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Hypervelocity collisions of binary stars at the Galactic Centre

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ABSTRACT

Recent surveys have identified seven hypervelocity stars (HVSs) in the halo of the Milky Way. Most of these stars may have originated from the breakup of binary star systems by the nuclear black hole SgrA*. In some instances, the breakup of the binary may lead to a collision between its member stars. We examine the dynamical properties of these collisions by simulating thousands of different binary orbits around SgrA* with a direct *N*-body integration code. For some orbital parameters, the two stars collide with an impact velocity lower than their escape velocity and may therefore coalesce. It is possible for a coalescing binary to have sufficient velocity to escape the galaxy. Furthermore, some of the massive S-stars near Sgr A* might be the merger remnants of binary systems, however this production method can not account for most of the S-stars.

Key words: black hole physics – stellar dynamics – Galaxy: centre – Galaxy: kinematics and dynamics.

1 INTRODUCTION

First theorized by Hills (1988), a hypervelocity star (HVS) has sufficient velocity to escape the gravitational pull of the Milky Way galaxy. The first HVS, SDSS J090745.0+024507, was recently discovered in the Galactic halo (Brown et al. 2005; Fuentes et al. 2005). This HVS is located at a heliocentric distance of ∼110 kpc and has radial velocity 853 ± 12 kms^{-1}, over twice that needed to escape the gravitational pull of the Milky Way. Since that initial discovery, six other HVSs have been identified (Edelmann et al. 2005; Hirsch et al. 2005; Brown et al. 2006a,b). Hills (1988) suggested that an HVS might result from a close encounter between a tightly bound binary star system and the black hole at the Galactic Centre, SgrA*. Yu & Tremaine (2003) refined Hills' argument and noted that HVSs might also be produced by three-body interactions between a star and a binary black hole system. Because the existence of a second (intermediate-mass) black hole in the Galactic Centre (Hansen & Milosavljević 2003) is only a hypothetical possibility (Schödel et al. 2003), we focus here on the disruption of a tightly bound binary by a single supermassive black hole (SMBH) with a mass of $\sim 4 \times 10^6\,\mathrm{M}_\odot$ whose existence is robustly supported by data (e.g. Schödel et al. 2003; Reid & Brunthaler 2004; Ghez et al. 2005).

Simulations show that tight binaries can produce HVSs with velocities comparable to the observed HVSs (e.g. Ginsburg & Loeb 2006 (hereafter Paper I); Bromley et al. 2006). In Paper I, we show that the companion to the HVS will be left in a highly eccentric orbit, which agrees with the known orbits of a number of S-stars orbiting Sgr A* (e.g. Eckart & Genzel 1997; Schödel et al. 2003, and Ghez et al. 2005). Therefore, we suggested that some of these stars are former companions of HVSs. Furthermore, a small fraction (∼10 per cent) of the binary systems were found to collide. Here we examine in detail the dynamical properties of such collisions, and check whether some of these collisions may end in coalescence.

In Section 2 we describe the *N*-body code and the simulation parameters that were used. In Section 3 we discuss our numerical results for the collisions, and in Section 4 we discuss the outcome of binary mergers at the Galactic Centre. Our goal is not to cover the entire range of binaries that could produce HVSs or end in collisions, but rather to determine whether some tight binaries with masses similar to the HVSs observed thus far could coalesce.

2 COMPUTATIONAL METHOD

In our study we have used the *N*-body code written by Aarseth (Aarseth 1999) whose details were described in Paper I. We treat the stars as point particles and ignore tidal and general relativistic effects on their orbits, since these effects are small at the distance (∼10 au) where the binary is tidally disrupted by the SMBH. We have set the mass of the SMBH to $M = 4 \times 10^6\,\mathrm{M}_\odot$. The masses of the binary members are set to either 3 and $3\,\mathrm{M}_\odot$ [since $3\,\mathrm{M}_\odot$ is the estimated mass of SDSS J090745.0+024507 (Fuentes et al. 2005)], or to 3 and $10\,\mathrm{M}_\odot$ [as $10\,\mathrm{M}_\odot$ is comparable to the estimated mass of HE 0437−5439 (Edelmann et al. 2005)]. All runs start with the centre of the circular binary located 2000 au ($=10^{-2}$ pc) away from the SMBH along the positive *y*-axis. This distance is comparable to the inner scale of the observed distribution of stars around SgrA* (Eckart & Genzel 1997; Schödel et al. 2003; Ghez et al. 2005), allowing the remaining star to populate this region after the ejection of its companion. This radius is also much larger than the

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binary size or the distance of closest approach necessary to obtain the relevant ejection velocity of HVSs, making the simulated orbits nearly parabolic.

We ran two sets of data. The first had the binary system rotating along the *xy* plane and the second along the *yz* plane. We used the same initial distance for all runs to make the comparison among them easier to interpret as we varied the distance of closest approach to the SMBH or the relative positions of the two stars within the binary. We chose initial binary separations between $a = 0.05$ and 0.2 au because such a range is likely to produce HVSs for the above parameters (see Paper I). Significantly wider binaries would give lower ejection velocities (Gualandris, Portegies Zwart & Sipior 2005). Much tighter binaries would not be easily disrupted by the black hole, or may coalesce to make a single star before interacting with the SMBH. The radius of a main-sequence star of a few solar masses is ∼0.01 au, and that of a 10 solar mass star is ∼0.03 au (see e.g. fig. 4 in Freitag & Benz 2005). Binaries tighter than ∼0.02 au are precluded because the two stars will develop a common envelope and eventually coalesce.

In the Galactic disc, about one-third to half of all stars form in binaries or small multiple systems (see e.g. Duquennoy & Mayor 1991; Lada 2006), with roughly equal probability per logarithmic interval of separations, $\mathrm{d}P/\mathrm{dln}\,(a) = \text{constant}$ (e.g. Abt 1983; Heacox 1998; Larson 2003). In the Galactic Centre environment, the maximum binary separation is limited by the tidal force of SgrA* at the distance *d* where the binary is formed (for conditions that enable star formation near the SMBH, see Milosavljević & Loeb 2004). Since the mass of the black hole is $\sim 10^6$ times larger than that of a star, this implies a maximum binary separation less than $(10^{-6})^{1/3} = 10^{-2}$ of the initial distance *d*. For $d = 2 \times 10^3$ au, the upper limit on the binary separation would be 20 au (or smaller if the tidal restriction applies during the formation process of the binary). If we assume a constant probability per ln (a) for $0.02 < a < 20$ au, then the probability of finding a binary in the range of $a = 0.05$–0.2 au is substantial, ∼20 per cent.

As shown in Paper I, the initial phase of the binary orbit plays a crucial role in the outcome. Therefore, we sampled cases with initial phase values of 0–360° in increments of 15°. As initial conditions, we gave the binary system no radial velocity but a tangential velocity with an amplitude in the range between 5 and 25 km s^{-1} at the distance of 2000 au. In total, we ran 2000 simulations.

3 PROPERTIES OF HYPERVELOCITY COLLISIONS

Given a binary system with stars of equal mass *m* separated by a distance *a* and a SMBH of mass $M \gg m$ at a distance *b* from the binary, tidal disruption would occur if $b \lesssim b_\mathrm{t}$ where

$$\frac{m}{a^3} \sim \frac{M}{b_\mathrm{t}^3}. \tag{1}$$

The distance of closest approach in the initial plunge of the binary towards the SMBH can be obtained by angular momentum conservation from its initial transverse speed $v_\perp$ at its initial distance from the SMBH, *d*,

$$v_\perp d = \left(\frac{GM}{b}\right)^{1/2} b. \tag{2}$$

The binary will be tidally disrupted if its initial transverse speed is lower than some critical value,

$$v_\perp \lesssim v_{\perp,\mathrm{crit}} \equiv \frac{(GMa)^{1/2}}{d}\left(\frac{M}{m}\right)^{1/6} = 10^2\,\frac{a_{-1}^{1/2}}{m_{0.5}^{1/6}\,d_{3.3}}\ \mathrm{km\,s^{-1}}, \tag{3}$$

where $a_{-1} \equiv (a/0.1\,\mathrm{au})$, $d_{3.3} = (d/2000\,\mathrm{au})$, $m_{0.5} \equiv (m/3\,\mathrm{M}_\odot)$. If $v_\perp \lesssim v_{\perp,\mathrm{crit}}$, one of the stars receives sufficient kinetic energy to become unbound, while the second star is kicked into a tighter orbit around the SMBH. The ejection speed v_ej of the unbound star can be obtained by considering the change in its kinetic energy $\sim v\delta v$ as it acquires a velocity shift of order the binary orbital speed $\delta v \sim \sqrt{Gm/a}$ during the disruption process of the binary at a distance $\sim b_t$ from the SMBH when the binary centre-of-mass speed is $v \sim \sqrt{GM/b_t}$ (Hills 1988; Yu & Tremaine 2003). At later times, the binary stars separate and move independently relative to the SMBH, each with its own orbital energy. For $v \lesssim v_{\perp,\mathrm{crit}}$, we therefore expect

$$\begin{aligned} v_\mathrm{ej} &\sim \left[\left(\frac{Gm}{a}\right)^{1/2}\left(\frac{GM}{b_\mathrm{t}}\right)^{1/2}\right]^{1/2} \\ &= 1.7 \times 10^3 m_{0.5}^{1/3} a_{-1}^{-1/2}\ \mathrm{km\,s^{-1}}. \end{aligned} \tag{4}$$

Under some circumstances, the binary is disrupted in such a way that the two stars collide. Assuming that the impulsive kick is given by the SMBH towards a random direction within the orbital plane and ignoring gravitational focusing (which is important at low speeds), the probability for a collision in a case that otherwise would have produced an HVS is four time the radius of a star divided by the circumference of a circle with a radius equal to the binary separation. The likelihood for a collision is expected to be smaller in the more general case where the binary lies in a different plane than its orbit around the SMBH, unless gravitational focusing dominates. Table 1 summarizes the actual statistical results from our runs.

The two stars would merge as a result of the collision if their relative speed is lower than the escape speed from their surface (∼500 km s^{-1}). In our runs 22 per cent of all collisions have impact velocities low enough to allow the two stars to coalesce (see Table 2). Also of note is the fact that many collisions involve hypervelocities of $v > 1000$ km s^{-1} upon impact. The typical impact velocity of the two stars can be crudely estimated from a model in which the SMBH removes the angular momentum from the binary and causes the two stars to fall towards each other from their initial orbital separation. Conservation of energy,

$$E = \frac{1}{2}\frac{m_1 m_2}{m_1 + m_2}\dot{r}^2 - \frac{G m_1 m_2}{r} = \text{constant}, \tag{5}$$

Table 1. Collision probability with different values of *a* for binaries of 3 and 3 M$_\odot$ (second column) and 10 and 3 M$_\odot$ (third column). The top four rows show the values obtained from our simulations with their corresponding Poisson errors. For comparison, the bottom rows show the expected probability from a simplistic 'billiard ball' model (without gravitational focusing) in which the probability of a collision is $2(R_1 + R_2)/2\pi a$. Here $\{R_i\}_{i=1,2}$ are the radii of the two stars and *a* the binary separation.

a (au)	$P(3\,\mathrm{M}_\odot)$	$P(10\,\mathrm{M}_\odot)$
0.05	0.11 ± 0.02	0.21 ± 0.05
0.10	0.11 ± 0.02	0.13 ± 0.04
0.15	0.06 ± 0.01	0.12 ± 0.03
0.20	0.03 ± 0.01	0.04 ± 0.02
0.05	0.09	0.27
0.10	0.06	0.13
0.15	0.03	0.09
0.20	0.02	0.07

Table 2. Probability of coalescence upon collision for different values of a for binaries of 3 and 3 $\mathrm{M}_{\odot}$ (second column) and 10 and 3 $\mathrm{M}_{\odot}$ (third column). The top four rows show the values obtained from our simulations for $a_{\min} = 0.02$ au, and the bottom rows for $a_{\min} = 0.04$ au. Here we assume that the two stars will merge if $v_{\mathrm{imp}} \lesssim 500\ \mathrm{km\,s^{-1}}$.

a (au)	$P(3\,\mathrm{M}_{\odot})$	$P(10\,\mathrm{M}_{\odot})$
0.05	0.46	0.13
0.10	0.19	0.05
0.15	0.08	0.00
0.20	0.00	0.00
0.05	N/A	N/A
0.10	0.81	0.33
0.15	0.93	0.05
0.20	0.25	0.03

yields the relative velocity upon impact,

$$v_f = \left[2G(m_1 + m_2)\left(\frac{1}{a_{\min}} - \frac{1}{a}\right)\right]^{1/2}. \qquad (6)$$

The actual impact speed would vary around this value due to the additional velocity induced by the SMBH tidal force along the axis connecting the stars. Nevertheless, equation (6) agrees well with the median of the distribution of impact speeds in our runs (see Fig. 1). Collisions always occur shortly after tidal disruption, as seen from the separation of the black and filled circles in Fig. 2.

4 FATE OF THE COALESCING BINARY

Stellar collisions are likely the main assembly line of blue stragglers (see e.g. Leonard 1989; Bailyn & Pinsonneault 1995; Lombardi et al. 2002), and ultracompact X-ray binaries (e.g. Ivanova et al. 2005; Lombardi et al. 2006) in globular clusters. The Galactic Centre of the Milky Way is another place where collisions are likely to occur. Tidal disruptions of a binary by the SMBH will produce ∼0.1 collisions per HVS (see Paper I). The ultimate fate of the binary depends on the velocity of its member stars upon impact. As evident from Fig. 1, the impact velocity v_{imp} can vary over a wide range of values. A star with $v_{\mathrm{imp}} > v_{\mathrm{esc}} \equiv [2G(m_1 + m_2)/(R_1 + R_2)]^{1/2}$ will likely pass through the other star, even during a head-on collision (Freitag & Benz 2005). However, in any collision there certainly will be interactions where the smaller star may gain mass and the larger star will likely lose mass (Freitag & Benz 2005). Furthermore, a collision where the impact velocity is less than the escape velocity v_{esc} will not necessarily end as a merger. A grazing collision might result in envelope-ejection but no core merger, whereas a head-on collision might result in core merger, and thus form a more massive star (Dale & Davies 2006). The results of smoothed particle hydrodynamics simulations of blue stragglers (Sills, Adams & Davies 2005) show that off-axis collisions initially have large angular momentum but eventually lose it to allow the merger to contract down to the main sequence. Off-axis collisions, which are more probable than head-on collisions, could nevertheless lead to HVSs which are rapidly spinning (Alexander & Kumar 2001). Finally, a merger between a lower mass star with a higher mass star may extend the massive star's main-sequence phase (Dale & Davies 2006).

Edelmann et al. (2005) notes that HVS HE 0437−5439 might be the merger of two 4 $\mathrm{M}_{\odot}$ stars, and that such a merger is consistent with the age of the HVS. Furthermore, Hirsch et al. (2005) suggests that HVS US 708, a subluminous O star, might be the merger of two helium-core white dwarfs. After losing mass, some of the coalescing binaries in our runs might end up with sufficient velocity to escape the galaxy. Unfortunately, our simulations cannot treat mass loss as well as the large amount of thermal energy deposited in each collision (see Leonard & Livio 1995). Coalescing binary systems that remain bound to the SMBH could end up as massive S-stars.

Aside from stellar collisions of main-sequence stars, it is possible for collisions to involve compact objects. As long as the colliding objects are gravitationally bound, the compact object will eventually settle to the centre of the merger remnant due to angular momentum transport by dynamical friction (gravitationally induced spiral arms) or viscosity in the stellar envelope (see e.g. the simulation of a black hole-helium star merger in Zhang & Fryer 2001) as well as gravitational radiation. The situation of a stellar mass black hole surrounded by a star also appears in the collapsar progenitors of long-duration gamma ray bursts (GRBs) (MacFadyen & Woosley

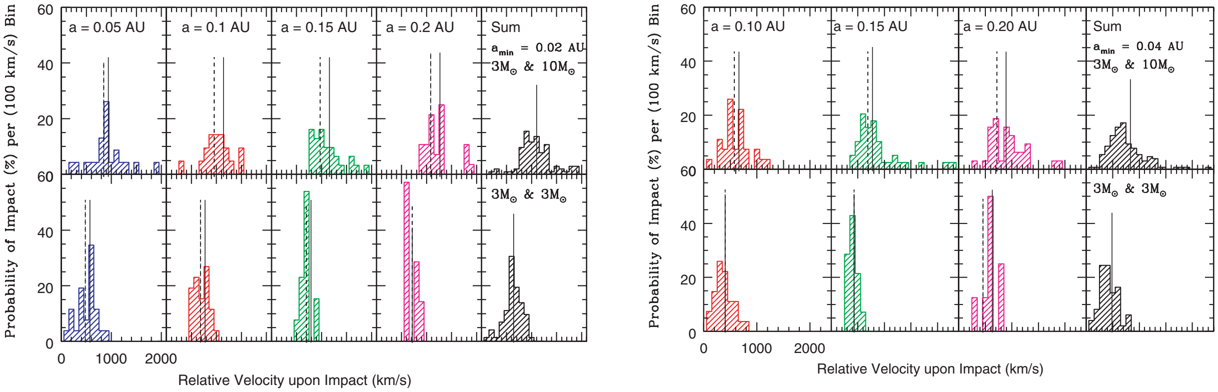

Figure 1. Fraction of all collisions (in per cent per 100 km s^{-1} bin) versus relative velocity upon impact (in km s^{-1}). The left-hand section is for $a_{\min} = 0.02$ au and the right-hand section is for $a_{\min} = 0.04$ au. The label of the lower left-hand panel corresponds to all panels. The dashed vertical line shows the impact velocity that would have resulted from free fall starting at the binary separation (see equation 6). The solid line is the median velocity of all runs. (We choose to use the median rather than the average value because outliers bias the data otherwise.) The minimum impact parameter for a collision is expected to be $a_{\min} = (R_1 + R_2) = 0.02$ au for a 3 and 3 $\mathrm{M}_{\odot}$ binary, but $a_{\min} = 0.04$ au for a 10 and 3 $\mathrm{M}_{\odot}$ binary. We show results in other cases for pedagogical purposes, namely to illustrate the dependence of the results on the binary masses and $a_{\min}$ separately. If the 10 $\mathrm{M}_{\odot}$ companion is a black hole then $a_{\min} \sim 0.01$ au.

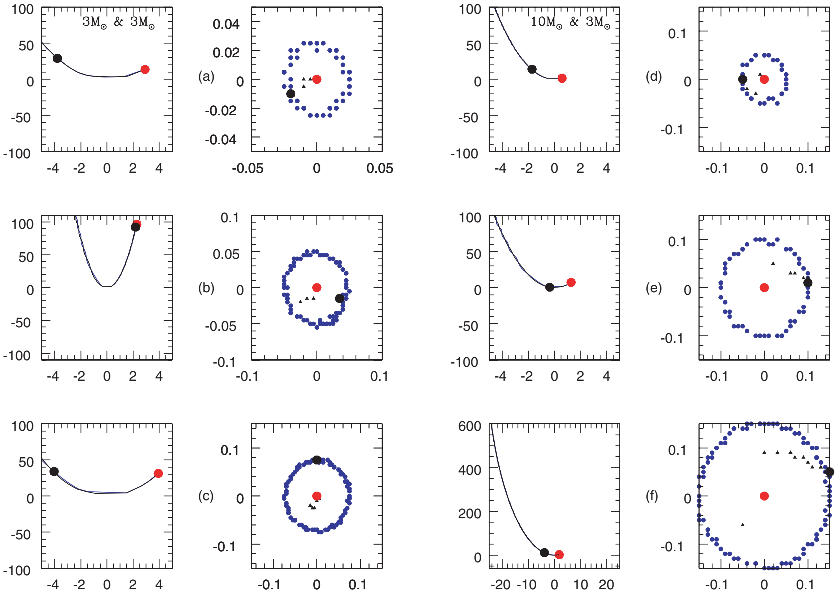

Figure 2. Orbits of stars (in units of au) prior to collision for binaries of 3 and 3 $\mathrm{M}_\odot$ in panels (a)–(c) and binaries of 10 and 3 $\mathrm{M}_\odot$ in panels (d)–(f). For all panels, the graphs on the left-hand side are the orbits of the stars as they pass near the SMBH located at the origin. For panels (a)–(c), the graphs on the right-hand side are plotted at the centre of mass frame. For panels (d)–(f), the graphs on the right-hand side are plotted at the rest frame of the 10 $\mathrm{M}_\odot$ star. The red filled circle denotes the collision instant and the black filled circle denotes the time when the stars started to move towards each other as a result of the SMBH tidal force. Note that before the binary is disrupted, the 3 $\mathrm{M}_\odot$ star makes many revolutions as denoted by the blue circles. After the binary is disrupted, the approaching stars are denoted by black triangles for clarity. Panels *a* and *d* both have an initial separation of $a = 0.05$ au. Panels *b* and *e* have $a = 0.10$ au, and panels *c* and *f* have $a = 0.15$ au.

1999). However, these events result from the collapse of the stellar core and so the accretion rate into the black hole is larger than the Eddington limit by more than 10 orders of magnitude (Narayan, Piran & Kumar 2001). In our case, the accretion might be limited by the Eddington luminosity and so the resulting sources would be much fainter than GRBs. It is unclear whether this accretion would result in an implosion or an explosion. In the case of a neutron star companion, one gets a Thorne–Żytkow object, with a similar accretion rate (Podsiadlowski 1996).

5 CONCLUSIONS

Our *N*-body simulations show that tight binaries with a separation between 0.05–0.20 au which approach within a distance $\simeq$10 au from SgrA* could produce both HVSs and collisions (in $\sim$10 per cent of all cases) where occasionally the two objects may coalesce. Coalescence occurs if the impact velocity is sufficiently low (Freitag & Benz 2005), otherwise the SMBH would likely eject the two stars into separate orbits (see Paper I). The large variance in collision velocity shown in Fig. 1 will result in a broad range of collision products.

Given the low production rate of HVSs in the Milky Way galaxy $\sim 10^{-5}\,\mathrm{yr}^{-1}$ (Brown et al. 2006b), and that collisions occur in $\sim$10 per cent of all cases with mergers accounting for $\sim$20 per cent of all collisions, the expected production rate of S-stars from binary mergers is once every 5 Myr. Since this period is comparable to the lifetime of the massive S-stars, most of these stars can not be the merger remnants of binary systems. It is unlikely that any of these collision events will be observed in real time. Following a coalescence event, the remnant will appear different from main-sequence stars of the same mass only if the progenitors evolved substantially before their collision time.

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