METAL-POOR HYPERVELOCITY STAR CANDIDATES FROM THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

Hypervelocity stars are believed to be ejected out from the Galactic center (GC) through dynamical interactions of (binary) stars with the central massive black hole(s). In this Letter, we report 13 metal-poor F-type hypervelocity star candidates selected from 370,000 stars of the data release 7 of the Sloan Digital Sky Survey. With a detailed analysis of the kinematics of these stars, we find that seven of them were likely ejected from the GC or the Galactic disk, four neither originated from the GC nor the Galactic disk, and the other two were possibly ejected from either the Galactic disk or other regions. Those candidates that unlikely originated from the GC or the Galactic disk may be explained by other mechanisms, like the tidal disruption of the Milky Way’s dwarf galaxies in the Galactic potential, or the gravitational interactions with a massive black hole at the center of M31 or M32.

Key words: galaxies: kinematics and dynamics – Galaxy: structure – stars: kinematics and dynamics

1. INTRODUCTION

Hypervelocity stars (HVSs), recently discovered in the Galactic halo (Brown et al. 2005; Hirsch et al. 2005; Edelmann et al. 2005), are moving so fast that they may escape from the Galaxy. A natural explanation for these HVSs is that they are ejected out from the Galactic center (GC) by interactions of stars with a massive black hole (MBH) or the hypothetical binary MBHs as predicted by Hills (1988) and Yu & Tremaine (2003). The ejection mechanisms of HVSs can be divided into three categories: tidal breakup of binary stars in the vicinity of a single MBH (Hills 1988; Yu & Tremaine 2003; Bromley et al. 2006), where the binary stars are probably injected into the vicinity of the MBH from the young stellar disk in the GC (e.g., Lu et al. 2010; Zhang et al. 2010) or from the Galactic bulge (Perets 2009a, 2009b); single star encounters with a binary MBH (Yu & Tremaine 2003; Sesana et al. 2006, 2007; Merritt 2006); or single star encounters with a cluster of stellar mass black holes around the MBH (O’Leary & Loeb 2008).

More than 16 HVSs have been reported in the literature (Brown et al. 2009; see also Tillich et al. 2009; Kollmeier et al. 2009; Tillich et al. 2010), most of them are 3–4 $M_\odot$ late B-type stars. Assuming a Salpeter initial mass function (IMF), the expected solar mass HVSs are about 10 times more abundant than 3–4 $M_\odot$ HVSs (Brown et al. 2009). Kollmeier et al. (2009) systematically searched for such low-mass HVSs in about 290,000 spectra of the Sloan Digital Sky Survey (SDSS); however, they found only six metal-poor stars that can be possibly taken as HVS candidates, which might suggest that the IMF of the parent population of these HVSs is top-heavy. A top-heavy IMF of the HVS parent population is possibly consistent with the disk origin (Bartko et al. 2010; Lu et al. 2010; Kollmeier et al. 2010). In order to distinguish the ejection mechanisms of HVSs and put constraints on the origin of the parent population of HVSs, it is quite necessary to search for low-mass HVSs.

In this Letter, we aim to find F/G-type low-mass HVS candidates from the data release 7 (DR7) of SDSS, which provides a large catalog of stars with precise multi-color photometry and medium resolution ($R \sim 1800$) spectra (York et al. 2000). We report the finding of 13 old metal-poor F-type HVS candidates and also discuss their possible origins by detailed analysis of their kinematics. The Letter is organized as follows. In Section 2, we introduce the searching process of our low-mass HVS candidates. Section 3 discusses their possible ejection mechanisms through kinematics. Finally, a brief conclusion is given in Section 4.

2. TARGET SELECTION

We analyze over 370,000 stars in the SDSS DR7 with their five-band photometry $ugriz$ and spectra, which are flux- and wavelength-calibrated in 3800–9200 Å and are reduced by the automated SEGUE Stellar Parameter Pipeline (Lee et al. 2008) to produce reliable heliocentric radial velocities $RV_\odot$ and atmospheric parameters.

2.1. High-velocity Objects

In order to find the F/G-type HVS candidates, we first select the high-velocity objects from the Galactic radial velocity distribution of F/G-type main-sequence samples with the following methods.

1. Select F/G-type main-sequence samples using the five photometric criteria and log($g$) > 3.0 in Section 2.3.1 of Ivezić et al. (2008): [130775].
2. Find objects at the high-velocity end, which significantly deviate from the best-fit Gaussian distribution of line-of-sight velocities in the Galactic rest frame $V_r$: [369].

The numbers in brackets indicate the number of stars left after each selection step. The $V_r$ distribution of our 130,775 samples, shown in the top panel of Figure 1, can be well fitted by two Gaussian distribution (red solid curve). The two Gaussian components have mean velocities (and scatters) of 0 km s$^{-1}$ (92 km s$^{-1}$) and 124 km s$^{-1}$ (55 km s$^{-1}$), respectively. Approximately 82% of the samples belong to the low-velocity component, and 18% of them belong to the high-velocity component (two dashed green curves). These two components probably correspond to the Galactic halo population (0 ± 100 km s$^{-1}$) and thick disk population (90 ± 45 km s$^{-1}$; Williams et al. 2011), respectively. The normalized residual of the observation from this two Gaussian distribution is shown in the bottom panel of the Figure 1, and at its high-velocity tail,
Figure 1. Top panel plots the histogram of line-of-sight velocities in the Galactic rest frame of 130775 F/G-type stars, the best-fit two Gaussian functions (solid red curve) and the two Gaussian components (dashed green curves). The bottom panel is the normalized residuals of the observations from the two Gaussian functions. The two red arrows show the region of 369 high-velocity objects.

high-significance deviations are found. So, we choose the high-velocity objects with $V_{\text{rf}} > 309 \text{ km s}^{-1}$ and $V_{\text{rf}} < -285 \text{ km s}^{-1}$, which have normalized residuals larger than 1 and are denoted by two red arrows.

2.2. HVS Candidates

To determine which high-velocity objects are unbound to the Galaxy, we first obtain the phase-space coordinates for them. The Galactic Cartesian coordinate system adopted here is centered on the GC: the X-axis points from the Sun to the GC with the Sun at $x = -8 \text{ kpc}$; the Y-axis points in the direction of Galactic rotation; the Z-axis points toward the Northern Galactic Pole. Assuming that the motion of the local standard of rest (LSR) is $220 \text{ km s}^{-1}$, and the velocity of the Sun with respect to the LSR is $220 \text{ km s}^{-1}$, the phase-space coordinates to the GC for these high-velocity objects can be derived by equatorial coordinates ($R_A, \text{Decl}$), galactic coordinates ($l, b$), $RV_\odot$, two components of the proper motion $\mu_\alpha \cos(\delta)$, $\mu_\delta$, and the heliocentric distances ($D_\odot$). Here, $D_\odot$ is equal to $1/100 \times 10^{0.2(r - M_r)}$, where $r$ is the dereddened $r$-band apparent magnitude given by the DR7 and $M_r$ is the $r$-band absolute magnitude calculated by the photometric parallax relation of Ivezić et al. (2008).

Then, we adopt two different Galactic potential models, i.e., a spherically symmetric model (Xue et al. 2008, hereafter Xue08) and a triaxial model (Gnedin et al. 2005, hereafter Gnedin05) to estimate the escape velocities ($V_{\text{esc}}$). There are a total of 13 objects (mpHVS1–mpHVS13, “mp” means metal-poor), listed in Table 1, which are unbound to the Galaxy in the Xue08 model, but only three (mpHVS1–mpHVS3) are unbound in the Gnedin05 model. The rest of the stars in the 369 high-velocity objects are all bound to the Galaxy in both models. We cross-check the $V_{\text{esc}}$ for these 13 unbound candidates using other Galactic potential models in the literature, e.g., a spherically symmetric model from Kenyon et al. (2008), two axisymmetric models from Koposov et al. (2010), and Paczynski (1990) with the same definition of unbound stars as in Kenyon et al. (2008), and find that the $V_{\text{esc}}$ from these divergent models are between the values obtained from the Gnedin05 and Xue08 models, and mpHVS1, mpHVS2, and mpHVS3 are unbound to the Galaxy in all models. Note that a small fraction of the bound stars at the $2\sigma$ level could be actually unbound due to the velocity measurement error, but
the possibilities are certainly much less than those of unbound candidates. The basic information of these 13 candidates is listed in Tables 1–3. Table 1 summarizes their basic parameters, i.e., the name and its notation, $\mu_\alpha \cos(\delta)$ and $\mu_\delta$, $RV_\odot$, $V_{rf}$, and $g$.}

### Table 3

| Notation | $D_\odot$ (kpc) | $V_\odot$ (km s$^{-1}$) | $V_{\text{esc}}$ (Xue08) (km s$^{-1}$) | $V_{\text{esc}}$ (Gnedin05) (km s$^{-1}$) |
|----------|----------------|-------------------------|---------------------------------|---------------------------------|
| mpHVS1   | 7.7 $\pm$ 0.3 | 1092 $\pm$ 103 | 494                             | 607                             |
| mpHVS2   | 8.4 $\pm$ 1.2 | 800 $\pm$ 174 | 487                             | 599                             |
| mpHVS3   | 9.6 $\pm$ 0.7 | 763 $\pm$ 180 | 477                             | 590                             |
| mpHVS4   | 7.7 $\pm$ 0.4 | 589 $\pm$ 76  | 494                             | 608                             |
| mpHVS5   | 10.8 $\pm$ 0.6 | 545 $\pm$ 151 | 468                             | 583                             |
| mpHVS6   | 14.3 $\pm$ 0.4 | 479 $\pm$ 166 | 447                             | 564                             |
| mpHVS7   | 9.9 $\pm$ 0.7 | 505 $\pm$ 128 | 475                             | 590                             |
| mpHVS8   | 10.8 $\pm$ 0.5 | 493 $\pm$ 130 | 468                             | 584                             |
| mpHVS9   | 9.4 $\pm$ 0.9 | 501 $\pm$ 226 | 479                             | 590                             |
| mpHVS10  | 12.1 $\pm$ 0.9 | 478 $\pm$ 182 | 459                             | 574                             |
| mpHVS11  | 9.2 $\pm$ 0.3 | 494 $\pm$ 92  | 480                             | 595                             |
| mpHVS12  | 7.4 $\pm$ 0.3 | 503 $\pm$ 68  | 496                             | 610                             |
| mpHVS13  | 7.3 $\pm$ 0.3 | 499 $\pm$ 124 | 497                             | 610                             |

**Notes.** $D_\odot$ and $V_\odot$ are the Galactocentric distance and 3D total velocity relative to the Galactocentric rest frame, respectively. $V_{\text{esc}}$ (Xue08) and $V_{\text{esc}}$ (Gnedin05) are escape velocities in the Xue08 and Gnedin05 models.
candidates are all valid because their spectroscopic metallicities [Fe/H] are in the valid range of that given by Ivezić et al. (2008). Table 3 compares their Galactic total velocities $V_G$ with $V_{esc}$ of the Gnedin05 and Xue08 models at their Galactocentric distances $D_G$, from which we can see whether they are unbound in a certain potential model. In addition, Kollmeier et al. (2009) found six analogous metal-poor HVS candidates, so we also check whether they are in our high-velocity objects. Consequently, only SDSS J074557.31+181246.7 is selected and belongs to our bound objects, while the other five candidates are not in our high-velocity objects mainly because they are inconsistent with the selection criterion 1 in Section 2.1.

3. POSSIBLE ORIGINS OF 13 mpHVS CANDIDATES

To investigate the origins of these 13 mpHVS candidates, it is essential to study their kinematics. By varying the 3D velocities and positions within their measurement errors, we calculate 10,000 tracing-back trajectories and the $1\sigma$ level intersection places with the Galactic disk for each of mpHVS1–3 with the Gnedin05 and Xue08 models, and those for each of mpHVS4–13 with the Xue08 model, because they are bound in the Gnedin05 model, which are shown in Figure 2. From the left panel of Figure 2, we can see that (1) the trajectories of mpHVS1 and mpHVS2 do not intersect with the Galactic disk; (2) the trajectories of mpHVS3 intersect with the Galactic disk about 12 and 15 Myr ago for the Gnedin05 and Xue08 models, respectively, and the $1\sigma$ intersection places are, respectively, shown by red and green ellipses. In the right panel: (1) the trajectories of mpHVS4 and mpHVS13 do not intersect with the Galactic disk; (2) the trajectories of mpHVS5, mpHVS7, mpHVS8, mpHVS10, mpHVS11, and mpHVS12 do intersect with the Galactic disk about 10–20 Myr ago and the $1\sigma$ intersection regions are depicted by six ellipses with different colors; (3) for mpHVS6 and mpHVS9, most trajectories do intersect with the Galactic disk, but most of the intersection regions are far away from the GC even to hundreds of kiloparsecs, so we just describe part of the trajectories for the two candidates, which are calculated with their present 6D phase-space coordinates, and do not show their intersection regions in the right panel.

The trajectories of mpHVS3 are consistent with being ejected out from the GC or the Galactic disk, while those of mpHVS5, mpHVS7, mpHVS8, mpHVS10, mpHVS11, and mpHVS12 are consistent with originating from the Galactic disk (see Figure 2). Therefore, a supernova explosion in a massive tight binary system (Blaauw 1961) or dynamical interactions in dense stellar clusters (Poveda et al. 1967; Leonard 1991; Gvaramadze et al. 2009; Gvaramadze & Gualandris 2011) are possible originating mechanisms for these seven candidates, and dynamical interactions between (binary) stars and MBH(s) in the GC are also possible ejection mechanisms for mpHVS3. For mpHVS1,
mpHVS2, mpHVS4, and mpHVS13, their trajectories are incompatible with the GC origin or the Galactic disk origin mechanisms (see Figure 2). However, their origins may be interpreted as follows.

Sherwin et al. (2008) proposed that there are a large number of low-mass (\(\approx 1 M_\odot\)) HVSs ejected by the MBH in the center of M31, and a fraction of them would be moving toward the Milky Way on the solar system side, with large Galactocentric radial approach velocities (\(\approx -500 \text{ km s}^{-1}\)) exceeding the local escape velocity. The Galactocentric radial velocities of mpHVS1, mpHVS2, mpHVS4, and mpHVS13 are \(-476 \pm 85 \text{ km s}^{-1}\), \(-597 \pm 177 \text{ km s}^{-1}\), \(413 \pm 96 \text{ km s}^{-1}\), and \(265 \pm 126 \text{ km s}^{-1}\), respectively, which means that the approaching velocities of mpHVS1 and mpHVS2 are well consistent with the predicted \(-500 \text{ km s}^{-1}\), but it seems unlikely that mpHVS4 and mpHVS13 originated from the central MBH of M31. mpHVS1 and mpHVS2 are low-mass stars (\(\approx 1 M_\odot\)) and on the side of the Sun (see Figure 2); considering these factors, they seem to have been ejected out from the central MBH of M31. The ejection rate of HVSs from M32 is even higher than that from M31 (Lu et al. 2007), and thus M32 is also a possible origin of the two mpHVS candidates.

Tidal disruptions of dwarf galaxies in the Milky Way can also produce high-velocity stars as proposed by Abadi et al. (2009). They suggested that the current detected HVSs surrounding the constellation Leo (\(l \approx 230^\circ\), \(b \approx 60^\circ\)) may be a stream of stars from a dwarf galaxy that was recently tidally disrupted (but see a different explanation of this in Lu et al. 2010), and Teyssier et al. (2009) further proposed that such tidal disruption process of massive satellites or satellites on eccentric orbits can also generate a population of old isolated high-speed “escaped” (unbound) or “wandering” (bound) stars. If mpHVS1, mpHVS2, mpHVS4, and mpHVS13 are stars in tidal stripping streams, they may originate from other star streams, as their loci (\(l : 58^\circ \sim 69^\circ\); \(b : -45^\circ \sim 33^\circ\)) are far away from the Leo area. If they are the isolated old “escaped” tidal stripping stars, we can roughly estimate their stripping times since they only pass through our galaxy once and never come back. Their estimated tidal stripping occurred about \(10^6\) yr ago, assuming that the dwarfs lie at the virial radius. Such a short stripping time suggests that their parent dwarf galaxies or streams may still be detectable along their trajectories. Therefore, further investigations are needed to find such dwarf galaxies, but the current comparatively large data errors impede such studies.

From the results of numerical experiments of mpHVS6 and mpHVS9, they are possibly ejected out from either the Galactic disk by corresponding mechanisms described above or other places. The Galactocentric radial velocities of mpHVS6 and mpHVS9 are \(364 \pm 223 \text{ km s}^{-1}\) and \(-273 \pm 262 \text{ km s}^{-1}\), respectively, so they are unlikely to be ejected by the central MBH of M31. The tidal interactions between satellite galaxies and our galaxy may be able to explain their origins, but they were surely not ejected out from star streams in the direction of constellation Leo because their loci (\(l : 56^\circ \sim 185^\circ\); \(b : 26^\circ \sim 31^\circ\)) are also far away from that region. More exact conclusions about the origins of these two candidates mainly depend on more accurate data measurements in the future.

Note that the large velocities of these mpHVS candidates could partly be due to orbital motions, if they were in compact binaries. Below, we give a simple estimation of the effect of binary orbital velocities on the observed heliocentric radial velocities and the Galactic total velocities. If each of these mpHVS candidates were in binaries, its companion could be a low-mass main-sequence star, a neutron star, or a black hole.

1. A low mass \((\lesssim 1 M_\odot)\) main-sequence companion. Rastegaev (2010) calculated the distribution of orbital periods for 60 detected metal-poor F-, G-, and early K-type binaries, and found that the minimum orbital period was larger than 10 days, and correspondingly the minimum semimajor axis \(\gtrsim 0.1 \text{ AU}\). If the mass and semimajor axis of the companion are \(1 M_\odot\) and 0.1 AU, respectively, the effects due to binary orbital motion could be most significant. The average effect of the projected orbital velocities on the line of sight is thus about \(27 \text{ km s}^{-1}\), and the maximum is about \(67 \text{ km s}^{-1}\), which introduce only approximately \(3 \sim 7 \text{ km s}^{-1}\) and \(9 \sim 31 \text{ km s}^{-1}\) effects to the 3D velocities of our candidates. In addition, if these candidates are really in such binaries, their heliocentric distances and Galactic total velocities would be larger than our estimations, and the escape velocities would be correspondingly smaller, so these binaries should more likely be able to escape from our Galaxy.

2. A neutron star companion. The maximum theoretical mass of a neutron star is \(\sim 3 M_\odot\) (Kiziltan et al. 2010), and if its semimajor is 0.1 AU, the average line-of-sight projected orbital velocity is about \(57 \text{ km s}^{-1}\) and the maximum value is about \(141 \text{ km s}^{-1}\). In this case, approximately \(11 \sim 24 \text{ km s}^{-1}\) and \(49 \sim 93 \text{ km s}^{-1}\) effects on the total space velocities of these mpHVS candidates are introduced.

3. A black hole companion. If the mass and semimajor axis of a black hole are \(10 M_\odot\) and 0.1 AU, respectively, the average line-of-sight projected orbital velocity is about \(115 \text{ km s}^{-1}\), and the maximum velocity is about \(284 \text{ km s}^{-1}\), which introduce approximately \(35 \sim 69 \text{ km s}^{-1}\) and \(150 \sim 228 \text{ km s}^{-1}\) effects on the total space velocities of these candidates. In this case, the binary effect appears significant, so multiple observations are important to investigate whether these HVS candidates are in binaries with black hole companions.

To close the discussion, we note here that only mpHVS1 is unbound with high statistical significance, although all 13 HVS candidates are unbound in some Galactic potential models. The proper motion estimates adopted in our analysis (see Table 1), given by the SDSS, may suffer some uncertainties as pointed out by Dong et al. (2011), which may affect our estimations on the 3D velocities of those mpHVS candidates. Applying the model of Dong et al. (2011, see their Equation (6)), we re-estimate statistically the true proper motions of those 13 HVS candidates at \(3\sigma\) significance level. Considering this correction, we find that the highest velocity candidate, mpHVS1, is still unbound to the Galaxy in both potential models though with a lower 3D velocity (877 km s\(^{-1}\)). However, the mpHVS4–13 of the other 12 candidates are bound to the Galaxy if the Xue08 potential or is adopted the mpHVS2–13 are bound if the Gnedin05 potential is used. So, those mpHVS candidates, except mpHVS1, could be bound halo stars. If they were, it is possible to use them to set constraints on the Galactic potential (W. Brown 2011, private communication).

4. CONCLUSION

In this Letter, we report 13 metal-poor F-type HVS candidates from over 370,000 stars in the SDSS DR7. Through kinematic analysis, we find that seven of them are likely to have been
ejected from the GC or the Galactic disk. Two of them were possibly ejected out from either the Galactic disk or other places. Meanwhile, the other four candidates were unlikely to originate from the GC or the Galactic disk. Those candidates impossibly ejected from the GC or the Galactic disk may be explained by other mechanisms, i.e., being ejected from the tidal break of the Milky Way’s dwarf galaxies (Abadi et al. 2009; Teyssier et al. 2009), or from the center of M31 or M32 by the interactions of stars with the MBH (Sherwin et al. 2008). In order to understand the origins of these mpHVS candidates well and solve the binary problem, second-epoch observations in the future are needed.

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