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 an hybrid approach to compute the rate of ejection and the total number of HVBs produced by a hypothetical intermediate-mass black hole (IMBH, M2 < 10⁵ M⊙) orbiting Sgr A∗. Depending on the mass of M2 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 Center before binary black hole coalescence ranges from zero to a few dozens 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×10⁸ years.

Key words: black holes physics – Galaxy: center – stellar dynamics

1 INTRODUCTION

Hypervelocity stars (HVSs) are a natural consequence of the presence of a massive black hole (MBH) in the Galactic Center (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 binary stars can be ejected by a MBHB without being tidally torn apart: the discovery of just one 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 M₁, and assume, for simplicity, that the secondary hole M₂ (m∗ ≪ M₂ ≪ M₁) is in a circular orbit of radius a around M₁. When the star experiences a close encounter with M₂, its velocity is of order the MBHB circular velocity, Vc ∼ (GM₂/a)¹/². A star having closest approach distance to M₂ equal to rₘₐₖ,₂ ≫ a will be subject to a velocity variation ΔVc ∼ (GM₂/rₘₐₖ,₂)¹/² as a result of a (specific) force ∼ GM₂/rₘₐₖ,₂ applied for an encounter timescale ∼ (rₘₐₖ,₂²/GM₂)¹/² (Quinlan 1996; Y03). This leads to

\[ \frac{\Delta v_e}{V_c} \sim \left( \frac{aM_2}{r_{\text{min},2}M_1} \right)^{1/2} \equiv \sqrt{q/x}, \quad (1) \]

where x ≡ rₘₐₖ,₂/a and q ≡ M₂/M₁. Since in the limit of close energetic encounters the ejection velocity of the star is, to first order, vₑ ≈ ΔVc, equation (1) shows two important scalings: (1), vₑ is inversely proportional to the square root of the closest approach distance to M₂ dur-
ing the interaction; and (2), the closest approach distance required to eject a star above a given speed (in units of \( V_c \)) scales with the MBHB mass ratio \( q \). To verify these simple analytical estimates, we have performed 15 sets of 3-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 5,000 orbits drawn from an isotropic distribution of stars bound to \( M_1 \), and recorded \( v_o, r_{\text{min},2} \), and \( r_{\text{min},1} \) (the closest approach distance to \( M_1 \)). The stellar semi-major axis \( a_\ast \) is randomly sampled from fifty logarithmic bins spanning the range \( 0.03a < a_\ast < 10a \). The stellar specific angular momentum \( L_\ast \) is sampled in the interval \([0, L_{\ast,\text{max}}]\), according to an equal probability distribution in \( L_{\ast,\text{max}} \) where \( L_{\ast,\text{max}} = \sqrt{G M_1 a_\ast} \) is the specific angular momentum of a circular orbit of radius \( a_\ast \). A population of stars with such distribution in \( L_{\ast} \) has mean eccentricity (\( e \)) = 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 \( r_{\text{min},2} \). Results are plotted in Figure 1 for an assumed characteristic eccentricity \( e = 0.1 \). The scaling \( v_o \sim x^{-1/2} \) breaks down for encounters closer than \( x \sim 0.1q \): the ejection velocity tends to \( (v_o) \sim 3V_c \), 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 \( (v_o) \).

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 \( m_a = m_{a,1} + m_{a,2} \) and semimajor axis \( a_b \) is broken apart by tidal forces if its center-of-mass approaches a compact object of mass \( M \) within the distance (e.g. Miller et al. 2005)

\[
r_T \approx \left( \frac{3}{m_b} \right)^{1/3} a_b \\
\approx 1.5 \times 10^{-5} \text{pc} \left( \frac{M}{10^8 M_\odot} \right)^{1/3} \left( \frac{a_b}{0.1 \text{AU}} \right). \tag{2}
\]

Such “breakup” radius must be compared with the closest approach distance \( r_{\text{min},2} \) required for a hypervelocity ejection. If \( r_T < r_{\text{min},2} \), 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 (Fregueau 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; Ginzburg & Loeb 2007) show that the merger of the two stars happens at most in ~10% 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 \( 3.5 \times 10^6 M_\odot \) MBHB. 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 \( M_\ast(<a) \approx M_2 \) (Matsubayashi et al. 2007). Following S08, we set the MBHB at initial separation \( a_0 \) such that \( M_\ast(<a) = 2M_1 \). From \( \gamma, \rho_0, r_0, \) and \( q \) we can derive the parameters \( a_0, \gamma, r_0 \), and the period \( P(a_0) \equiv P_0 \). We take a velocity threshold for escaping the MW potential of \( v_{\text{esc}} = 850 \text{ km s}^{-1} \) at \( r_0 \) (e.g. Smith et al. 2007). The horizontal lines in Figure 1 depict the quantity \( v_{\text{esc}}/V_c \) at orbital separation \( a = a_0 \) and \( a = a_0/10 \), while vertical lines mark the tidal disruption radius \( r_T \) in units of \( a \) for the same two MBHB separations. An equal-mass stellar binary with \( m_b = 2 M_\odot \), and \( a_b = 0.1 \text{ AU} \) was assumed. The figure shows that, on average, stars must approach \( M_2 \) within a distance \( x < r_T/a \) 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 \( a_b \lesssim 0.1 \text{ AU} \) may be survive intact and become HVBs. Note that, while stellar binaries can be also broken apart by \( M_1 \) (\( r_T,1 \gg r_T,2 \)), 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 \( M_1 \) and hypervelocity kicks, while a close approach to \( M_2 \), required to gain hypervelocity, can break up the binary.

### Table 1. Parameters of the different models.

\[
\begin{array}{ccccccc}
\gamma & r_0 & \rho_0 & q & a_0 & P_0 & V_c,0 \\
\text{[pc]} & [M_\odot \text{pc}^{-3}] & & & [\text{pc}] & [\text{yr}] & [\text{km s}^{-1}] \\
\hline
1.5 & 2.25 & 7.1 \times 10^4 & 1/81 & 0.12 & 4032 & 355 \\
1/243 & 5.8 \times 10^{-2} & 1344 & 510 \\
1/729 & 2.8 \times 10^{-2} & 448 & 735 \\
\end{array}
\]


3. HYPERVERSPEEDY 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 semi-major distributions. In our default model, we assume a log-flat distribution of semi-major axis,

\[
p(a_b) = da_b/a_b, \tag{3}
\]

in the range \( 10^{-2} < a_b < 1 \text{ AU} \) (Heacock 1998). The lower limit is set by the contact separation of two solar-mass stars, while the upper limit considers that binaries with \( a_b > 1\text{AU} \) are unlikely to survive the dense stellar environment of the GC (e.g. Y03). We have also run a case with the distribution of semi-major axis arising from a log-normal distribution of binary periods \( P_1 \):
of the dimensionless minimum distance of approach to $M_2$, $x = r_{\text{min},2}/a$. 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 $v_{\text{esc}} = 850$ km s$^{-1}$ in units of $V_\odot$ 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 $r_{T,2}/a$ for an equal-mass binary with $m_0 = 2 M_\odot$ and $a_0 = 0.1$ 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 corresponding upper right quadrant, where $r_{\text{esc}} > v_{\text{esc}}$, and denote their number with $N_{\text{TD}}(a)$. We shall discuss later the effect of 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 5,000 simulated orbits those resulting in an ejection with $v_{ej} > v_{\text{esc}}$, and denote their number with $N_{ej}(a)$. We then assume that each of these “ejection orbits” is followed by a binary stellar system with parameters ($a_0, m_{1,1}, m_{1,2}$) drawn from the distributions described above, and calculate the radii $r_{T,2}$ and $r_{T,1}$ using equation (5). Finally, if during the chaotic interaction with the MBH pair it is $r_{\text{min},2} < r_{T,2}$ or $r_{\text{min},1} < r_{T,1}$, the stellar binary is counted as “disrupted before ejection”, and added to $N_{\text{TD}}(a)$. The fraction of HVBs as a function of $a$ is then

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

(5)

Results are shown in Figure 2 for our default model with MBHB eccentricity $e = 0.6$. The fraction of undisrupted HVBs is of order 20 – 40%, dropping to 5 – 20% if the distribution of semi-major axis is derived from equation (4). Similar fractions are obtained for all the eccentricity values we sampled. Surviving hypervelocity binaries have $(a_0) \lesssim 0.1$ AU, i.e. only tight binary stars can be ejected undisrupted. It is clear from the figure that $f_{\text{HVB}}$ and $(a_0)$ do not significantly change as the MBHB shrinks. We can understand this result by noting that $v_{ej}/V_\odot \propto \sqrt{a/r_{\text{min},2}}$, i.e. $v_{ej} \propto r_{\text{min},2}^{-1/2}$. The ejection velocity (in physical units) does not depend then on MBHB separation, but only on the minimum approach distance to $M_2$. Figure 2 also shows that the quantities $f_{\text{HVB}}$ and $(a_0)$ decrease slightly with decreasing black hole mass ratios $q$. This occurs because $r_{T,2} \propto M_2^{2/3} \propto q^{1/3}$, while $r_{\text{min},2} \propto q$, 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 $r_{T,2}$ decreases by just a factor $3^{2/3}$, fewer tighter stellar binaries can survive undisrupted the tidal field of $M_2$.  

Figure 1. Thick curves: mean stellar ejection velocity (in unit of $V_\odot$) as a function of the approach distance to $M_2$, $x = r_{\text{min},2}/a$. 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 $v_{\text{esc}} = 850$ km s$^{-1}$ in units of $V_\odot(a)$ 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 $r_{T,2}/a$ for an equal-mass binary with $m_0 = 2 M_\odot$ and $a_0 = 0.1$ 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 corresponding upper right quadrant, where $v_{ej} > v_{\text{esc}}$ and $r_{\text{min},2} > r_{T,2}$. Note how, on average, these stellar binaries tend to be disrupted and do not become HVBs.

Figure 2. Upper panel: fraction of binaries that survive the interaction with the MBHB and are ejected intact with $v_{ej} > v_{\text{esc}}$, as a function of MBHB separation. Open squares: $q = 1/81$. Filled circles: $q = 1/243$. Stars: $q = 1/729$. Lower panel: mean semi-major axis distributions derived from equation (4). Similar fractions are obtained for all the eccentricity values we sampled. Surviving hypervelocity binaries have $(a_0) \lesssim 0.1$ AU, i.e. only tight binary stars can be ejected undisrupted. It is clear from the figure that $f_{\text{HVB}}$ and $(a_0)$ do not significantly change as the MBHB shrinks. We can understand this result by noting that $v_{ej}/V_\odot \propto \sqrt{a/r_{\text{min},2}}$, i.e. $v_{ej} \propto r_{\text{min},2}^{-1/2}$. The ejection velocity (in physical units) does not depend then on MBHB separation, but only on the minimum approach distance to $M_2$. Figure 2 also shows that the quantities $f_{\text{HVB}}$ and $(a_0)$ decrease slightly with decreasing black hole mass ratios $q$. This occurs because $r_{T,2} \propto M_2^{2/3} \propto q^{1/3}$, while $r_{\text{min},2} \propto q$, 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 $r_{T,2}$ decreases by just a factor $3^{2/3}$, fewer tighter stellar binaries can survive undisrupted the tidal field of $M_2$.  

$$p(\log P_\odot) = C \exp \left[ -\frac{(\log P_\odot - \langle \log P_\odot \rangle)^2}{2\sigma_{\log P_\odot}^2} \right].$$  

(4)
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 figure 8 in S08), and estimated the stellar mass ejection rate dm∗/dt.

Here, we assume that a fraction f0 of scattered stars are binaries, and account for the evolving MBHB eccentricity during orbital decay by linearly interpolating the fraction fHVB(a, e) along the correct e(a) curve. The ejection rate of HVBs can be written as

\[ R_{HVB} = \frac{1}{\langle m_\star \rangle} \frac{dm_\star}{dt} \frac{f_0}{2} f_{HVB}, \]

where \( \langle m_\star \rangle \) is the mean stellar mass. Results are shown in Figure 3 for our default model and \( f_0 = 0.1 \). The HVB ejection rate peaks between \( 5 \times 10^{-7} - 2 \times 10^{-5} \) yr\(^{-1} \) over a timescale 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 \( N_{HVB} = 28, 9, 4 \) for \( q = 1/81, 1/243, 1/729 \), respectively. If the \( a_0 \) distribution is log-normal (equation 1), 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, \( (m_\star) \simeq 2.5 \, M_\odot \) and \( R_{HVB} \) is further reduced by the same factor (see eq. 2). The number of HVBs would trivially increase linearly with \( f_0 \). The number of ejected hypervelocity binaries is well approximated by

\[ N_{HVB} \approx 280 (170) f_{0, c<1} \frac{M_\odot}{\langle m_\star \rangle} \frac{M_2}{5 \times 10^4 \, M_\odot}, \]

where \( f_{0, c<1} \) is the fraction of stars in binaries with \( a_0 < 1 \) AU, and 280 (170) is the normalization constant appropriate for a log-flat (log-normal) \( a_0 \) 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 unbound population of \( 6 \times 10^{-6} \) 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 timescale of \( \sim 10^5 \) 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 one 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 hypervelocity binary stars 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 Milky Way, 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 \( 5 \times 10^4 \, M_\odot \) IMBH would generate \( \sim 40 \) HVBs, assuming a stellar binary fraction of 0.1, \( m_\star = 1 \, M_\odot \), and a log-flat distribution of stellar semi-major axis \( a_0 \). A 10% binary stellar fraction with \( a_0 < 1 \) 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 \( m_\star \), 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 semi-major axis is log-normal instead of log-flat, the number of tight binaries that can survive a strong interaction with the MBH pair is smaller. The combination of these factors 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 hypervelocity stars may not be used to rule out the existence of an IMBH-Sgr A* pair in the GC.

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