Three-body encounters in the Galactic centre: the origin of the hypervelocity star SDSS J090745.0+024507

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ABSTRACT
Hills (1988) predicted that runaway stars could be accelerated to velocities larger than 1000 km s$^{-1}$ by dynamical encounters with the supermassive black hole (SMBH) in the Galactic center. The recently discovered hypervelocity star SDSS J090745.0+024507 (hereafter HVS) is escaping the Galaxy at high speed and could be the first object in this class. With the measured radial velocity and the estimated distance to the HVS, we trace back its trajectory in the Galactic potential. Assuming it was ejected from the center, we find that a $\sim 2$ mas yr$^{-1}$ proper motion is necessary for the star to have come within a few parsecs of the SMBH. We perform three-body scattering experiments to constrain the progenitor encounter which accelerated the HVS. As proposed by Yu & Tremaine (2003), we consider the tidal disruption of binary systems by the SMBH and the encounter between a star and a binary black hole, as well as an alternative scenario involving intermediate mass black holes. We find that the tidal disruption of a stellar binary ejects stars with a larger velocity compared to the encounter between a single star and a binary black hole, but has a somewhat smaller ejection rate due to the greater availability of single stars.

Key words: Stars: individual (SDSS J090745.0+024507) – Methods: N-body simulations

1 INTRODUCTION
The recent discovery by Brown et al. (2005) of the hypervelocity star SDSS J090745.0+024507 (hereafter the HVS) has lent credence to the prediction of Hills (1988) that dynamical encounters with the black hole in the Galactic centre can eject stars with velocities up to several thousand kilometers per second. At a distance of 40-70 kpc, the HVS has a heliocentric radial velocity of $853 \pm 12$ km s$^{-1}$ in a direction of $174^\circ$ from the Galactic centre (Brown et al. 2005). Once corrected for solar motion and galactic rotation, this translates into a velocity of about 730 km s$^{-1}$ relative to the Local Standard of Rest. This velocity, which represents the lower limit of the total space velocity, is significantly higher than that of any other runaway or high-velocity star in the Galaxy (Stone 1991).

We investigate the origin of the extreme velocity of the HVS by means of kinematic analyses, binary evolution calculations and numerical scattering experiments. There are three possible explanations for the velocity of the HVS: (i) ejection upon supernova explosion of the companion in a binary system; (ii) dynamical ejection after a close encounter with main sequence stars or stellar mass compact objects; (iii) dynamical ejection from the Galactic centre as a result of an encounter with the supermassive black hole.

The paper is organised as follows: in §2 we analyse the possibility of an origin in the Galactic disk and an ejection by supernova explosion, in §3 we back-trace the orbit of the star in the Galactic potential and constrain the value of its proper motion and in §4 we describe numerical scattering experiments of 3-body encounters involving main sequence (MS) stars, the supermassive black hole (SMBH) and intermediate-mass black holes (IMBHs).

2 THE ORIGIN OF THE HIGH VELOCITY OF THE HVS
To address the possibility that the HVS is a high-velocity runaway resulting from the disintegration of a binary system, we turned to population synthesis. Making use of the SeBa stellar evolution package (Portegies Zwart et al. 2001), we generated two sets of $10^6$ binaries each. In the first set, primary masses ranged from $100 M_\odot$ down to the hydrogen burning limit. In the second set, the minimum primary mass was increased to $8 M_\odot$, in order to get a larger sam-
ple of events for statistical purposes. The mass ratio in both cases was chosen from the distribution of \cite{Hogeveen1992}, whilst the initial orbital separation was drawn from that of \cite{Duquennoy1991} and truncated at 10^5 R⊙. The distribution of natal kick speeds for neutron stars was taken from \cite{Paczynski1990}, with a dispersion of 300 km s^{-1}. We assumed that the escape speed was the orbital speed of the secondary immediately before the binary disintegrated. As well, we only considered secondary stars with a mass below 10 M⊙, given the known constraints on the mass of the HVS. From this synthesis experiment, we obtained maximum escape speeds of ∼ 70 km s^{-1}, an order of magnitude below the space velocity of the HVS. Based upon this, we reject the high-velocity runaway hypothesis. The possibility that the system is a binary and that its high speed is the result of an asymmetric supernova kick can be discounted because, if we assume that the visible companion is on the main sequence, a kick magnitude in excess of 2000 km s^{-1} would be required. While this can not be ruled out physically, the probability of the system remaining bound in such an event is negligible.

The only alternative explanation for the high velocity of the HVS is an ejection during a dynamical encounter. Stellar encounters involving MS stars, neutron stars or stellar mass black holes eject stars with maximum velocities on the order of the orbital velocity in binary systems \cite{Gualandris2004, Sigurdsson1993, Brown2003} assume therefore that the HVS was ejected from the Galactic centre by a strong encounter with the SMBH. This possibility was first proposed by \cite{Hills1988}, who considered encounters of binaries with a SMBH, and then further developed by \cite{Yu2003}, who found that encounters between binaries and the SMBH or between single stars and a binary black hole represent the most efficient channel to eject hypervelocity stars.

3 THE TRAJECTORY OF THE HVS IN THE GALAXY

In the previous section we argue that the HVS must have been ejected from the Galactic centre by a dynamical encounter with the SMBH. This implies that the HVS originated in the Milky Way’s central region. Despite the incompleteness of available kinematic data, we trace back the orbit of the HVS in the Galactic potential. The distance of the object is still uncertain, as it depends on its spectral type and evolutionary state. \cite{Brown2002} estimate a distance of 71 kpc for a B9.2 MS star and 39 kpc for a blue horizontal branch star, with an average value d = 55 kpc. We consider all three values in our analysis. We first assume that the star has no proper motion and trace its trajectory backward in time until it crosses the disc, using Paczynski’s model (1990) for the potential of the Galaxy. The orbit, shown in Fig. 1 (solid line), is based upon this assumption. We then randomly generate the two proper motion components in the range 1-3 mas yr^{-1} and derive the three-dimensional positions and velocities in the galactocentric reference frame \cite{Johnson1987}. For each distance value we generate about 5000 sets of initial conditions, integrate the trajectories and determine the minimum distance d_{min} to the Galactic centre. We find that there is at least one combination of proper motion components for each distance such that d_{min} < 5 pc. In Tab. 1 we report, for each distance d, the average values \mu_α and \mu_δ of the proper motion components such that d_{min} < 10 pc, the corresponding heliocentric velocity V_{SUN} and the velocity V_{ej} at a distance d_{min} from the centre corrected for galactic rotation.

![Figure 1. Trajectory of the HVS integrated backward in time in the Galactic potential without any proper motion component (dashed line) and with a proper motion of about 1.8 mas yr^{-1} (solid line). The integration is stopped upon passage through the disc. The full dot represents the present position of the star at a distance of 55 kpc while the grey dots represent a schematic model of the Galaxy.](image)

| d (kpc) | \mu_α (mas/yr) | \mu_δ (mas/yr) | V_{SUN} (km/s) | V_{ej} (km/s) |
|--------|----------------|----------------|---------------|---------------|
| 39     | -1.4916 ± 0.0007 | 2.1679 ± 0.0009 | 982 ± 1       | 1246 ± 144    |
| 55     | -0.9769 ± 0.0004 | 1.5379 ± 0.0003 | 976 ± 1       | 1260 ± 66     |
| 71     | -0.7214 ± 0.0002 | 1.1917 ± 0.0003 | 973 ± 1       | 1249 ± 142    |

We can use this analysis to calculate the minimum velocity with which the HVS should have been ejected from the disk in the case of the binary supernova scenario. Assuming a random proper motion in the range 1-3 mas yr^{-1}, the minimum velocity at disk crossing (corrected for galactic rotation) is about 500 km s^{-1}, much larger than the average recoil velocity from a supernova explosion (see § 2). This result supports the scenario of an origin in the Galactic centre.
4 THREE-BODY SCATTERINGS WITH THE SUPERMASSIVE BLACK HOLE

We now explore the hypothesis of a dynamical ejection from the Galactic centre by means of numerical simulations of three-body scatterings with the SMBH. In Fig. 2 we show three examples of encounters involving MS stars, the SMBH and an IMBH. The experiments are carried out with the \texttt{sim} package included in the STARLAB\footnote{http://www.manybody.org/manybody/starlab.html} software environment \cite{McMillan&Hut1996,PortegiesZwartetal2004}. For each simulation we specify: the masses of the three stars, the semi-major axis and eccentricity of the binary and the relative velocity at infinity between the binary’s centre of mass and the single star. In order to classify possible collisions and mergers, physical radii are also specified for the stars. Additional parameters like the orbital phase of the binary and its orientation relative to the incoming star are randomly drawn from uniform distributions \cite{Hut&Bahcall1983}. The initial eccentricity is drawn from a thermal distribution \cite{Heggie1975}. The impact parameter $b$ is randomized according to an equal probability distribution for $b^2$ in the range $[0 - b_{\text{max}}]$. The maximum value $b_{\text{max}}$ is determined automatically for each experiment \cite{Gualandris,PortegiesZwart,Eggleton2004} for a description. Energy conservation is usually better than one part in $10^6$ and, in case the error exceeds $10^{-5}$, the encounter is rejected. The accuracy in the integrator is chosen in such a way that at most 5% of the encounters are rejected.

In all the experiments, we consider MS stars of mass $m = 3M_{\odot}$ (as indicated by \cite{Brownetal2003} for a B9 star) and radius $R = 2.4R_{\odot}$, an IMBH of mass $m_{\text{BH}} = 3000M_{\odot}$ and a SMBH of mass $M_{\text{BH}} = 3.5 \times 10^6 M_{\odot}$ \cite{Ghezetal2003,Schodeletal2003}. The relative velocity at infinity between the single star and the binary’s centre of mass is set equal to the dispersion velocity in the Galactic centre ($\sim 100\text{ km s}^{-1}$). The ejection velocities of escapers are taken at the distance at which the integrator stops \cite{McMillan&Hut1996}. The effect of the black hole potential is negligible at this distance.

4.1 Encounters between a binary of MS stars and the SMBH

Close encounters between a binary and a very massive object can (i) break up the binaries and eject the two components with high speed (ionizations), (ii) eject one star and leave the second star bound to the SMBH (exchange) (see the left panel of Fig. 2). We perform scattering experiments between the SMBH and binaries of MS stars. In all the runs, the binary stars have equal mass $m$ and the semi-major axis is varied in the range $0.05\text{ AU} < a < 1\text{ AU}$.

In Fig. 3 we show the average ejection velocity $V_{ej}$ of escapers as a function of the initial binary semi-major axis. Sufficiently high ejection velocities ($V_{ej} \gtrsim 1250\text{ km s}^{-1}$) are obtained for $a \lesssim 0.3\text{ AU}$. The dotted line represents the theoretical prediction by \cite{Yu&Tremaine2003} with an ejection speed parameter $v_{ejH} = 130\text{ km s}^{-1}$ (see Eq. 20).

In Fig. 4 we show the fraction of encounters resulting in ionization, exchange of the secondary star or merger for the range of $a$ under consideration. The fraction of encounters resulting in an exchange of the secondary star increases slowly from about 25% for $a = 0.005\text{ AU}$ to about 30% for $a = 1\text{ AU}$. Since the binary components have equal masses, the probability of ejection for the two stars is equal in exchange encounters. Ionizations are rare and only occur for $a \gtrsim 0.2\text{ AU}$, which marks the transition between hard and soft binaries \cite{Heggie1977}. As a result, high ejection velocities are mostly produced in exchange encounters. The total fraction of scatterings whose outcome is a star escaping with a velocity larger than $1250\text{ km s}^{-1}$ decreases rapidly with increasing $a$, and therefore binaries with semi-major axis $0.05\text{ AU} \lesssim a \lesssim 0.3\text{ AU}$ are the most suitable progenitors of hypervelocity stars. If we consider that about 20% of the simulated encounters result in the ejection of a hypervelocity star over the suggested range of orbital separations, the ejection rate provided by \cite{Yu&Tremaine2003} can be refined to $\sim 3 \times 10^{-6} \text{ (}\eta/0.1\text{)} \text{ yr}^{-1}$, where $\eta$ is the binary fraction.
Figure 3. Average recoil velocity of escapers as a function of the initial binary semi-major axis in the interaction of a stellar binary with the SMBH. The error bars indicate the 2σ deviation from the mean. The squares indicate the velocity $V_{\text{max}}$ for which 1% of the encounters have $V_{ej} > V_{\text{max}}$. The triangles indicate the velocity $V_{\text{min}}$ for which 1% of the encounters have $V_{ej} < V_{\text{min}}$. The horizontal line marks the 1250 km s$^{-1}$ ejection velocity of the HVS while the dotted line gives the theoretical estimate by Yu & Tremaine (2003).

Figure 4. Branching ratios as a function of the initial binary semi-major axis for encounters between a stellar binary and the SMBH. The empty symbols indicate the total fraction of ionizations, exchanges and mergers while the full dots indicate the fraction of encounters which produce escaping stars with a velocity larger than 1250 km s$^{-1}$.

The fraction of physical collisions and mergers decreases steadily with increasing $a$ from $\sim$20% to $\sim$2%, and mainly involve the binary components. Collisions with the SMBH occur in less than 1% of the cases. The merger products can remain bound to the SMBH or escape its gravitational potential. We perform additional scattering experiments of encounters between binaries and the SMBH to study the properties of the merger products. We consider equal mass binaries with mass $m = 1.5 M_\odot$ (in such a way that the mass of any possible merger is $\sim 3 M_\odot$) and radius $R = 1.4 R_\odot$. Escapers are ejected with velocities larger than 1000 km s$^{-1}$ if the initial semi-major axis is in the range $0.03 \text{ AU} < a < 0.05 \text{ AU}$. In this range, only about 6% of the encounters result in a binary merger with escape of the collision product. We therefore consider this scenario inefficient for the production of hypervelocity stars.

4.2 Encounters between a single star and a binary black hole

We now consider the hypothesis that the SMBH is in a binary with an IMBH and interacts with single stars (see the central panel of Fig. 2). The semi-major axis of the black hole binary is taken in the range $2 \text{ AU} < a < 1000 \text{ AU}$. All the simulated encounters result in a preservation of the black hole binary, during which the single star gains kinetic energy and escapes.

In Fig. 5 we show the average ejection velocity of the escaping star as a function of $a$. The maximum velocity obtained in these encounters is about 1000 km s$^{-1}$, barely sufficient to explain the velocity of the HVS. The comparison with the theoretical estimate (dotted line) by Yu & Tremaine (2003) reveals a discrepancy of about a factor of 2 in the ejection velocities. The numerical results also flatten at large initial semi-major axes and deviate from the expected $V_{ej} \propto a^{-1/2}$ scaling. We have performed additional calculations with 1$M_\odot$ incoming stars but the average $V_{ej}$ appears to be insensitive to the mass of the single star.
4.3 Encounters between a SMBH and a main sequence star in a binary with an IMBH

It has been proposed that the Galactic centre is populated by IMBHs, with masses in the range $100 - 10000 M_\odot$. These IMBHs may form in young dense star clusters as a result of runaway collisions and sink toward the Galactic centre together with their parent cluster due to dynamical friction. While the cluster dissolves in the Galactic potential, the IMBHs continue to spiral in, possibly with a stellar companion, until they eventually interact with the SMBH. If this is the case, IMBHs must play a role in the dynamical encounters taking place in the few inner parsecs of the Galaxy. We consider encounters between the SMBH and a binary consisting of a MS star and an IMBH. We select the binary semi-major axis in the range $0.1 \text{ AU} < a < 100 \text{ AU}$, with the lower limit set by the IMBH’s tidal radius $R_t = R(m_{BH}/m)^{1/3} = 24 R_\odot$ for the adopted masses and radii. We focus on the encounters whose final outcome is the break-up of the binary with subsequent ejection of star $m$ to infinity, while the IMBH can either remain bound to the SMBH or escape (see the right panel of Fig. 2). Figure 5 reports the velocity of the escaping star after the encounter as a function of the initial $a$. This type of encounter can easily eject stars with velocities of thousands of kilometers per second. A theoretical estimate derived from Yu & Tremaine (2003) (see Eq. 1–3) is shown with a dotted line. The numerical results agree well with the theoretical estimate.

In Fig. 6, we show the fraction of encounters resulting in ionization, exchange of the secondary star or merger for the range of $a$ under consideration. For $a \lesssim 0.3 \text{ AU}$ the binary is hard and the total cross-section is dominated by exchange encounters. In this case, the escaping star gains energy at the expense of the IMBH, which becomes bound to the SMBH. For larger semi-major axes, the binary is soft and tends to be ionized. The highest recoil velocities are generally obtained in exchange encounters.

Although this scenario can eject stars with hypervelocities over a wide range of orbital separations, only rarely eccentric orbits result in prompt ionization. Prompt ionization only occurs for low angular momentum orbits, which comprise a fraction of about $10^{-3}$ if we assume an isotropic velocity distribution. Adopting a formation rate of $\sim 10^{-7} \text{ yr}^{-1}$ for IMBHs Portegies Zwart et al. (2005), the ejection rate can be as small as $\eta 10^{-11} \text{ yr}^{-1}$, where $\eta$ represents the fraction of IMBHs with a stellar companion. Low eccentricity orbits result in a slow inspiral of the binary due to dynamical friction, but, in this case, it is not clear whether the stellar density is sufficiently high to drag the binary to the tidal radius of the SMBH. If an encounter with the SMBH does take place, we expect the ejection velocity to be much lower than in the case of a prompt ionization.

5 SUMMARY AND CONCLUSIONS

We have investigated the origin of the extreme velocity of the HVS by means of kinematic analyses, binary evolution calculations and numerical simulations of three-body encounters.

By tracing the trajectory of the HVS in the Galactic potential (using the available measurements for the distance and the radial velocity), we have shown that a proper motion of about $\sim 2 \text{ mas yr}^{-1}$ is required for the star to have come within a few parsecs from the SMBH.

We confirm the prediction by Hills (1988) and Yu & Tremaine (2003) that dynamical encounters with the SMBH can eject hypervelocity stars to the Galactic halo; the HVS is likely the first discovered object of this kind. The most promising scenarios are dynamical encounters of MS stars with the SMBH, possibly in a binary with an IMBH. In particular, the encounter between a SMBH and a stellar...
binary or between a single star and a binary black hole provide enough kinetic energy to eject hypervelocity stars over a restricted range of initial semi-major axes. We have also investigated the more exotic encounter between a SMBH and an IMBH orbited by a stellar companion. Although this type of encounter can be very energetic and doesn’t require any constraint on the binary’s hardness, it has a very low probability. The possibility that the HVS is the product of a merger induced by the SMBH is intriguing but not very likely.

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