Ejection of Hyper-Velocity Stars by Intermediate-Mass Black Holes

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Abstract. We have performed \( N \)-body simulations of the formation of hyper-velocity stars (HVS) in the centre of the Milky Way due to inspiralling intermediate-mass black holes (IMBHs). We find that due to dynamical friction, IMBHs sink into the centre of the Galaxy 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.

Our simulations show that HVS are generated in short bursts which last only a few Myrs until the IMBH is swallowed by the supermassive black hole (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. Finally, our simulations show that the presence of an IMBH in the Galactic centre changes the stellar density distribution inside \( r < 0.02 \text{ pc} \) into a core profile, which takes at least 100 Myrs to replenish.

1. Introduction

[9] was the first to show that the ejection of stars with velocities > 1000 km/sec is a natural consequence of galaxies hosting supermassive black holes and he named these stars ‘hyper-velocity stars’ (HVS). Recently, several HVS have been discovered in the Galactic halo [4, 9, 5]. Except for one star which might have been ejected from the LMC [6], 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 [3] and dynamical encounters [12] cannot produce main-sequence stars with velocities exceeding a few hundred kilometers per second [7], leaving the interaction of stars in galactic nuclei around super-massive black holes (SMBHs) as the only possible source for HVS.

[13] considered three processes which could eject stars with high velocities 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. For the SMBH in the Galactic centre they found that close encounters between single stars can
create HVS with a rate of only $10^{-11}\text{yr}^{-1}$ which would create less than one star during the lifetime of the Milky Way. The other two processes were found to eject stars with rates of up to $10^{-4}\text{yr}^{-1}$, sufficiently high to explain the observed number of HVS in the halo of the Milky Way.

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 binary should show characteristic variations with time and spatial direction (see e.g. [10]).

In the present work we have performed collisional $N$-body simulations of the dynamics of inspiralling IMBHs in stellar cusps around supermassive black holes. The aim of our simulations was 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 [1] on the GRAPE6 computers [11] of Bonn and Tokyo University. Our runs contained three different components: a central super-massive black hole (SMBH), an IMBH and $10^5$ 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 Galactic centre SMBH. The mass of the IMBHs was varied in the different runs. In total we performed 3 runs, using IMBH masses of $M_{\text{IMBH}} = 10^3 M_\odot, 3 \times 10^3 M_\odot$ 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 power-law cusp around the SMBHs. Stars were merged with the black holes (both SMBH or IMBH) if their separation became smaller than their tidal radius. 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 3 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 Myrs, whichever happened first.

3. Results

Fig. 1 depicts the inspiral of the 3 studied IMBHs. As predicted by theory, more massive IMBHs spiral in faster. Inside $r = 0.003$ pc the stellar cusps contain only few stars, (for the cusp profile chosen in our runs only $M(< r) = 2 \cdot 10^3 M_\odot$ 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.

Fig. 2 depicts the evolution of orbital eccentricity of the IMBHs. During the inspiral phase, the orbits of all IMBHs stay nearly circular, while the eccentricities can reach values as large as $1 - e = 10^{-3}$ once the IMBHs have reached the centre. This is large enough that the IMBHs can merge with the central SMBH due to the emission of gravitational waves (dotted lines). The lifetime of an IMBH in the galactic centre is therefore limited to a few Myrs.

Fig. 3 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
Figure 1. Semi-major axis of the IMBHs as a function of time. IMBHs spiral in as a result of dynamical friction. Inside $r = 0.003$ pc, the central cusp contains too few stars and the inspiral stalls.

Figure 2. Evolution of the orbital eccentricity of the inspiralling IMBHs. The orbits remain nearly circular during the inspiral phase and become highly eccentric in the stalling phase.

when the IMBHs have spiralled into the centre. It drops on a similar timescale during which the IMBHs scatter away all stars from the inner cusp region. 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. 3 with 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.

In order to find the HVSs in our simulations, we followed the orbits of all escapers in the potential of the Galaxy after they left the Galactic centre and considered as HVSs only those stars which acquired large enough velocities to be unbound and escape the Milky Way potential. Fig. 4 shows the spatial distribution of HVS for the $M_{\text{IMBH}} = 3000 M_\odot$ run 100 Myrs after the start of the simulation, assuming that the inspiral plane of the IMBH agrees with the plane of the galactic disc ($z=0$). For the $M_{\text{IMBH}} = 3000 M_\odot$ run, 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. Also shown in Fig. 4 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 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.

Fig. 5 shows the density profile of the stellar cusp for the $M_{\text{IMBH}} = 10^4 M_\odot$ and $M_{\text{IMBH}} = 3 \times 10^3 M_\odot$ runs at the start and by the time the runs were stopped. The initial density profile follows an $\alpha = 1.75$ power-law cusp for radii $r < 1$ pc down to about $r = 3 \times 10^{-4}$ pc, at which radius the cusp runs out of stars. Due to the merger of cusp stars with the central SMBH and the ejection of stars by the IMBHs, the initial cusps are turned into core profiles with a core 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.
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 Myrs, 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 $T \approx 100$ Myrs and possibly even longer. 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 Myrs 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 $10^8$ years or less [5].

4. Conclusions
We have performed simulations of the inspiral of massive black holes into the centres of galaxies and of the subsequent ejection of hyper-velocity stars. We found that the spatial distribution of HVS is nearly isotropic and would be difficult to distinguish from a HVS 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 short bursts, lasting only a few Myrs 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 happen within a few Myrs for typical IMBH masses. Even if merging can somehow be avoided, the ejection rate of HVS is a factor of 30 to 100 lower than during the burst maximum. The currently observed HVS show a broad distribution of escape times [4], which argues against ejection due to a single IMBH, but would still be consistent with
Figure 5. Density distribution of stars at three different times for the $M_{\text{IMBH}} = 10^4 M_\odot$ and $M_{\text{IMBH}} = 3 \cdot 10^3 M_\odot$ runs. In both runs, 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 $M_{\text{IMBH}} = 10^4 M_\odot$ IMBH 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 Myrs.

the inspiral of several IMBHs. In case HVS are ejected by IMBHs, we expect a strong correlation of escape velocity with galactocentric distance in the sense that the fastest HVS can be found at the largest distances. A more detailed discussion of our results can be found in [2].

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