A hypervelocity star from the Large Magellanic Cloud

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Abstract

We study the acceleration of the star HE 0437–5439 to hypervelocity and discuss its possible origin in the Large Magellanic Cloud (LMC). The star has a radial velocity of 723 km s$^{-1}$ and is located at a distance of 61 kpc from the Sun. With a mass of about 8 $M_\odot$, the travel time from the Galactic centre is of about 100 Myr, much longer than its main sequence lifetime. Given the relatively small distance to the LMC (18 kpc), we consider it likely that HE 0437–5439 originated in the cloud rather than in the Galactic centre, like the other hypervelocity stars. The minimum ejection velocity required to travel from the LMC to its current location within its lifetime is about 500 km s$^{-1}$. Such a high velocity can only be obtained in a dynamical encounter with a massive black hole. We perform 3-body scattering simulations in which a stellar binary encounters a massive black hole and find that a black hole more massive than $10^3 M_\odot$ is necessary to explain the high velocity of HE 0437–5439. We look for possible parent clusters for HE 0437–5439 and find that NGC 2100 and NGC 2004 are young enough to host stars coeval to HE 0437–5439 and dense enough to produce an intermediate mass black hole able to eject an 8 $M_\odot$ star with hypervelocity.

Key words: Stars: black-holes – Stars: individual (HE 0437-5439) – Methods: N-body simulations – Binaries: dynamics.

1 INTRODUCTION

Recent radial velocity measurements of young stars in the Galactic halo has led to the discovery of a new class of stars, the so-called hypervelocity stars (HVS), which travel with velocities exceeding the escape speed of the Galaxy (Brown et al. 2005, 2006). A total of 7 HVSs has been discovered so far, of which six are consistent with an ejection from the centre of the Milky Way.

The existence of a population of HVSs was first proposed by Hills (1988), who considered hypervelocity ejections as a natural consequence of galaxies hosting supermassive black holes (SMBHs). The interaction between a SMBH and a stellar binary can result in the dynamical capture of one of the binary components at the expense of the high velocity ejection of its companion star (Hills 1988; Yu & Tremaine 2003; Gualandris et al. 2005). Later an alternative was proposed by Baumgardt et al. (2006), who argue that an intermediate-mass black hole (IMBH) can eject stars with extremely high velocities as it spirals in towards the Galactic centre. The latter mechanism tends to produce HVSs in bursts which last a few Myr (Baumgardt et al. 2006). Since the reconstructed ejection times of the observed HVSs are roughly evenly distributed over about 100 Myr, it seems likely that they were ejected in a continuous process. For 6 of the observed HVSs, in fact, the travel time from the Galactic centre and the estimated age are consistent and, by assuming a suitable proper motion, it is possible to calculate a realistic trajectory.

For HE 0437–5439, however, an ejection from the Galactic centre appears problematic as the time required to travel from the centre to its observed location exceeds the maximum lifetime of the star. HE 0437–5439 is a main-sequence star with spectral type B and a mass of about 8.4 $M_\odot$ for a solar metallicity or of about 8 $M_\odot$ for a Z = 0.008 metallicity, which corresponds to main-sequence lifetimes of 25 and 35 Myr, respectively. Adopting a distance of 61 kpc from the Sun (Edelmann et al. 2005) and considering a total space velocity equal to the radial velocity only, the travel time for a straight orbit from the Galactic centre is of about 80 Myr, much longer than the main-sequence lifetime of the star. The estimated proper motion for which the orbit of the star comes within 10 pc from the centre is of about 0.55 mas yr$^{-1}$ (Edelmann et al. 2005). This results in a tangential velocity of about 160 km s$^{-1}$ and hence in a total space velocity of 740 km s$^{-1}$, which corresponds to a travel time of 100 Myr for a realistic orbit.

We discard the possibility that HE 0437–5439 is a blue straggler originated in the Galactic centre since, even in the case of a merger between two less massive stars, the merger
product would not survive as an 8 M_☉ star for much longer than the main-sequence lifetime of such a star.

Given the fact that HE0437–5439 is much closer to the LMC galaxy than to the Milky Way, Edelmann et al. (2003) suggest that HE0437–5439 might have been ejected from the LMC. Considering a total distance of 18 kpc from the LMC centre, the minimum ejection velocity required to travel to the current position is about 500 km s^−1. (Here we adopted a travel time of 35 Myr, which is equal to the main-sequence lifetime in a low metallicity environment.) The radial velocity of HE0437–5439 relative to the LMC is 461 km s^−1, and the required tangential velocity is then 160 km s^−1, which in turns implies a proper motion of 1.9 mas yr^−1. A velocity of the order of 500 km s^−1 can only be obtained in a dynamical interaction with a massive black hole (see Gualandris et al. (2003)).

If HE0437–5439 was ejected by an IMBH and if it came from the LMC, the natural consequence is that there must then be an IMBH in the LMC. We investigate this hypothesis by studying the dynamical ejection of an 8 M_☉ main-sequence star in an interaction with a massive black hole. We simulate the encounter between a stellar binary and a black hole to study the minimum mass of the black hole required to accelerate one of the interacting stars to a velocity of at least 500 km s^−1. We then investigate where in the LMC such an interaction could have taken place.

We find that a black hole of \( \gtrsim 10^3 \) M_☉ is required to explain the velocity of HE0437–5439. Such an IMBH could form in a young and dense star cluster (Portegies Zwart et al. 2004) and would help driving the frequent strong encounters with massive stars needed to make high-velocity ejections likely (Baumgardt et al. 2004). The IMBH must still be present in a star cluster which contains stars as massive as HE0437–5439. In addition, the parent star cluster must have been massive enough and with a short enough relaxation time to produce an IMBH (Portegies Zwart et al. 2004). The most likely clusters are NGC 2100 and NGC 2004.

2 THREE-BODY SCATTERINGS WITH A MASSIVE BLACK HOLE IN THE LMC

In this section we explore the hypothesis of a dynamical ejection from the LMC by means of numerical simulations of three-body scatterings with a massive black hole. In §2.1 we focus on interactions in which a binary containing a young 8 M_☉ main-sequence star (representing HE0437–5439) encounters a single black hole of 10^2 M_☉ to 10^4 M_☉, whereas in §2.2 a single 8 M_☉ main-sequence star encounters a binary black hole. In the first case, an exchange interaction can lead to the high velocity ejection of one of the binary components while in the latter case the main-sequence star can be accelerated in a fly-by.

The simulations are carried out using the sigma3 package, which is part of the STARLAB software environment (McMillan & Hut 1996, Portegies Zwart et al. 2001).

For each simulation we select 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. The phase of the encountering binary is randomly drawn from a uniform distribution (Hut & Bahcall 1983) and the orbital eccentricity is taken randomly between circular and hyperbolic from the thermal distribution. The impact parameter \( b \) is randomised according to \( b^2 \) in the range \( [0 - b_{max}] \) to guarantee that the probability distribution is homogeneously sampled. The maximum value \( b_{max} \) is determined automatically for each set of experiments (see Gualandris et al. 2004 for a description). Energy conservation is typically better than one part in \( 10^6 \) and, in case the error exceeds \( 10^{-3} \), the encounter is rejected. The accuracy in the integrator is chosen in such a way that at most 5% of the encounters are rejected. During the simulations we allow for physical collisions when the distance between any two stars is smaller than the sum of their radii. The black hole is assumed to be a point mass, while for the stars we adopt zero-age main-sequence radii, taken from Eggleton et al. (1989).

2.1 Encounters between a stellar binary and a massive black hole

We consider encounters between a binary consisting of two main-sequence stars with masses \( m_1 \) and \( m_2 \) and a single black hole with mass \( M_{bh} \). The mass of one binary component is fixed to 8 M_☉ while the mass of the companion star has values of 2 M_☉, 4 M_☉, 8 M_☉ and 16 M_☉. For each choice of stellar masses, the semi-major axis \( a \) is varied between a minimum value, which is set by the physical radii of the stars so that the two components do not touch at the first pericentre passage, and a maximum of 1 AU. We consider black holes of masses \( 10^2 \) M_☉, \( 10^3 \) and \( 10^4 \) M_☉. The relative velocity at infinity between the black hole and the binary’s centre of mass is set equal to 20 km s^−1.

In Fig.1 we present the probability of different outcomes (branching ratios) in the simulations of an encounter between an equal mass binary \( (m_1 = m_2 = 8 \) M_☉) and a \( 10^3 \) M_☉ black hole. For each of the initial semi-major axes we perform a total of 1500 scattering experiments, which result either in a fly-by, an exchange or a merger. Mergers occur preferentially in the case of tight binaries, leaving place to preserves and exchanges for wider binaries. In an exchange interaction one of the main-sequence stars is captured by the black hole while the other star is ejected, possibly with high velocity. If the velocity exceeds \( 500 \) km s^−1, we regard the star as a possible candidate for HE0437–5439. This occurs in about 10% or less of all encounters for semi-major axes in the range 0.1 – 1.0 AU.

In Fig.2 we show the branching ratios for high velocity ejections for binaries with a 8 M_☉ star and a companion with mass in the range 2.0 – 16.0 M_☉. While the 8 M_☉ main-sequence star is ejected, the companion star is captured by the IMBH. As in the previous plot, the black hole mass is of \( 10^3 \) M_☉. Exchange encounters with fast escapers are more likely in the case of binaries with larger companion masses and/or shorter orbital periods.

Analytical estimates by Yu & Tremaine (2003) for the case of tidal breakup predict an ejection velocity at infinity

\[
V_\infty = \left( \frac{M_{bh}}{m} \right)^{1/6} \left( \frac{0.1 \text{ AU}}{a} \right)^{1/2} \left( \frac{m}{1 \text{ M}_\odot} \right)^{1/2},
\]

\(^1\) http://www.manybody.org/manybody/starlab.html
where $v'$ is a function of the distance of closest approach $R_{\text{min}}$. If we define a dimensionless closest approach parameter $R_{\text{min}}' = \left( \frac{M_{\text{bh}}}{m} \right)^{-1/3}$, $v'$ varies in the range 130–160 km s$^{-1}$ for $R_{\text{min}} = 0 - 1$. For $m = 8 M_\odot$ and $a = 0.1$ AU Eq. 1 yields $v_\infty \approx 560$ km s$^{-1}$ for $M_{\text{bh}} = 10^2 M_\odot$; a $100 M_\odot$ IMBH would in principle be sufficient to explain the origin of HE 0437–5439.

In Fig. 2 we show the velocity distributions of the escaping single star in the case of equal mass binaries ($m_1 = m_2 = 8 M_\odot$). The different panels refer to different values of the black hole mass, from $10^2 M_\odot$ (left) to $10^3 M_\odot$ (middle) and $10^4 M_\odot$ (right). In each panel, the different distributions refer to three different values of the initial semi-major axis. While it appears possible to reach the required recoil velocity in the case of $M_{\text{bh}} = 10^2 M_\odot$, the smallest possible semi-major axis is needed ($a = 0.1$ AU) for this to happen, and only in about 10% of exchange encounters, which corresponds to about 3% of all simulated scatterings. In the case of the $10^4 M_\odot$ black hole it is possible to achieve such high velocities even for rather wide binaries. Based on these data we conclude that a $100 M_\odot$ black hole is unlikely to have resulted in the ejection of HE 0437–5439 and a black hole mass $> 10^3 M_\odot$ is favoured for typical values of $a$.

We note that the velocity distributions are not sensitive to the initial velocity between the binary and the single star as the total energy of the system is dominated by the binding energy of the binary rather than by the kinetic energy of the incoming star. Additional experiments performed with initial velocities of $5$ km s$^{-1}$ and $10$ km s$^{-1}$ showed no appreciable difference in the ejection velocities.

We also note that for detached binaries the binary tidal radius is always larger than the tidal radius of the single stars and therefore tidal breakup and ejection occur before the stars can be disrupted by the black hole. For (near) contact binaries, instead, it is possible to disrupt a star before an ejection can take place. This process does not depend on the black hole mass but on the size of the binary compared to the size of the stars. Our simulations only include detached binaries as the proper treatment of contact binaries would require hydrodynamical simulations.

The analytical estimates obtained with Eq. 1 are considerably larger than the results of our simulations (see Fig. 3). This discrepancy is probably caused by the assumption of Yu & Tremaine (2003) that the binary is disrupted well within the tidal radius, i.e. $R_{\text{min}}' \ll 1$, whereas in 10% to 20% of our simulated encounters $R_{\text{min}}' > 1$. For example, for $R_{\text{min}}' \simeq 3 - 4$, a capture can occur which eventually leads to the ejection of one star. Since the ejection velocity depends largely on the Keplerian velocity of the binary at the position of tidal breakup, we expect a dependence of the final velocity of escapers on the parameter $R_{\text{min}}'$. Fig. 3 shows the velocity at infinity of the ejected star versus the dimensionless distance of closest approach. In this example we consider equal mass binaries with $m = 8 M_\odot$ and a black hole of mass $10^3 M_\odot$. The figure shows that the highest ejection velocities are preferentially achieved in close encounters. The neglect of relatively wide encounters by Yu & Tremaine (2003) might therefore be the origin of the apparent discrepancy in the velocities. The agreement between our numerical simulations and the analytical estimates of Yu & Tremaine (2003)
improves for higher black hole masses, and is very good for encounters with a SMBH (see Gualandris et al. 2005).

In our systematic study of the effect of the initial semi-major axis of the interacting binary we adopted a homogeneous sampling in log $a$. Furthermore, the number of scattering experiments performed per initial selection of $a$ are weighted with equal cross section. If the distribution of orbital separations in a star cluster is flat in log $a$, like in the case of young star clusters (Kouwenhoven et al. 2005), we can superpose the results of these experiments in order to acquire a total velocity distribution of the ejected star. In Fig. 5 we present this superposed velocity distribution for a binary consisting of two $8 \ M_\odot$ stars. The three histograms in this figure give the velocity distribution for a $100 \ M_\odot$ (left), $10^3 \ M_\odot$ (middle) and $10^4 \ M_\odot$ (right) black hole.

### 2.2 Encounters between a single star and a binary black hole

We now consider encounters between a single star and a binary black hole. In a recent study Gürkan et al. (2006) argue that it is possible to form a black hole binary as a result of two collision runaways in a star cluster. The binary eventually merges due to the emission of gravitational wave radiation (Peters 1964) but, before coalescing, the two black holes experience frequent interactions with other cluster stars, possibly accelerating them to larger velocities.

We simulate these encounters and study the probability of high velocity ejections as a function of the binary parameters: the masses of the two black holes $M_{bh1}$ and $M_{bh2}$ and the initial semi-major axis $a$. The mass of the single
star is fixed to $8M_\odot$, in accordance with the observed mass of HE0437–5439. We consider black hole masses of $10^2M_\odot$, $10^3M_\odot$ and $10^4M_\odot$ in both equal mass and unequal mass binaries. For each choice of black hole masses, the semi-major axis is varied between a minimum value of $1$ AU and a maximum value of $1000$ AU. The minimum value is chosen in order to guarantee that the binary remains unaffected by the emission of gravitational wave radiation during the period over which the encounter takes place.

Except for a few mergers (about 1-2% of all cases), the vast majority of the encounters result in a fly-by. The velocity at infinity of the escaping star depends sensitively on the impact parameter of the encounter. Only in encounters for which the impact parameter is comparable to the binary separation are high velocity ejections realized. Most of these encounters are resonant, allowing the incoming star to come close to one the black holes as a fraction of the orbital separation. Only a few % of the encounters result in ejection velocities as high as $500\ km\ s^{-1}$ and we argue that this mechanism is unlikely to have produced the observed velocity of HE 0437–5439.

### 3 AN IMBH IN THE LMC?

The analysis carried out in the previous sections suggest the intriguing idea that HE 0437–5439 was ejected by an encounter with an IMBH of $\gtrsim 10^3 M_\odot$ in the LMC. Such an IMBH would most likely be found in a young dense cluster containing stars coeval to HE 0437–5439. Recently Mackev & Gilmore (2003) measured the structural parameters for 53 LMC clusters. A total of nine clusters in this database are younger than 35 Myr. Three of these clusters, NGC 1810, NGC 1847 and NGC 1850, have the appropriate age to be the host of HE 0437–5439 but their current densities are much smaller than what is required to produce an IMBH (Portegies Zwart et al. 2004; Miller & Hamilton 2002). Of the six remaining clusters, three (NGC 1805, NGC 1984, NGC 2011) have a mass below $5000 M_\odot$ and are therefore unlikely to have produced an IMBH. Also, the presence of an IMBH in these clusters would have been noticed easily (Baumgardt et al. 2003).

The remaining three clusters are listed in Tab. 1. For these clusters we reconstruct the initial relaxation time via the method described by Portegies Zwart & Chen (2006). In this relatively simple model, the current relaxation time has a one-parameter relation with the cluster’s initial relaxation time. Of the three clusters listed in Tab. 1, one (R 136) is too young to produce an IMBH and experience a strong encounter with a binary. The best candidate clusters to host an IMBH are then NGC 2100 and NGC 2004. We can estimate the mass of a possible black hole in these clusters by adopting the relation between the cluster structural parameters and the mass of a central black hole presented by Heggie et al. (2006). The authors performed direct N-body simulations to quantify the relation between the mass of a central IMBH and the ratio of the core radius to the half-mass radius. The last column in Tab. 1 provides an estimate

| name | $M$ ($M_\odot$) | $r_c$ (pc) | $r_c/r_h$ | age (Myr) | $T_{rlx}$ (Myr) | $T_{rlx}^0$ (Myr) | $M_{bh}$ ($M_\odot$) |
|------|----------------|----------|-----------|-----------|----------------|-----------------|----------------|
| R 136 | 35000          | 0.32     | 0.29      | 3         | 7–17           | 6–14            | 1000           |
| NGC 2004 | 27000       | 1.37     | 0.50      | 20        | 71–170         | 41–98           | 1600           |
| NGC 2100 | 30200       | 1.22     | 0.62      | 16        | 51–120         | 31–73           | 2200           |

Table 1. List of young (age $\gtrsim 35$ Myr) LMC clusters with an estimated initial relaxation time smaller than 100 Myr. The columns give the name of the cluster, the mass, the core radius, the ratio of the core radius to the half-mass radius, the age, the current two-body relaxation time, the initial two-body relaxation time (computed using Eq. 1 of Portegies Zwart & Chen (2006) with $\kappa = 0.1$) and the black hole mass based on Heggie et al. (2006). For estimating the relaxation time we adopted a mean mass ($\langle m \rangle = 1$) and a Coulomb logarithm parameter $\gamma = 0.4$ for the lower limit, and ($\langle m \rangle = 0.65$ and $\gamma = 0.01$ for the upper limit. The core and half-mass radius for R 136 are from Brandl et al. (1996).

for the mass of the IMBH using this relation. We find that, given the structure of the observed clusters, a 1600 $M_\odot$ to 2200 $M_\odot$ IMBH could be present.

We argue that NGC 2100 and NGC 2004 form the most promising birth places for HE0437–5439. If this were the case, the travel time from the parent cluster to the current location would be less than about 20 Myr. Such a short travel time would require an ejection velocity $\gtrsim 800\ km\ s^{-1}$ for the adopted total distance to the LMC of 18 kpc. This large velocity could only be obtained with a black hole of several $10^3 M_\odot$, somewhat higher than the estimated mass of a possible black hole in these clusters.

We now compute the rate for ejection of hypervelocity stars from NGC 2100 and NGC 2004 using the parameters listed in Tab. 1 and a dimensionless cross-section for exchange encounters $\sigma \approx 5000$, as derived from the scattering experiments. Adopting a central density of $2 \times 10^4$ pc$^{-3}$ (consistent with a King $W_0 = 9$ initial profile), a velocity of $10\ km\ s^{-1}$ and a semi-major axis of $0.2$ AU, we obtain an encounter rate of about one per 2 Myr for both clusters. Since only one in about ten exchange encounters produces a fast escaper (see Fig. 2), we derive a production rate of one per 20 Myr. This value represents a lower limit as we don’t take into account the effects of a mass function in the core and the semi-major distribution. It is therefore conceivable that NGC 2100 or NGC 2004 has produced one high velocity escaper, in which case an IMBH must be present in one of these clusters.

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