg I., Loeb A., 2007, MNRAS, 376, 492
Heacox W. D., 1998, AJ, 115, 325
Hills J. G., 1988, Nat, 331, 687
Lu Y., Yu Q., Lin D. N. C., 2007, ApJ, 666, 89 (L07)
Matsubayashi T., Makino J., Ebisuzaki T., 2007, ApJ, 656, 879
Miller M. C., Freitag M., Hamilton D. P., Lauburg V. M., 2005, ApJ, 631, 117
Perets H. B., 2008a, ApJ, in press (arXiv:0712.1888)
Perets H. B., 2008b, preprint (arXiv:0802.1004)
Portegies-Zwart S. F., McMillan S. L. W., Makino J., 2007, MNRAS, 374, 95
Quinlan G. D., 1996, New Astron., 1, 35
Quinlan G. D., Hernquist L., Sigurdsson S., 1995, ApJ, 440, 554
Schodel R. et al., 2007, A&A, 469, 125
Sesana A., Haardt F., Madau P., 2007, MNRAS, 379, L45
Sesana A., Haardt F., Madau P., 2008, ApJ, 686, 432 (S08)
Shara M. M., Hurley J. R., 2006, ApJ, 646, 464
Smith M. C. et al., 2007, MNRAS, 379, 755
Yu Q., Tremaine S., 2003, ApJ, 599, 1129 (Y03)

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