Ejection of hypervelocity stars from the Galactic Centre by intermediate-mass black holes

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ABSTRACT

We have performed $N$-body simulations of the formation of hypervelocity stars (HVS) in the centre of the Milky Way due to inspiralling intermediate-mass black holes (IMBHs). We considered IMBHs of different masses, all starting from circular orbits at an initial distance of 0.1 pc. We find that the IMBHs sink to the centre of the Galaxy due to dynamical friction, where they deplete the central cusp of stars. Some of these stars become HVS and are ejected with velocities sufficiently high to escape the Galaxy. Since the HVS carry with them information about their origin, in particular in the moment of ejection, the velocity distribution and the direction in which they escape the Galaxy, detecting a population of HVS will provide insight in the ejection processes and could therefore provide indirect evidence for the existence of IMBHs.

Our simulations show that HVS are generated in short bursts which last only a few Myr until the IMBH is swallowed by the supermassive black hole (SMBH). HVS are ejected almost isotropically, which makes IMBH-induced ejections hard to distinguish from ejections due to encounters of stellar binaries with a SMBH. After the HVS have reached the galactic halo, their escape velocities correlate with the distance from the Galactic Centre in the sense that the fastest HVS can be found furthest away from the centre. The velocity distribution of HVS generated by inspiralling IMBHs is also nearly independent of the mass of the IMBH and can be quite distinct from one generated by binary encounters. Finally, our simulations show that the presence of an IMBH in the Galactic Centre changes the stellar density distribution inside $r < 0.02$ pc into a core profile, which takes at least 100 Myr to replenish.

Key words: black hole physics – stellar dynamics – globular clusters: general.

1 INTRODUCTION

Hills (1988) was the first to show that the ejection of stars with velocities $>1000$ km s$^{-1}$ is a natural consequence of galaxies hosting supermassive black holes (SMBHs). He named these stars ‘hypervelocity stars’ (HVS). Recently, several HVS have been discovered in the Galactic halo (Brown et al. 2005; Hirsch et al. 2005; Brown et al. 2006a,b). Except for one star which might have been ejected from the Large Magellanic Cloud (LMC) (Edelmann et al. 2005), the travel times of all HVS are short enough that the stars could have been ejected from the Galactic Centre within the lifetimes of the stars, confirming Hills’ predictions.

The exact formation mechanism of HVS is however still a matter of debate. The ejection of stars by supernova explosions in close binary systems (Blaauw 1961) and dynamical encounters (Poveda, Ruiz & Allen 1967) cannot produce main-sequence stars with velocities exceeding a few hundred kilometres per second (Gualandris, Portegies Zwart & Sipior 2005), leaving the interaction of stars in galactic nuclei around SMBHs as the only possible source for HVS.

Yu & Tremaine (2003) considered three processes which could eject stars from the vicinity of SMBHs: (1) close encounters between two single stars; (2) encounters between stellar binaries and the central SMBH and (3) encounters between single stars and a massive black hole binary. In the case of the SMBH in the Galactic Centre, they found that close encounters between single stars can eject stars with a rate of only $10^{-11}$ yr$^{-1}$ which would create less than one HVS during the lifetime of the Milky Way. The other two processes were found to eject stars with rates of up to $10^{-4}$ yr$^{-1}$, sufficiently high to explain the observed number of HVS in the halo of the Milky Way.

Similar results were also obtained by Gualandris et al. (2005), who studied the ejection of stars by SMBHs by means of scattering experiments and found that HVS formation is possible by both processes. The tidal disruption of binaries was found to create HVS with higher velocities while the ejection from binary black hole systems

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creates HVS with a higher rate. Similarly, Ginsburg & Loeb (2006) found that the tidal breakup of stellar binaries can create HVS with velocities significantly higher than what has been found so far.

A distinction between the two scenarios might come from a detailed analysis of the spatial and kinematical distribution of HVS: the ejection of stars due to the interaction of stellar binaries with an SMBH should be nearly constant with time since the reservoir of binary stars in the Galactic Centre is depleted only slowly. Furthermore, the distribution of binary orbits should be nearly isotropic in sufficiently relaxed nuclei, implying that the resulting HVS distribution will also be isotropic. In contrast, the ejection of stars from an SMBH–IMBH (intermediate-mass black hole) binary should show characteristic variations with time and spatial direction: HVS are mainly ejected when the inspiralling IMBH reaches the centre since the density of stars is highest in the centre and the velocity dispersion is also highest close to the SMBH. In addition, escaping stars acquire their extra velocities mainly in the direction of motion of the IMBH, introducing a spatial anisotropy in the HVS distribution.

These considerations were confirmed by Levin (2005), who studied analytically the distribution of escapers created by an SMBH–IMBH pair in a dense stellar cusp. He found that the ejection of stars in case of a black hole binary is happening mainly in a burst which lasts a few dynamical friction time-scales and that if the IMBH is initially in a nearly circular orbit, the velocity vectors of the ejected stars also cluster around the orbital plane. If the IMBH moves in an eccentric orbit, stars are ejected in a broad jet roughly perpendicular to the Runge–Lenz vector of the IMBHs orbit. Similarly, Sesana, Haardt & Madau (2006) found through three-body scattering experiments that eccentric black hole binaries eject stars along a broad jet perpendicular to the semimajor axis of the binary.

IMBHs could form in galaxies through runaway collisions of stars in star clusters, giving rise to ultraluminous X-ray sources (Portegies Zwart et al. 2004). They could later be brought into the centres of galaxies through dynamical friction of the star clusters (Portegies Zwart et al. 2006). Their merger with the central SMBHs would be an important source of gravitational waves, detectable with the next generation of gravitational wave detectors, like Laser Interferometer Space Antenna (LISA). IMBHs might also be an important contribution for the growth of SMBHs in the early universe (Ebisuzaki et al. 2001).

In the present paper we have therefore performed collisional N-body simulations of the dynamics of inspiralling IMBHs in stellar cusps around SMBHs. The aim of our simulations is to study whether the ejection of stars by IMBHs leads to observable consequences in the distribution of HVS which might help to distinguish between different ejection scenarios and which could give an indirect hint for the presence of one or more IMBHs in the centre of the Milky Way.

2 DESCRIPTION OF THE N-BODY RUNS

All runs were performed with the collisional N-body code NBODY4 (Aarseth 1999) on the GRAPE6 computers (Makino et al. 2003) of Bonn and Tokyo University. Our runs contained three different components: a central SMBH, an IMBH and 105 stars. In all simulations the SMBH was initially at rest at the origin and had a mass of $M_{\text{SMBH}} = 3 \times 10^6 M_\odot$, similar to the mass of the SMBH at the Galactic Centre (Ghez et al. 2005; Schödel et al. 2005). The mass of the IMBHs was varied in the different runs. In total we performed three runs, using IMBH masses of $M_{\text{IMBH}} = 10^3$, $3 \times 10^3$ and $10^4 M_\odot$, respectively. All IMBHs moved initially in circular orbits at a distance of 0.1 pc from the SMBH.

The stars had masses of $m_\star = 30 M_\odot$ and were initially distributed in a cusp around the SMBHs according to the following density law:

$$\rho(r) = \frac{\rho_0}{r^{7/4} \left(1 + \left(\frac{r}{r_0}\right)^5\right)}$$

with $\rho_0 = 3 \times 10^5 M_\odot \text{pc}^{-5/4}$ and $r_0 = 1 \text{pc}$. For distances $r \ll r_0$, this distribution corresponds to a $r^{-7/4}$ power-law cusp which theoretical arguments and N-body simulations have shown to evolve in a stellar system around an SMBH (Bahcall & Wolf 1976; Baumgardt, Makino & Ebisuzaki 2004a,b; Preto, Merritt & Spurzem 2004). The chosen form for the cusp is also compatible with observations of the stellar density distribution in the Galactic Centre, which shows a power-law cusp inside 10 arcsec (Genzel et al. 2003). It has the additional advantage that at larger distances, where the stellar distribution has little influence on the outcome of the simulations, the stellar density drops off quickly. The overall density was chosen in such a way to be compatible with current limits on the density of stars in the Galactic Centre (Genzel et al. 2003).

Stars were merged with the black holes (both SMBH or IMBH) if their separation became smaller than their tidal radius given by

$$r_1 = \left(\frac{M_{\text{BH}}}{m_\star}\right)^{1/3} R_\star,$$

where $R_\star$ is the radius of the stars, which we set equal to 1 $R_\odot$. The mass of disrupted stars was added to the mass of the black holes. IMBHs were merged with the central SMBH if they passed within the radius of the last stable orbit, assumed to be three Schwarzschild radii. We did not include the effects of gravitational radiation into our runs. Neither was any softening used in calculating the gravitational forces between the particles in our calculation.

Simulations were stopped when an IMBH merged with the SMBH or the runs reached 15 Myr, whichever happened first.

2.1 Scaling issues

The mass of the ‘stars’ in our simulations are probably too high compared to real Galactic nuclei, since even if the central parts are enriched in black holes which spiralled into the centres through dynamical friction (Baumgardt et al. 2004b; Freitag, Amaro-Seoane & Kalogera 2006), the average mass is unlikely to be higher than a few $M_\odot$. We therefore have to study to which extent the high stellar masses in our runs can bias our results.

The inspiral time of the IMBHs should not change since dynamical friction is independent of the mass of the background particles as long as $M_{\text{IMBH}} \gg m_\star$ (Binney & Tremaine 1986), which is the case both in our simulations and in real Galactic nuclei. Stochastic changes to the orbits of the IMBHs happen on a relaxation time-scale and should scale with the average stellar mass ($m_\star$) of cusp stars as $(m_\star)^{-1}$, i.e. in real nuclei the IMBHs change their orbital parameters slower than in our simulations, although the change should not be larger than a factor of a few.

The number of stars removed from the cusps after the IMBHs have spiralled into the centre will to first order scale linearly with the number of stars present if the overall mass density profile is fixed, i.e. would roughly be a factor of 10 higher in the Milky Way than in our simulations. At later stages, the inner cusps become depleted and stars have to be scattered into low-angular momentum orbits through relaxation processes in the outer cusp. The number of stars scattered into low-angular momentum orbits scales as $dn \sim n(r) t_\star/dt$, where $n(r)$ is the number density of stars at radius $r$ and $t_\star$ is the relaxation time at radius $r$. Since the relaxation time-scales with the
mass of the stars as \( n^{-1} \) (Spitzer 1987), and since the number of
stars \( n(r) \) scales as \( m^{-1} \) if the overall mass density profile is fixed,
the number of stars scattered into low-angular momentum orbits is
to first approximation independent of the average mass of stars. We
will come back to this point in Section 3.4.

3 RESULTS

3.1 IMBH inspiral and core formation

Initially all IMBHs sink towards the central SMBH due to dynamical
friction. Since in all runs the masses of the IMBHs are much higher
than the masses of the background stars, the frictional drag on the
IMBHs is given by (see Binney & Tremaine 1986, equation 7.18)

\[
\frac{dv}{dt} = -4\pi r \int \frac{\Delta G^2 \rho(r)M_{\text{IMBH}}}{v^3} \left( \text{erf}(X) - \frac{2X}{\sqrt{\pi}} e^{-X^2} \right) v,
\]

where \( \rho(r) \) is the background density of stars, \( \Lambda \) the Coulomb
logarithm and \( X = v/(\sqrt{2}\sigma) \) is the ratio between the velocity of the
IMBH and the [one-dimensional (1D)] stellar velocity dispersion \( \sigma \).

For an \( r^{-3/5} \) cusp profile, \( \sigma \) is approximately 0.60 times the circular
velocity. Assuming that the IMBH moves in a circular orbit, and
setting \( \Lambda = 6.6 \) (Spinazzato, Fellhauer & Portegies Zwart 2003),
equation (3) can be rewritten as

\[
F = -47.51 \frac{G^2 \rho_0 M_{\text{IMBH}}}{v^2 r^{3/5}}.
\]

Since the rate of angular momentum change is equal to \( dL/dt = F r/M_{\text{IMBH}} \)
and since the angular momentum itself is given by \( L = r v_c = \sqrt{GM_{\text{SMBH}} r} \),
this can be rewritten as

\[
r^{-3/4} \frac{dr}{dt} = -95.0 \frac{G \rho_0 M_{\text{IMBH}}}{M_{\text{SMBH}}}.
\]

Solving this equation with the initial condition \( r_0 = 0.1 \) pc gives for the
radius reached at time \( t \):

\[
r(t) = \left( \frac{1}{r_0^{1/4}} - 23.8 \frac{G \rho_0 M_{\text{IMBH}}}{M_{\text{SMBH}}^{1/2}} t \right)^4,
\]

and for the time required to reach the centre of the galaxy:

\[
T_{\text{inc}} = \frac{r_0^{1/4} M_{\text{SMBH}}^{1/2}}{G \rho_0 M_{\text{IMBH}}}.
\]

\[
= 6.11 \left( \frac{M_{\text{SMBH}}}{3 \times 10^6 M_\odot} \right)^{1.5} \left( \frac{M_{\text{IMBH}}}{10^4 M_\odot} \right)^{-1} \text{Myr}.
\]

Fig. 1 compares the inspiral predicted by the above theory with the
results of the \( N \)-body runs. We obtain reasonable agreement with
the \( N \)-body data as long as the distance of the IMBHs is larger than
\( r > 0.003 \) pc: the differences between the theoretical curves and the
data are within the errors with which the Coulomb logarithm was
determined by Spinnatto et al. (2003).

Inside \( r = 0.003 \) pc the stellar cusps contain only few stars (for the
cusp profile chosen in our runs only \( M\langle r \rangle = 2 \times 10^3 M_\odot \) in stars
were inside this radius), so the mass in stars becomes comparable to
the mass of the inspiralling IMBHs. In this case dynamical friction
becomes inefficient and the inspiral stalls since the IMBHs cannot
displace enough stars to lose further orbital energy. The remaining
evolution until the simulations were stopped at \( T = 15 \) Myr is mainly
driven by relaxation between stars at larger radii, due to which some
stars are scattered into the central loss cone around the SMBH. The
resulting interactions between the stars and the IMBHs cause a much
slower inspiral of the IMBHs (Begelman, Blandford & Rees 1980;
Makino 1997).

Fig. 2 depicts the evolution of orbital eccentricity of the IMBHs. The
orbital eccentricity of an IMBH is influenced by dynamical
friction, which arises due to many distant encounters, and a few
close interactions. During the inspiral phase, the orbits of all IMBHs
stay nearly circular, despite a decrease in semimajor axis by almost a
factor of 100. This is in agreement with analytic estimates which predict that dynamical friction in power-law haloes with an isotropic
velocity distribution should circularize the orbit of an infalling body (Tsuchiya & Shimada 2000).

After the IMBHs have reached the centre and removed most stars from the inner cusp, dynamical friction is unimportant and the orbits of the IMBHs change due to interactions with passing stars coming from larger radii. In this phase, the orbits acquire eccentricities as high as \(1 - e = 10^{-5}\) or larger, which, in case of the \(M_{\text{IMBH}} = 10^3 M_\odot\) IMBH, was high enough for the IMBH to pass within the radius of the last stable orbit around the SMBH, resulting in the merger of the two black holes.

In the absence of perturbations, the time for two orbiting black holes to merge due to the emission of gravitational waves can be approximated with (Peters 1964)

\[
T_{GW} = 0.0353 \frac{a^4 c^5}{G^2 m_1 m_2 (m_1 + m_2)} (1 - e^2)^{7/2}.
\] (8)

Here \(a\) and \(e\) are the semimajor axis and eccentricity of the orbit of the two black holes, \(m_1\) and \(m_2\) are their masses and \(c\) is the speed of light. The dashed lines in Fig. 2 show the eccentricity for which the time for merging due to GW emission becomes smaller than 10 orbital periods. In this regime the emission of gravitational waves dominates the evolution of the orbit, and the two black holes are likely to merge before dynamical interactions can reduce the eccentricity again. It can be seen that the lifetime of an IMBH in the galactic centre is limited to a few Myr. The time over which stars are ejected by an IMBH is therefore also limited to a few Myr, i.e. the majority of HVS are generated in short bursts. This sets IMBH-induced ejections apart from encounters of stellar binaries with a SMBH, which would create escapers nearly continuously and is therefore an important criterion to distinguish between the two cases.

As explained earlier, another possibility to distinguish the ejection of HVS due to IMBHs from binary-induced ejections is by studying the spatial distribution of ejected stars. Since stars ejected by an IMBH acquire their velocities mainly in the direction of motion of the IMBH, they should be ejected preferentially in the orbital plane of the IMBH. If the orbit is eccentric during the inspiral phase, stars should be ejected mainly in one direction since the density of stars increases strongly towards the centre (Levin 2005). In both cases it is however necessary that the orbital angular momentum vector and the Runge–Lenz vector of the IMBH stay constant for a sufficiently long time interval.

Fig. 3 depicts the direction of the orbital angular momentum vector of the \(M_{\text{IMBH}} = 3 \times 10^3 M_\odot\) runs at the start and by the time the runs were stopped. The initial density distribution follows a \(\rho \sim r^{-1.75}\) power-law cusp which is depleted in the central parts and turned into a core profile after the IMBHs have spiralled into the centre. After the \(M_{\text{IMBH}} = 10^3 M_\odot\) merged with the SMBH, the central cusp is replenished only very slowly (dotted lines). The density profile in the Galactic Centre should show a similar core if it contained an IMBH within the last 100 Myr.
radius of about $r = 0.02$ pc. The core radii stay nearly constant in time since the ejection rate of stars is low after the initial peak. The only exception is the $M_{\text{IMBH}} = 10^3 M_\odot$ run which did not last long enough to completely deplete the central cusp.

Although so far no indication for a cored density profile has been found in the Galactic Centre, present observational techniques are only about now reaching the spatial resolution to measure the density profile inside 1 arcsec. If future observations reveal a cored density profile this would be additional evidence for an IMBH in the Galactic Centre. In order to test how quickly the core is replenished, we continued the $M_{\text{IMBH}} = 10^4 M_\odot$ run after the IMBH merged with the SMBH. Even after running the simulation for 10 Myr, there was only a slight increase in central density. Since the relaxation time in our runs is about a factor of 10 smaller than in real Galactic nuclei, replenishing the cusp in the Galactic Centre should take at least $T \approx 100$ Myr and possibly even longer. Similar large refilling times were also obtained by Merritt & Wang (2005) through analytic estimates. If observations show that the power-law cusp in the Galactic Centre extends down to radii much smaller than 0.02 pc, the presence of massive IMBHs in the Galactic Centre within the last 100 Myr could be excluded. In this case the observed HVS would not have been ejected by IMBHs, since typical travel times of HVS are of order $10^8$ yr or less (Brown et al. 2006a).

3.2 Ejection of HVS

As the IMBHs sink towards the Galactic Centre, interactions with the background stars that orbit the SMBH result in a large number of ejections. We consider as escaping stars all stars that acquire positive energies during the calculation, i.e. which can leave the inner cusp region modelled in our simulations. Fig. 5 depicts the escape rate of all ejected stars as a function of time. The overall evolution is very similar for the three IMBH masses: the escape rate rises with time and reaches a maximum when the IMBHs have spiralled into the centre. It drops on a similar time-scale during which the IMBHs scatter away all stars from the inner cusp region (see also Fig. 4). At later times, escapers are created mainly by relaxation processes in the outer cusp, due to which stars with large semimajor axes can be scattered to low angular momentum orbits and reach the inner cusp.

As shown in Fig. 2, the orbital evolution of the IMBH around the SMBH may be terminated by the emission of gravitational waves before the end of the calculation. We have therefore shown the further evolution of the escape rate in Fig. 5 with the dotted lines. For the higher mass IMBHs ($M_{\text{IMBH}} \geq 3 \times 10^3 M_\odot$), the majority of escapers are ejected well before the two black holes merge due to GW emission.

The dashed lines in Fig. 5 show the contribution of star–star interactions to the escape rate. Since we did not check for collisions between the stars during the simulations, the rate of star–star escapers should be higher in our runs than it would be in reality. We can estimate the rate of star–star escapers from the $M_{\text{IMBH}} = 10^4 M_\odot$ run where in the beginning the IMBH moves through a low-density environment and encounters only few stars. We find about 40 escapers Myr$^{-1}$ in this phase, which gives an upper limit for the rate of star–star escapers. We find a similar escape rate for the $M_{\text{IMBH}} = 10^5 M_\odot$ run after the IMBH merged with the SMBH. Hence, star–star interactions contribute only a small fraction to the overall escape rate once the IMBHs have reached the centres and can therefore be neglected when discussing the properties of HVS.

In order to find the HVS in our simulations, we followed the orbits of all escapers in the potential of the Galaxy after they left the Galactic Centre. We chose a fifth-order Runge–Kutta method with adaptive step size as the integrator. The model for the galactic potential was a combination of four separate components: the galactic centre, represented by a power-law density profile (Genzel et al. 2003), the bulge, represented by a Plummer model, the disc, represented by a Kazmin axisymmetric profile and the halo, represented by the Paczynski model (Paczynski 1990). We computed the trajectories of all escapers for 200 Myr or until the stars reached...
nuclei, depending on the central density of stars. The average rate of these numbers could be a factor of 10–30 higher for real Galactic mass of $10^4$, 3 with the SMBH after 5 Myr, we can estimate that IMBHs with escape within the following 40–100 Myr. depending on which IMBH mass we assume, about as many stars an IMBH creates HVS only in a short span of time before merging with the central SMBH. However, even if the IMBH can somehow escape within 1 Myr after the IMBH has reached the centre as would the galactic centre. The HVS distribution created by stellar binaries can be significantly different from the one created by IMBHs, which is nearly independent IMBH. A s spiralled down to a radius of about $r = 0.002$ pc, are 150 stars Myr$^{-1}$ for $M_{\text{IMBH}} = 10^4 M_\odot$, 42 stars Myr$^{-1}$ for $M_{\text{IMBH}} = 3 \times 10^3 M_\odot$ and 15 stars Myr$^{-1}$ for $M_{\text{IMBH}} = 10^3 M_\odot$, scaling roughly with $M_{\text{IMBH}}$. These numbers could be a factor of 10–30 higher for real Galactic nuclei, depending on the central density of stars. The average rate of HVS after the cusps have been depleted are 15 stars Myr$^{-1}$ for $M_{\text{IMBH}} = 10^3 M_\odot$, 10 stars Myr$^{-1}$ for $M_{\text{IMBH}} = 3 \times 10^2 M_\odot$ and 4 stars Myr$^{-1}$ for $M_{\text{IMBH}} = 10^3 M_\odot$, scaling roughly with $M_{\text{IMBH}}^3$. As explained in Section 2.1, we expect these numbers to be independent of the average mass of stars in our runs. As already explained before, an IMBH creates HVS only in a short span of time before merging with the central SMBH. However, even if the IMBH can somehow avoid merging, HVS will show a peak in their escape times since depending on which IMBH mass we assume, about as many stars escape within 1 Myr after the IMBH has reached the centre as would escape within the following 40–100 Myr.

Based on the above numbers, and assuming that the IMBH merges with the SMBH after 5 Myr, we can estimate that IMBHs with masses of $10^4$, $3 \times 10^3$ or $10^3 M_\odot$ create 1700, 900 and 600 HVS, respectively. If we assume a standard initial mass function (IMF), about 3 per cent of these stars would be O- or B-type stars. Especially for the high-mass IMBHs, the numbers are therefore large enough to explain the six observed HVS.

Fig. 7 shows the cumulative distribution of ejection velocities of HVS for the three different IMBH runs (solid line, dotted line, dashed line). The left-hand panel shows the distribution when the HVS are ejected from the cusp, while the right-hand panel shows the distribution when the HVS have reached a distance of $R = 100$ kpc from the galactic centre. The distribution was determined from all escaping HVS, but introducing a cut-off in time due to the possible merger of the IMBHs has little effect. At ejection, the velocities span a range between $\sim 800$ and $\sim 5000$ km s$^{-1}$, with the minimum being determined by the Galactic escape velocity. The distribution is very similar for the three runs, implying that the velocity with which stars escape does not depend strongly on the IMBH mass but rather on the local orbital velocity at the radius where the interaction takes place. We compare these distributions with those generated by encounters between stellar binaries and the SMBH as simulated by Gualandris et al. (2005). We consider equal mass binaries with 3 $M_\odot$ stars and two extreme values for the initial semimajor axis: $a = 0.05$ au (dash-dotted line) and $a = 1$ au (long dash–dotted line). The distribution for the smallest semimajor axis, which is the one that generates the fastest escapers, is significantly different from the distribution of HVS ejected by an IMBH. When a large sample of HVS will be available, it will be possible to discriminate between the two ejection scenarios based on the measured velocity distribution. We notice here that three-dimensional (3D) velocities are needed for this kind of analysis.

### 3.3 Spatial distribution of HVS

Fig. 8 shows the spatial distribution of HVS for the $M_{\text{IMBH}} = 3000 M_\odot$ and the $M_{\text{IMBH}} = 10^4 M_\odot$ runs 100 Myr after the start of the simulation during which the orbits of the HVS have been followed in the potential of the Galaxy, assuming that the inspiral plane of the IMBH agrees with the plane of the galactic disc ($z = 0$). For the $M_{\text{IMBH}} = 3000 M_\odot$ IMBH, the distribution of HVS is nearly isotropic and would thus be indistinguishable from a HVS distribution created by encounters of stellar binaries with a single SMBH. For the $M_{\text{IMBH}} = 10^4 M_\odot$ case, there is an overdensity of stars around the $z = 0$ plane. This is due to the fact that the inspiralling IMBH had $L_z/L_r^2 + L_y^2 + L_z^2 \approx 1$ during the first Myr of the inspiral, and consequently ejected stars preferentially in the $x$-$y$ plane. For the other runs we could not find such overdensities and they disappear for the $M_{\text{IMBH}} = 10^5 M_\odot$ IMBH if we assume that the orbital plane of the IMBH does not coincide with the Galactic plane. Although it is not impossible to find a non-isotropic spatial distribution of HVS, we conclude that this is at least unlikely.

Also shown in Fig. 8 are the velocity vectors of the HVS. As expected, they all point away from the galactic centre. Since HVS are created in a short burst whose duration is much smaller than the time required to travel into the galactic halo, the escape velocities of

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Figure 7. Velocity distribution of HVS for three different black hole masses (solid line, dotted line, dashed line), compared with the distribution of escapers generated by encounters between stellar binaries and the SMBH (dash–dotted line and long dash–dotted line, see Gualandris et al. 2005). Left-hand panel shows the velocity distribution of HVS when they are ejected from the cusp, right-hand panel shows the distribution after they have reached a distance of 100 kpc from the galactic centre. The HVS distribution created by stellar binaries can be significantly different from the one created by IMBHs, which is nearly independent of the IMBH mass.
Figure 8. Spatial distribution of all HVS created in the $M_{\text{IMBH}} = 3000 M_\odot$ run (upper plots) and in the $M_{\text{IMBH}} = 10^4 M_\odot$ run (lower plots) 100 Myr after the start of the simulations. The orbits of all escapers are followed in a realistic 3D Galactic potential to obtain their spatial distribution. The Galactic disc is assumed to be in the $x$–$y$ plane. The distribution of HVS after 100 Myr is isotropic in the $x$–$y$ plane for both IMBHs, but some overdensity can be seen in the $M_{\text{IMBH}} = 10^4 M_\odot$ case around $z = 0$. Also shown are the velocity vectors of each star. If HVS are created by IMBHs, the fastest stars should be found at the largest distances.

HVS also increase in magnitude with the distance from the centre. In case HVS are created by an IMBH, we therefore expect a similar correlation between escape velocity and galactocentric distance with the fastest HVS being found at the largest distances.

3.4 Dependence on the assumed mass of stars

As explained in Section 2.1, the average mass of stars in our runs is probably too high compared to real galactic nuclei. In order to test which influence this might have on our results, we repeated the $M_{\text{IMBH}} = 3000 M_\odot$ run, using stars with higher masses. In the first case we used $N = 5 \times 10^4$ stars with average mass $m = 60 M_\odot$ and in the second case $N = 2.5 \times 10^5$ stars with $m = 120 M_\odot$. All other parameters, like the density distribution of the stars and the total mass in stars were held constant.

Figs 9 and 10 show the results for the inspiral of the IMBHs and the ejection of HVS. Since $M_{\text{IMBH}} \gg m$, the inspiral of the IMBHs should not depend on the mass of individual stars but only on their overall density and this is confirmed by Fig. 9 since all three black holes spiral in at more or less the same rate. The slight differences visible in Fig. 9 between different runs are probably due to statistical effects since they become important only in the innermost part of the cusp where only relatively few stars are present and do not show a trend with the stellar mass used. We also find that the eccentricity evolution of the IMBHs is independent of the stellar mass: in all three runs, the orbits of the IMBHs stay nearly circular in the inspiral phase and become highly eccentric in the stalling phase. All IMBHs would merge with the SMBH after a few Myr due to gravitational wave emission from high-eccentricity orbits.

Fig. 10 depicts the ejection rate of stars in the three runs. As discussed in Section 2.1, we expect the maximum ejection rate to drop linearly with the number of stars in the cusp and this is confirmed by our runs since we obtain maximum ejection rates of $N = 1000, 500$ and $300$ stars Myr$^{-1}$ for runs with $N = 10^5, 5 \times 10^4$ and $2.5 \times 10^4$ stars. Fig. 10 also shows that in the later phases, when the central cusp has been depleted in stars, the ejection rate is nearly independent of the number of stars which is also in very good agreement with our theoretical considerations in Section 2.1. We finally found no significant dependence of stellar escape velocity with the mass of stars used, and conclude therefore that the results of our paper should be robust against changes of the average stellar mass.

4 CONCLUSIONS

We have performed simulations of the inspiral of massive black holes into the centres of galaxies and of the subsequent ejection of HVS. We found that the spatial distribution of HVS is nearly isotropic and would be difficult to distinguish from a HVS
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A broad distribution of escape times (Brown et al. 2005), which argues against ejection due to a single IMBH, but would still be consistent with the inspiral of several IMBHs. The evidence is not conclusive yet and requires more HVS to be found, which should be possible with future astrometric surveys like Global Astrometric Interferometer for Astrophysics (GAIA). In case HVS are ejected by an IMBH, we also expect a strong correlation of escape velocity with galactocentric distance in the sense that the fastest HVS can be found at the largest distances.

Another prediction from our runs is that IMBHs deplete the central region in stars so that an initial cusp profile is turned into a nearly constant density core with core radius \( r = 0.02 \) pc. If an IMBH was present in the Galactic Centre within the last \( 100 \) Myr, such a core should still be visible in the stellar density distribution. If on the other hand the cusp profile observed at larger radii continues all the way down to the centre, this would be evidence against the presence of an IMBH in the Galactic Centre within the last \( T \approx 100 \) Myr.

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Figure 9. Semimajor axes as a function of time of three IMBHs with mass \( M_{\text{IMBH}} = 3000 \) \( M_\odot \) moving through nuclei composed of stars with different stellar masses \( m \). The resulting inspiral is very similar for all three IMBHs, showing that the inspiral results do not depend on the average mass of stars used in our runs.

Figure 10. Rate of stars ejected from the central cusp as a function of time for an IMBH mass of 3000 \( M_\odot \) but three different stellar masses. As expected from theoretical arguments, the maximum ejection rate drops linearly with the number of stars while the escape rate at later times is nearly independent of the average stellar mass.

A distribution created by interactions of stellar binaries with an SMBH if only few HVS were found, as is presently the case. A better indication comes from the escape times of HVS: our simulations confirm that most HVS are ejected in a short burst, lasting only a few Myr for typical IMBH masses, as soon as the IMBH reaches the galactic centre. The ejection ends when the IMBH merges with the central SMBH, which should take less than 10 Myr. Even if merging can be avoided, the ejection rate of HVS is a factor of 30–100 lower than during the burst maximum. The currently observed HVS show...
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