The nature of hypervelocity stars as inferred from their galactic trajectories

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Accepted 2007 September 24. Received 2007 September 21; in original form 2007 August 02

ABSTRACT

We have computed the galactic trajectories of twelve hypervelocity stars (HVSs) under the assumption that they originated in the Galactic Centre. We show that eight of these twelve stars are bound to the Galaxy. We consider the subsequent trajectories of the bound stars to compute their characteristic orbital period, which is 2 Gyr. All eight bound stars are moving away from the centre of the Galaxy, which implies that the stars’ lifetimes are less than 2 Gyr. We thus infer that the observed HVSs are massive main sequence stars, rather than blue horizontal branch stars. The observations suggest that blue HVSs are ejected from the Galactic Centre roughly every 15 Myr. This is consistent with the observed population of blue stars in extremely tight orbits round the central super-massive black hole (SMBH), the so-called S-stars, if we assume that the HVSs are produced by the breakup of binaries. One of the stars in such a binary is ejected at high velocities to form a HVS; the other remains bound to the SMBH as an S-star.

We further show that the one high-velocity system observed to be moving towards the Galactic Centre, SDSS J172226.55+594155.9, could not have originated in the Galactic Centre; rather, we identify it as a halo object.

Key words: stars:general; Galaxy:kinematics and dynamics; Galaxy: centre

1 INTRODUCTION

The existence of stars moving at velocities several times higher than the escape velocity of the galaxy was first proposed by Hills (1988). These hypervelocity stars (HVSs) would have been ejected from the very centre of the Galaxy through interactions between binary stars and the central black hole. Since the first discovery of an HVS in 2005 several more have been found. Brown et al. (2007a) and Brown et al. (2006b) report the results of a targeted survey for HVSs. Candidate early-type stars are identified with SDSS photometry and observed with the 6.5 MMT telescope or the Whipple 1.5 m Tillinghast telescope. Precise spectral types and heliocentric radial velocities are measured from the obtained stellar spectra. The evolutionary stage is undetermined; stars of the observed colours could be on either the main sequence or blue horizontal branch. The survey is complete to a distance of 100 to 150 kpc for B-type stars. Brown et al. (2007a) report that 11 stars are believed to belong to a population of HVSs ejected from the Galactic Centre on bound orbits on the basis of measurement of their radial velocities. The radial velocities are transformed into the galactic restframe via

\[ v_{\text{rf}} = v_r + (10 \cos l \cos b + 5.2 \sin l \cos b + 7.2 \sin b) \text{km s}^{-1} + 220 \text{ km s}^{-1} \sin l \cos b. \] (1)

where \( v_r \) is the heliocentric radial velocity and \( l \) and \( b \) are the galactic longitude and latitude respectively. Thus \( v_{\text{rf}} \) is the component of the galactic restframe velocity of a star that lies along the line connecting the star to the Sun. As only this component of the velocity is known, the star’s Galactic restframe velocity must be at least \( v_{\text{rf}} \).

A plot of \( v_{\text{rf}} \) versus observed number of stars for a clean sample of B-type stars can be seen in figure 3 of Brown et al. (2007a). The majority of stars have \( v_{\text{rf}} \) in the range \(-275 \text{ km s}^{-1} < v_{\text{rf}} < 275 \text{ km s}^{-1}\). This is consistent with them being either halo or disc stars. Eleven stars, however, are found with larger \( v_{\text{rf}} \), between 275 km s\(^{-1}\) and 450 km s\(^{-1}\). One star is found to have a comparably large but negative \( v_{\text{rf}} \), SDSS J172226.55+594155.9, which has \( v_{\text{rf}} = -286 \text{ km s}^{-1}\). In our sample of possibly-bound hypervelocity stars we also include HVS 7, SDSS J113312.12+010824.9 (Brown et al. 2006b), since it has \( v_{\text{rf}} = 418 \text{ km s}^{-1}\) and the escape velocity at its current position is 421 km s\(^{-1}\).

In this paper we consider the origin and nature of these
stars. We use their galactocentric origin to calculate their space velocities and subsequent trajectories, which allows us to determine whether they are bound to the Galaxy.

2 PRODUCING HYPERVELOCITY STARS

In the ejection mechanism suggested by Hills (1988) a stellar-mass binary approaches the supermassive black hole (SMBH), Sgr A*. The binary is tidally disrupted by interaction with the SMBH, leading to the capture of one of its stars and the ejection of the other. Conservation of energy leads to extreme ejection velocities as the captured star is extremely tightly bound to the black hole. These captured stars are suggested as the origin of the so-called S-stars found in the Galactic Centre.

Bromley et al. (2006) have performed numerical simulations of the ejection mechanism. They derive the following relation between ejection velocity, $v_{ej}$, binary separation, $a_{bin}$, masses of the binary components, $M_1$ and $M_2$, and the mass of the black hole $M_{bh}$:

$$v_{ej} = 1760 \left( \frac{a_{bin}}{0.1 \text{ AU}} \right)^{-0.5} \left( \frac{M_1 + M_2}{2 M_\odot} \right)^{1/3}$$

$$\times \left( \frac{M_{bh}}{3.5 \times 10^9 M_\odot} \right)^{1/6} f_t \text{ km s}^{-1}.$$  \hspace{1cm} (2)

The ejection velocity depends on $f_t$, given by

$$f_t = 0.774 + 0.0204D - 6.23 \times 10^{-4} D^2 + 7.62 \times 10^{-6} D^3$$

$$- 4.24 \times 10^{-8} D^4 + 8.62 \times 10^{-11} D^5,$$  \hspace{1cm} (3)

where $D$ is the Hills parameter, defined as

$$D = \left( \frac{R_{\text{min}}}{a_{bin}} \right) \left( \frac{2 M_{bh}}{10^9 (M_1 + M_2)} \right)^{-1/3}.$$  \hspace{1cm} (4)

Here $R_{\text{min}}$ is the closest approach between the binary and the black hole and $a_{bin}$ is the semimajor axis of the binary. The Hills parameter also relates to the probability of an interaction leading to an ejection, $P_{ej}$ via

$$P_{ej} \approx 1 - D \frac{v_{ej}}{175}.$$  \hspace{1cm} (5)

The case $R_{\text{min}} = 0$ corresponds to $D = 0$; interesting encounters have $D$ between 0 and 175. This leads to values of $f_t$ in the range $0.5 < f_t < 1$.

3 TRAJECTORIES OF HYPERVELOCITY STARS

If $v_{ej}$ is greater than the galactic escape velocity at the position of the HVS then it is unbound. For HVSs with slightly lower observed velocities the lack of measured proper motions precludes a solid determination of whether they are bound or unbound. However, we know that the HVSs have been ejected from the centre of the Galaxy. Hence we determine the range of proper motions that give them trajectories that pass through the Galactic centre. Thus equipped with full space velocities we are able to determine if the stars are bound or unbound.

To determine their trajectories we add components of proper motion to the known heliocentric radial velocities. The velocity is transformed into galactic $(U, V, W)$ velocities according to Johnson & Soderblom (1987). The equations of motion are then integrated in a model of the galactic potential. We use the model suggested by Paczynski (1990). This consists of two Miyamoto-Nagai potential terms which represent the disc and bulge, and a spherically symmetric halo component. We truncate the halo density profile to keep its mass finite. Following Wilkinson & Evans (1999) we adopt a halo mass of $1.9 \times 10^{12} M_\odot$, which implies truncation of the halo at a radius of 237 kpc. Outside this we model the halo as a central potential.

We sample proper motions from a grid covering all possible space velocities. The absolute magnitudes depend on the evolutionary stage, thus the heliocentric distances will be different depending on whether the stars are on the main sequence (MS) or blue horizontal branch (BHB). The galactic coordinates $(R, z)$ will also be different, giving different trajectories depending on the evolutionary stage assumed. The trajectories are integrated backwards from the current position to the Galactic Centre, both under the assumption that the stars are on the MS and that they are on the BHB.

4 RESULTS

In Figure 1 we plot proper motions that take a typical star from our sample, SDSS J081828.07+570922.1, within 75 pc, 50 pc and 10 pc from the centre of the Galaxy. In Figure 2 we plot the trajectory of SDSS J081828.07+570922.1 that takes it closest to the Galactic Centre.

For each star in our sample of twelve possibly-bound HVSs there exists a small range of proper motions consistent with ejection from the Galactic Centre; that is, for which the corresponding trajectory takes the star through the Galactic Centre. The twelve HVSs are all found to have been ejected within the last 170 Myr, with a reasonably uniform distribution in ejection times and a mean ejection rate of one HVS every 15 Myr. Yu & Tremaine (2003) predict a binary breakup rate of $10^{-5}$ yr$^{-1}$. Some of these binaries will contain massive stars, some of which will be ejected and observed as HVSs. Taking into account selection effects the observed rate is compatible with the predictions of Yu & Tremaine (2003), as shown by Brown et al. (2006a).

The results from our investigation are given in Table 1. For each star we consider its position, velocity and trajectory in the cases where it is on the MS and the BHB. At the present day we list the proper motions most consistent with a Galactic Centre origin, the $(R, z)$ coordinates, the lab-frame speed given these proper motions and the escape speed at the current position. We also list the ejection speed, which is the speed of the star when its trajectory crosses the Galactic Centre, and the time since ejection. We find that eight out of our twelve stars are bound in the galactic potential. The ejection velocities for the bound HVSs are typically about 800 km s$^{-1}$.

To estimate the robustness of the results, we let the mass of the galactic halo assume other values and then observe which stars in the sample remain unbound. Reducing the halo mass to half of the best fit value causes only one star, SDSS J141723.34+101245.7, to become unbound. Investigating the limits of the 1-sigma confidence interval of Wilkinson & Evans (1999), $2.0 \times 10^{11} M_\odot$ and
Trajectories of hypervelocity stars

Figure 1. Proper motions for SDSS J081828.07+570922.1 that represent trajectories that pass close to the Galactic Centre. The outer region of solid squares represents proper motions such that the trajectories pass within 75 pc of the Galactic Centre. The dotted region represents proper motions with trajectories that pass within 50 pc of the Galactic Centre and the innermost region of circles are proper motions taking the trajectory within 10 pc of the Galactic Centre. For these calculations we assume that the star is on the MS.

Figure 2. The trajectory of SDSS J081828.07+570922.1 integrated in the Galactic potential, assuming that it is a MS star. The cylindrical radius, $R$ (top) and height above the plane of the Galaxy, $z$ (lower) are plotted against time. The trajectory starts at the point of ejection from the Galactic Centre and continues for the subsequent 10 Gyr. This trajectory is calculated assuming that the star is on the MS.

Figure 3. The heliocentric radial velocity versus time of SDSS J081828.07+570922 from ejection and for the projected trajectory for 10 Gyrs. The trajectory here is integrated assuming that the star is on the MS.

$5.5 \times 10^{12} M_\odot$ respectively, we find that none of the suspected bound hypervelocity stars remain bound with halo mass of only $2.0 \times 10^{11} M_\odot$. On the other side, a halo mass of $5.5 \times 10^{12} M_\odot$ means that SDSS J110224.37+025002.8 and SDSS J115245.91-021116.2 become bound.

5 DISCUSSION

5.1 The evolutionary stage of bound HVS

The return time, the time between peri-galacticon passages for a bound HVS, is typically 2 to 3 Gyr when we assume that the stars are on the MS. If we assume instead that they are on the BHB the return time is typically 1 to 2 Gyr. If the stars are on the MS then their colours correspond to masses between 2 and 4 $M_\odot$; if they are on the BHB then they can be considerably less massive. The MS lifetime is a sensitive function of the stellar mass; low mass stars are long-lived compared to their massive counterparts. Assuming the stars are on the MS the least massive, and hence most long-lived, star in Table 1 has a MS lifetime of about 450 Myr. The shortest MS lifetime is 100 Myr. The orbital periods for these stars are sufficiently long that they will evolve to become white dwarfs before they return to the Galaxy. However if they are BHB stars their progenitors can be of substantially lower mass. If they are ejected from the Galactic Centre as low-mass MS stars they can undergo several orbits before evolving onto the BHB. In Figure 3 we plot heliocentric radial velocities as a function of time for a bound HVS, SDSS J081828.07+570922. Over a whole orbit the star spends equal amounts of time approaching the Galactic Centre as receding from it. The high-frequency oscillation has a period of 240 Myr, and is an effect of the Sun’s galactic orbit.

A low mass HVS, ejected from the Galactic Centre
As SDSS J172226.55+594155.9 is not a HVS, we cannot find its proper motion by constraining its trajectory to pass through the Galactic Centre. We consider the case where its velocity tangential to the line of sight is small compared to its radial velocity and integrate the trajectory taking its velocity tangential to the line of sight to be equal to the observed radial velocity. The trajectory under these assumptions resembles a typical halo object, extending to 45 kpc in $R$ and 40 kpc in $z$. Hence the observed radial velocity of SDSS J172226.55+594155.9 is consistent with it being a halo object. Indeed this can also be the case for some of the stars we claim to be bound. However, the velocity distribution observed by Brown et al. (2007a) suggests that this cannot be the case for all of them.

### Table 1

Values calculated from our trajectories for the 11 hypervelocity stars found in the survey of Brown et al. (2007a) and HVS 7 (final row). For each star the first line (labelled MS) represents the trajectory calculated assuming that the star is a main-sequence star, and the second line the trajectory calculated assuming that it is a blue horizontal branch star. Proper motions are observed with negative heliocentric radial velocities, it is most likely that they are main-sequence stars with masses of 3 to 4 $\odot$. We note that this agrees with arguments also made by Kollmeier & Gould (2007), Yu & Madau (2007) and Brown et al. (2007b). The eight bound HVSs in Table 1 all have positive radial velocities, and positive $v_{\text{esc}}$ and $v_{ej}$. However this is not true for SDSS J172226.55+594155.9, which is dealt with in the subsection that follows.

#### Bound:

| ID | $\mu_{\alpha}$ [mas/yr] | $\mu_{\delta}$ [mas/yr] | $R$ [kpc] | $z$ [kpc] | $v$ [km/s] | $v_{\text{esc}}$ [km/s] | $v_{ej}$ [km/s] | $t_{ej}$ [Myr] |
|----|----------------------|----------------------|----------|----------|-----------|-------------------|----------------|-------------|
| SDSS J074950.24+243841.2 | MS -0.01 | -0.55 | 61.8 | 23.2 | 301. | 407. | 845. | 171. |
| BHB -0.34 | -1.71 | 25.9 | 7.8 | 305. | 482. | 806. | 69. |
| SDSS J075055.24+472822.9 | MS 0.06 | -1.68 | 38.3 | 17.1 | 312. | 446. | 830. | 106. |
| BHB -1.05 | -6.38 | 16.3 | 4.7 | 326. | 518. | 792. | 41. |
| SDSS J075712.93+512938.0 | MS -0.07 | -2.56 | 29.3 | 12.8 | 341. | 468. | 829. | 76. |
| BHB -3.55 | -12.25 | 12.7 | 2.8 | 367. | 540. | 795. | 29. |
| SDSS J081828.07+570922.1 | MS -0.08 | -1.87 | 37.0 | 19.9 | 300. | 446. | 825. | 109. |
| BHB -0.54 | -3.90 | 22.0 | 9.7 | 307. | 491. | 802. | 61. |
| SDSS J090710.08+365957.5 | MS -0.19 | -0.87 | 45.6 | 34.2 | 282. | 419. | 832. | 155. |
| BHB -0.73 | -1.97 | 24.7 | 15.2 | 288. | 476. | 804. | 77. |
| SDSS J140432.38+352258.4 | MS -1.30 | -0.54 | 14.2 | 49.0 | 339. | 429. | 849. | 122. |
| BHB -4.49 | -1.08 | 7.5 | 16.4 | 371. | 511. | 816. | 40. |
| SDSS J141723.34+101245.7 | MS -1.55 | 0.07 | 14.7 | 45.7 | 410. | 434. | 877. | 100. |
| BHB -2.88 | -0.55 | 1.5 | 18.9 | 340. | 506. | 806. | 45. |
| SDSS J142001.94+124404.8 | MS -2.34 | -0.27 | 4.5 | 26.6 | 372. | 480. | 835. | 61. |
| BHB -5.57 | -0.39 | 2.5 | 11.7 | 385. | 539. | 804. | 26. |

#### Unbound:

| ID | $\mu_{\alpha}$ [mas/yr] | $\mu_{\delta}$ [mas/yr] | $R$ [kpc] | $z$ [kpc] | $v$ [km/s] | $v_{\text{esc}}$ [km/s] | $v_{ej}$ [km/s] | $t_{ej}$ [Myr] |
|----|----------------------|----------------------|----------|----------|-----------|-------------------|----------------|-------------|
| SDSS J110224.37+025002.8 | MS -0.81 | 0.39 | 31.9 | 39.8 | 432. | 429. | 890. | 102. |
| BHB -2.53 | 1.18 | 16.2 | 16.4 | 461. | 493. | 871. | 44. |
| SDSS J115245.91-021116.2 | MS -0.98 | 0.52 | 28.8 | 44.5 | 445. | 425. | 898. | 104. |
| BHB -3.98 | 2.15 | 11.4 | 13.9 | 494. | 511. | 879. | 32. |
| SDSS J144955.58+310351.4 | MS -7.44 | 0.53 | 6.3 | 14.7 | 644. | 519. | 967. | 23. |
| BHB -28.96 | 12.88 | 6.4 | 6.3 | 1094. | 561. | 1292. | 8. |
| SDSS J113312.12+010824.9 | MS -0.94 | 0.71 | 31.1 | 46.6 | 567. | 421. | 967. | 90. |
| (HVS 7) BHB -5.27 | 3.58 | 11.7 | 12.3 | 464. | 516. | 970. | 24. |

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5.2 A returning star?

SDSS J172226.55+594155.9 is the only star in our sample that has a comparatively large, but negative, $v_{rf}$. The heliocentric radial velocity is $-476 \text{ km/s}$. Is this a bound HVS observed as it is returning towards the Galactic Centre? We perform the same investigation as for the other HVSs: that is, we set a grid of proper motions and integrate the trajectories back in time to find if any initial conditions are reconcilable with a Galactic Centre origin. We discover that no proper motion will give SDSS J172226.55+594155.9 a trajectory that passes through the Galactic Centre. Given its current radial velocity and position we can find a proper motion such that the star will pass through the Galactic Centre in the future. However such a trajectory is always unbound given a reasonable mass of the galactic halo. Making this star bound would require a halo many orders of magnitude more massive than suggested in literature, corresponding to a radius large enough to include other galaxies. Given this, SDSS J172226.55+594155.9 can not be a returning, bound HVS.
5.3 The captured stars

The suggestion of Gould & Quillen (2003) that the captured stars are the observed S-stars in the galactic centre is compared with our data. As seen from Equation[4] for encounters between binaries and the SMBH that eject stars that form HVSs we expect the Hills parameter $D$ to lie between 0 and 175. For an ejection probability of 0.5 we have $D = 88$. Taking this typical value we obtain $f_i$ from Equation[3] and then the separation of the binary that produced the HVS from Equation[2]. The binary separation and the assumed $D$ allow us to calculate the closest approach to the black hole, $R_{\text{min}}$, via Equation[4]. We find that $R_{\text{min}}$ is typically 50 AU.

If we further assume that the energy in the binary is small compared to the potential and kinetic energies post ejection, the binding energy of the captured star is comparable to the kinetic energy of the ejected star, hence writing the semi-major axis of the captured star’s orbit as $a_{\text{bh}}$ we obtain

$$\frac{GM_{\text{bh}}M_{\star}}{2a_{\text{bh}}} \simeq \frac{M_{\text{hvs}}v_{ej}^2}{2}. \tag{6}$$

With typical masses for the bound HVS and S-star, $M_{\text{hvs}} \simeq M_{\star} \simeq 3M_\odot$ and a typical ejection velocity of about 800 km/s, we calculate the semimajor axis of the black hole - captured star system as $a_{\text{bh}} \simeq 5000 \text{AU}$. The eccentricity of the captured star’s orbit is given by

$$e = 1 - \frac{R_{\text{min}}}{a_{\text{bh}}}. \tag{7}$$

and is typically very large, 0.99. These values are similar to those for some of the observed S-stars, see Eisenhauer et al. (2003) and Ghez et al. (2005). A number of the S-stars have eccentricities significantly lower than this, suggesting that if they were produced by tidal disruption of a binary they were produced in encounters with $R_{\text{min}}$ larger than 50 AU.

6 CONCLUSIONS

We assume that the twelve hypervelocity stars with $v_{ej}$ between 275 km s$^{-1}$ and 450 km s$^{-1}$, listed in Table II come from the Galactic Centre. Hence we have obtained their proper motions by constraining the trajectory that takes them to their current position and space velocity to have originated in the Galactic Centre.

From this present-day space velocity we evaluate whether the stars are bound to the Galaxy. The range of proper motions that are consistent with a Galactic Centre origin are sufficiently small to allow us to unambiguously determine whether the stars are bound or not. We find that eight of our sample of twelve stars are bound to the Galaxy.

We further obtain the velocity with which the stars were ejected from the Galactic Centre, $v_{ej}$. These velocities have a range of magnitudes between 750 km s$^{-1}$ and 900 km s$^{-1}$. The unbound stars have similar but higher kick velocities, consistent with them having the same origin.

We integrate the trajectories of the bound stars forward in time in order to calculate their return time. Were the lifetimes of these objects greater or equal to the return times we would observe an equal number of systems moving towards the Galactic Centre as away from it. As we do not see any such returning objects we conclude that the lifetimes of the observed HVSs must be much shorter than their return times, and hence that they must be massive main-sequence stars.

One system, SDSS J172226.55+594155.9, is observed moving towards the Galactic Centre with a high velocity. We find that there are no trajectories consistent with it having been produced in the Galactic Centre. We calculate its trajectory if given a small proper motion and conclude that this is consistent with it being a halo object.

The production rate of bound, high-mass HVSs is about one system per 15 Myr. These stars are produced by the breakup of a binary, where the other star is left bound to the central supermassive black hole. On the assumption that the binaries have a mass ratio roughly equal to unity we show that this is consistent with the other star becoming one of the S-stars.

ACKNOWLEDGEMENTS

The authors would like to thank W. R. Brown for generously providing data on SDSS J172226.55+594155.9. RPC would like to thank the Swedish Institute for a Guest Scholarship. MBD is a Royal Swedish Academy Research Fellow supported by a grant from the Knut and Alice Wallenberg Foundation.

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