ORIGIN AND STATUS OF LOW-MASS CANDIDATE HYPERVERSITY STARS

BUM-SUK YEOM1,2, YOUNG SUN LEE1, JAE-RIM KOO1, TIMOTHY C. BEERS3, AND YOUNG KWANG KIM1

1Department of Astronomy and Space Science, Chungnam National University, Daejeon 34134, Korea
2Jeollabukdok Institute of Science Education, Iksan 54549, Korea
3Department of Physics and JINA Center for the Evolution of the Elements, University of Notre Dame, IN 46556, USA

Received ; accepted

Abstract: We present an analysis of the chemical abundances and kinematics of six low-mass dwarf stars, previously claimed to be candidate hypervelocity stars (HVSs). We obtained moderate-resolution ($R \sim 6000$) spectra of these stars to estimate their abundances of several chemical elements (Mg, Si, Ca, Ti, Cr, Fe, and Ni), and derived their space velocity components and orbital parameters using proper motions from Gaia Data Release 2. All six stars are shown to be bound to the Milky Way, and in fact are not even considered high-velocity stars with respect to the Galactic rest frame. Nevertheless, we attempt to characterize their parent Galactic stellar components by simultaneously comparing their abundance patterns and orbital parameters with those expected from various Galactic stellar components. We find that two of our program stars are typical disk stars. For four of the program stars, even though their kinematic probabilistic membership assignment suggests membership in the Galactic disk, based on their distinct orbital properties and chemical characteristics, we cannot rule out the exotic origins of these objects, as follows. Two stars appear to be runaway stars from the Galactic disk. One program star has possibly been accreted from a disrupted dwarf galaxy or dynamically heated from a birthplace in the Galactic bulge. The last object may be either a runaway disk star or has been dynamically heated. Spectroscopic follow-up observations with higher resolution for these curious objects will provide a better understanding of their origin.

Key words: Method: data analysis – technique: spectroscopy – Galaxy: disk – stars: abundances

1. INTRODUCTION

Hypervelocity stars (HVSs) are unbound and rare fast-moving objects in the Galactic halo, possessing space velocities that exceed the Galactic escape speed. The first HVS was discovered from a radial velocity survey of faint blue horizontal branch stars (Brown et al. 2005). It is a 3 $M_\odot$ main-sequence B-type star moving with a Galactic rest-frame velocity of about 700 km s$^{-1}$ at a distance of about 100 kpc. Since then, about 20 B-type HVS candidates have been discovered in the Galactic halo (Brown et al. 2015).

These intriguing objects are believed to originate from the so-called “Hills mechanism”, which is associated with the supermassive black hole (SMBH) at the Galactic Center. This theory suggests that, in the case of a binary system interacting with the SMBH, the SMBH can destroy the binary system and “release” one of its stars, attaining speeds up to ~1000 km s$^{-1}$ (Hills 1988; Yu & Tremaine 2003). It is known that this mechanism can also produce HVSs bound to the Milky Way (MW) (Bromley et al. 2009; Brown et al. 2014).

In addition to the HVSs, there are other types of fast-moving stars, referred to as “runaway stars” among O- and B-type stars, which have peculiar velocities larger than 40 km s$^{-1}$ (e.g., Gies 1987; Stone 1991; Tetzlaff et al. 2011). Several scenarios have been proposed to explain the runaway stars. The binary ejection mechanism (Blaauw 1961; Tauris & Takens 1998; Tauris 2015) postulates that these objects could be formed in a binary system and “released” out of their system by the explosive death of their companion in the Galactic disk. The dynamical ejection mechanism proposed by Poveda et al. (1967) assumes that a star can be ejected by multi-body interactions in a high-density environment such as star clusters. Another explanation to account for these stars is the ejection from a star-forming galaxy such as the Large Magellanic Cloud (LMC) (Boubert & Evans 2016). An alternative theory suggests that these objects are members of a tidally disrupted dwarf galaxy (Abadi et al. 2009). Even though there exist many scenarios to explain the HVSs and runaway stars, full understanding of their origin remains elusive.

In spite of the ambiguity of their origin, high-velocity stars have received attention because they can provide a mean for measuring the local escape velocity at a given distance from the Galactic Center, which can in turn constrain the total mass of the MW, still uncertain by more than a factor of two (Xue et al. 2008; Watkins et al. 2010). Even though the origin of these objects is uncertain, we can utilize their general characteristics to infer where they originated. What HVSs have in common is that they are young, massive main-sequence stars typically found at present distances beyond 50 kpc from the Sun (See Brown 2015, and references therein). Therefore, we can hypothesize that
the high-velocity stars may originate from star-forming regions in the disk, bulge, or dwarf satellites of the MW.

Although most of the currently known HVSs and runaway stars are early type (high-mass) main-sequence stars, one might expect that the proposed ejection mechanisms could work for any stellar type, leading to the prospect of identifying low-mass HVSs (Kollmeier & Gould 2007). For this reason, various efforts to search for such stars have been carried out from the stellar database constructed by large spectroscopic surveys such as Sloan Digital Sky Survey (SDSS; York et al. 2000) and Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST; Cui et al. 2012).

Indeed, Kollmeier et al. (2009) and Li et al. (2012) identified 6 and 13 HVS candidates, respectively, from SDSS. In addition, Zhong et al. (2014) reported 28 HVS candidates, 17 of which are F-, G-, and K-type dwarf stars. Li et al. (2015) reported another 19 low-mass HVS candidates from LAMOST. Palladino et al. (2014, hereafter Pal14) also reported the discovery of 20 low-mass G-, and K-type HVS candidates from Sloan Extension for Galactic Understanding and Exploration (SEGUE; Yanny et al. 2009). One interesting feature of many of these low-mass candidates is that they appeared to be associated with birth in the Galactic disk, rather than the Galactic Center, as is the case for the high-mass HVSs.

Previous studies of low-mass HVSs or runaway star candidates were carried out exclusively on the basis of derived stellar kinematics, since proper motion information, when combined with an observed radial velocity and distance estimate, provides the full space velocity of a star. In keeping with this, it is interesting to note that HVSs thought to have a Galactic Center origin (e.g., the high-mass HVSs) are often well-separated in their proper motions from likely disk origins, which is not the case for the low-mass runaway-star candidates. For this reason, one might consider use of their detailed chemical-abundance patterns in order to identify the possible birthplaces of the runaway-star candidates – bulge, disk, or halo, and thereby constrain the possible ejection mechanisms of such stars.

We note here that a number of recent studies claim that most of the low-mass HVS candidates and runaway stars identified thus far are bound to the MW. For example, Ziegerer et al. (2015) have re-calculated the proper motions for the 14 HVS candidates that Pal14 reported, using images from SDSS4, Digitized Sky Survey2 (DSS), and UKIDSS8 (Lawrence et al. 2007). They found that the newly measured proper motions are much smaller than the ones used by Pal14, and, as a result, all of their HVS candidates are bound to the MW under three different potentials for the MW. More recently, Boubert et al. (2018) reported using Gaia Data Release 2 (DR2; Gaia Collaboration et al. 2018) proper motions and radial velocities that all late-type stars, which have been claimed to be HVSs previously are likely to be bound to the MW, except one object (LAMOST J115209.12+120258.0).

Prior to clarification on the proper motions for low-mass HVS candidates in the Pal14 sample, we carried out follow-up spectroscopic observations and obtained medium-resolution ($R = 6000$) spectra for six of them, in order to study their chemical abundance patterns. As we report in this paper, we make use of chemical tagging (Freeman & Bland-Hawthorn 2002), in an attempt to understand their characteristics and likely parent populations of their birthplaces. This approach has already proven to be useful to constrain the origin of HVSs or runaway stars (Hawkins & Wyse 2018). In addition, we make use of the greatly improved proper motion information from Gaia DR2 to carry out a kinematics analysis of our program objects. Although we confirm that none of our program stars unbound, and thus are no longer viable HVS candidates, for simplicity we refer to them as HVS candidates through this paper. This paper is organized as follows. The spectroscopic observations and reduction of the six low-mass candidate HVSs are described in Section 2. In Section 3, we determine the stellar parameters and chemical abundances for our program stars. In Section 4, we present results of the analysis of the chemical and kinematic properties of our objects. Section 5 discusses the characteristics and possible origin of each HVS candidate. A summary of our results, and brief conclusions are provided in Section 6.

### 2. Spectroscopic Observations and Reduction

Among the 20 HVS candidates reported by Pal14, we obtained spectroscopy for six stars during the period between January and May, 2014, including two stars that were not studied by Ziegerer et al. (2015). The spectra were obtained with the Dual Imaging Spectrograph (DIS) on the Apache Point Observatory 3.5 m telescope in New Mexico. We selected the grating combination B1200/R1200, which has wavelength coverage of 4200 – 6400 Å and 5600 – 6700 Å in the blue and red channels, respectively, along with a 1.5 arcsec slit, a yielding spec-

---

1. [http://skyserver.sdss3.org/public/en/tools/chart/navi.aspx](http://skyserver.sdss3.org/public/en/tools/chart/navi.aspx)
2. [http://archive.stsci.edu/cgi-bin/dss_plate_finder](http://archive.stsci.edu/cgi-bin/dss_plate_finder)
3. [http://www.ukidss.org/](http://www.ukidss.org/)

### Table 1

| Object              | Magnitude | Date (UT) | Exposure Time (c) | N_{obs} | S/N   | Pal14 ID |
|---------------------|-----------|-----------|-------------------|---------|-------|---------|
| **PROGRAM STARS**   |           |           |                   |         |       |         |
| HIP 33562           | 9.01      | 2014.01.05 | 5                  | 4        | 4     |         |
| HIP 59330           | 8.50      | 2014.01.05 | 5                  | 3        | 15    |         |
| HIP 44075           | 5.96      | 2014.01.12 | 5                  | 3        | 15    |         |
| HIP 60551           | 8.00      | 2014.01.12 | 5                  | 3        | 15    |         |
| HIP 64426           | 7.29      | 2014.01.12 | 5                  | 3        | 15    |         |
| HR 2721             | 5.58      | 2014.01.25 | 5                  | 3        | 15    |         |
| HR 2233             | 5.60      | 2014.03.30 | 5                  | 3        | 15    |         |
| HIP 62862           | 8.30      | 2014.04.03 | 5                  | 3        | 15    |         |

N_{obs} is the number of observations. Pal14 ID is the ID of a star used in Pal14. r indicates the reddening-corrected r magnitude. S/N is the signal-to-noise ratio of the co-added spectrum of each star after data reduction. The S/N range of the standard stars can be seen in Figure 3.
In addition, we observed eight well-studied disk stars as comparison stars, to verify the accuracy of our derived stellar parameters ($T_{\text{eff}}$, log $g$, and [Fe/H]) and chemical abundances for our program stars. For the comparison stars, we took several exposures to obtain the spectra at various signal-to-noise (S/N) ratios, enabling an evaluation of the effect of S/N on the estimated stellar parameters and chemical abundances of our target stars. As our targets are mostly faint ($r > 16.0$), we took one or two exposures between 60 and 75 minutes each. Table 1 lists details of the observations.

We followed the standard spectroscopic reduction steps such as aperture extraction, wavelength calibration, and continuum normalization using IRAF\(^4\). Radial velocities were measured using the cross-correlation function by applying xcsao task of the rvsao package (Kurtz & Mink 1998) in IRAF. In that process, we used a synthetic model spectrum of $T_{\text{eff}} = 6000$ K and log $g = 4.0$ as a template. We also considered the night-sky emission lines to check for any additional instrumental shifts. The spectra of each star were co-added after application of radial velocity corrections, to obtain a final spectrum with higher S/N, typically S/N $\sim 30 - 50$.

\(^4\)IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

The spectra of our standard stars and program stars are shown in Figures 1 and 2, respectively.

### 3. Estimation of Stellar Parameters and Chemical Abundances

We determined estimates of the stellar parameters ($T_{\text{eff}}$, log $g$, and [Fe/H]), and elemental abundances for Mg, Si, Ca, Ti, Cr, and Ni using the Stellar Parameters And chemical abundances estimator (SP_Ace; Boeche & Grebel 2016) code. The SP_Ace code employs similar methodology to that used in the RAAdial Velocity Experiment (RAVE; Steinmetz et al. 2006) chemical abundance pipeline (Boeche et al. 2011), which was developed to derive elemental abundances for the stellar spectra obtained by the RAVE survey. SP_Ace estimates the stellar parameters and abundances based on a library of the equivalent widths (EWs) for 4643 absorption lines. The EWs are generated from a synthetic grid in the ranges of $3600 < T_{\text{eff}} < 7400$ K, $0.2 < \log g < 5.4$, and $-2.4 < [\text{M/H}] < 0.4$. Each spectrum in the synthetic grid was synthesized by MOOG (Sneden 1973), after adopting the ALTA59 model atmospheres (Castelli & Kurucz 2003). Based on input trial values of $T_{\text{eff}}$, log $g$, and [elements/H], SP_Ace calculates by interpolation the expected EWs using the library to generate a normalized model spectrum. Then, using the Levenberg-Marquardt method, it attempts to minimize the $\chi^2$ between the model and the observed spectrum to determine the stellar parameters and chemical abundances. As the lines used to measure the abundances of the individual elements and stellar parameters in SP_Ace are well described in Boeche & Grebel (2016), we refer the interested reader to their paper.

Even though we obtained spectra of both the blue and red channels with the DIS instrument, we exclusively used the red channel spectra, because the adopted wavelength ranges ($5212 - 6860\ \text{Å}$ and $8400 - 8920\ \text{Å}$) used by SP_Ace cover a much larger wavelength range.

**Figure 1.** Spectra of standard stars in the wavelength range used to derive stellar parameters and chemical abundances.

**Figure 2.** Same as in Figure 1, but for our program stars.
in the red. We applied SP_Ace to the spectra of the co-added spectra of our program stars as well as to the spectra of individual exposures of the reference stars to derive final estimates of the stellar parameters and chemical abundances.

Before we finalized the stellar parameters and chemical abundances of our program stars for the analysis of the abundance patterns, we first compared our derived values with the values for the standard stars from the various references, as a function of S/N, in order to check for systematic offsets and estimate the precision of the derived stellar parameters and chemical abundances. Table 2 lists the adopted stellar parameters and chemical abundances of the comparison stars from various references.

Table 3

| Star                | T_{\text{eff}} (K) | log g | [Fe/H] | [Mg/H] | [Si/H] | [Ca/H] | [Ti/H] | [Cr/H] | [Ni/H] | References   |
|---------------------|------------------|-------|--------|--------|--------|--------|--------|--------|--------|--------------|
| HIP 33582           | 5782             | 4.30  | –0.68  | –0.23  | –0.36  | –0.50  | –0.33  | –0.64  | –0.64  | ···           |
| HIP 44075           | 5880             | 4.10  | –0.90  | –0.53  | –0.55  | –0.60  | –0.57  | –0.89  | –0.87  | 1, 2, 3, 4, 5, 7, 11 |
| HIP 59330           | 5749             | 4.02  | –0.75  | –0.45  | –0.42  | –0.58  | –0.47  | –0.74  | –0.75  | 1, 3, 4      |
| HIP 60551           | 5724             | 4.38  | –0.86  | –0.53  | –0.52  | –0.61  | –0.59  | –0.85  | –0.76  | 1, 3, 4      |
| HIP 62882           | 5692             | 3.81  | –1.26  | –0.73  | –0.79  | –0.93  | –0.99  | –1.30  | –1.21  | 1, 3, 5, 11  |
| HIP 64426           | 5892             | 4.19  | –0.76  | –0.39  | –0.50  | –0.62  | –0.58  | –0.81  | –0.73  | 1, 3, 4, 8   |
| HR 2333             | 6240             | 3.97  | –0.19  | –0.06  | –0.11  | –0.11  | 0.11   | –0.22  | –0.22  | 4, 5, 6, 7, 11 |
| HR 2721             | 5872             | 4.30  | –0.32  | –0.13  | –0.21  | –0.25  | –0.17  | –0.35  | –0.33  | 4, 5, 7, 9, 11 |

The numbers in the last column indicate the following references: (1) Bensby et al. (2003), (2) Bensby et al. (2005), (3) Fulbright (2000), (4) Lee et al. (2011), (5) Prugniel et al. (2011), (6) Houk & Swift (2000), (7) Takeda & Honda (2005), (8) Battistini & Bensby (2015), (9) Mishenina et al. (2013), (10) Delgado et al. (2014), (11) Cenarro et al. (2007). When possible, we took an average of the listed references for the stellar parameters and elements.

Note that the systematic offsets are corrected for these values. [α/Fe] is a mean value of [Mg/Fe], [Si/Fe], [Ca/Fe], and [Ti/Fe]. Typical errors for elements are σ[Mg/Fe] = 0.27 dex, σ[Si/Fe] = 0.17 dex, σ[Ca/Fe] = 0.15 dex, σ[Ti/Fe] = 0.18 dex, σ[Cr/Fe] = 0.20 dex, and σ[Ni/Fe] = 0.18 dex, respectively.

We carried out a similar exercise for the chemical abundances (Mg, Si, Ca, Ti, Cr, and Ni): Figure 4 displays the results. Similar to [Fe/H], there is a tendency for larger derived abundances with decreasing S/R. For S/N < 50, we found median offsets with of [Mg/H] = –0.16 ± 0.03 dex, [Si/H] = –0.06 ± 0.14 dex, [Ca/H] = –0.10 ± 0.11 dex, [Ti/H] = –0.08 ± 0.15 dex, [Cr/H] = –0.21 ± 0.17 dex, and [Ni/H] = –0.15 ± 0.15 dex. The uncertainty is the MAD. We applied these offsets to our program stars. Table 3 lists the offset-corrected stellar parameters and chemical abundances for our program stars. The value of [α/Fe] is a mean of the four ratios [Mg/Fe], [Si/Fe], [Ca/Fe], and [Ti/Fe]. The typical errors on the abundances for our target stars are σ[Mg/Fe] = 0.27 dex, σ[Si/Fe] = 0.17 dex, σ[Ca/Fe] = 0.15 dex, σ[Ti/Fe] = 0.18 dex, σ[Cr/Fe] = 0.20 dex, and σ[Ni/Fe] = 0.18 dex. These uncertainties and the uncertainties on T_{\text{eff}}, log g, and [Fe/H] are calculated by adding in quadrature the internal error from SP_Ace and the MAD in the range of S/N < 50 for the standard stars. We use these corrected values for the analysis of chemical properties throughout this paper.

As setting S/N values to different limits in Figures 3 and 4 can result in different levels of the offsets in each parameter and abundance, we carried out an exercise to evaluate its effect by applying different limits of S/N, for example bins of S/N < 50, S/N = 50 – 90, S/N > 90. We found a median offset of T_{\text{eff}} = 99 ± 183 K, log g = –0.16 ± 0.34 dex, and [Fe/H] = –0.04 ± 0.09 dex, respectively, in the sense that our values are higher for T_{\text{eff}} and lower for log g and [Fe/H]. The uncertainty is the MAD. We decided to adjust the parameter scales by these offsets for derivation of the final estimates for our program stars.
Kinematic and Chemical Properties of Hypervelocity Stars

4. Kinematic Properties of Our Program Stars

4.1. Kinematic Properties

The contradicting results on the status of the SEGUE low-mass candidates HVSs between Pal14 and Ziegerer et al. (2015) stem from the proper motions that they adopted. Pal14 used the SDSS proper motions (Munn et al. 2004, 2008), while Ziegerer et al. (2015) derived the proper motions with the images from SDSS, DSS, and UKIDSS. Table 4 summarizes these different sets of proper motions for our target stars, along with those reported in Gaia DR2.

Comparison of the three sets of the proper motions reveals that the proper motions adopted by Pal14 are consistently larger than the other two; the proper motions of the four stars that Ziegerer et al. (2015) derived are closer to the Gaia proper motions. Munn (priv. communication) notes that the reported proper motions from Pal14, based on SDSS data, are almost certainly the result of mis-identification of the targets with other nearby stars. The SDSS proper motions of the other two stars (Pal14 IDs 7 and 10) that Ziegerer et al. (2015) could not measure the proper motions for are also larger than those from Gaia DR2. These smaller proper motions imply that our objects are probably bound to the MW. One program star, Pal14 ID 4, exhibits a larger proper motion than the other program stars, and deserves further investigation.

We computed space velocity components and orbital parameters, as listed in Table 5, using radial velocities measured from the obtained spectra, proper motions from Gaia DR2, and distances estimated by SEGUE Stellar Parameter Pipeline (SSPP; Allende Prieto et al. 2008; Lee et al. 2008a,b), based on the methodology of Beers et al. (2000, 2012). The quoted distance uncertainty is on the order of 15–20%. Because the parallaxes to determine the distance do not exist in Gaia DR2 for two objects of our program stars, we adopted the photometric distances from the SSP, even though the distance uncertainties of four program stars derived by Gaia DR2 are much smaller (around 10%). We also compared the photometric distances of our programs with those from the Gaia DR2 parallaxes, and confirmed that our photometric distances agreed with the Gaia distances within the error ranges.

The $U$, $V$, and $W$ velocity components were calculated assuming 220 km s$^{-1}$ of the rotation velocity of the local standard of rest (LSR) and $(U_0, V_0, W_0) = (–10.1, 4.0, 6.7)$ km s$^{-1}$ of the solar peculiar motion (Hogg et al. 2005). Each velocity component is positive in the radially outward direction from the Galactic center for $U$, the direction of Solar rotation for $V$, and the direction of the North Galactic Pole for $W$.

The orbital parameters for individual objects were
proper motions. The black and red circles roughly delineate the boundaries of the thin and thick disks, at constant velocities of 70 km s$^{-1}$ and 180 km s$^{-1}$ (Venn et al. 2004), respectively. The blue line indicates the local Galactic escape speed of $V_{esc} = 533$ km s$^{-1}$ (Piffl et al. 2014) is plotted as a blue circle. The figure clearly indicates that our spectroscopically-observed HVS candidates are all bound to the MW when the Gaia DR2 proper motions are used. According to this diagram, kinematically, two of our stars appear to belong to the thick disk, while four of them are likely members of the thin disk.

This component separation is confirmed by the following test. With the space velocity components ($U, V, W$) of our program stars in hand, we performed a test to compute the likelihood of belonging to the thin disk, thick disk, and the halo, following the methodology of Bensby et al. (2003). The basic idea is that by assuming that a stellar population in the thin disk, thick disk, or the halo has Gaussian distributions with different space velocities ($U, V, W$) and asymmetric drifts, we attempt to separate our HVS candidates into the thin disk, thick

Figure 5. Toomre diagram for our program stars, which can be used to kinematically classify different Galactic stellar components. In the figure, the blue and red squares represent the velocities computed with the proper motions from SDSS and Gaia DR2, respectively. Black and red circles roughly delineate the boundaries of the thin and thick disks, at constant velocities of 70 km s$^{-1}$ and 180 km s$^{-1}$ (Venn et al. 2004), respectively. The local Galactic escape speed of $V_{esc} = 533$ km s$^{-1}$ (Piffl et al. 2014) is plotted as a blue circle. The figure clearly indicates that our spectroscopically-observed HVS candidates are all bound to the MW when the Gaia DR2 proper motions are used. According to this diagram, kinematically, two of our stars appear to belong to the thick disk, while four of them are likely members of the thin disk.

This component separation is confirmed by the following test. With the space velocity components ($U, V, W$) of our program stars in hand, we performed a test to compute the likelihood of belonging to the thin disk, thick disk, and the halo, following the methodology of Bensby et al. (2003). The basic idea is that by assuming that a stellar population in the thin disk, thick disk, or the halo has Gaussian distributions with different space velocities ($U, V, W$) and asymmetric drifts, we attempt to separate our HVS candidates into the thin disk, thick

Table 5
Velocities and orbital parameters of our program stars

| SDSS ID  | Pal14 ID | $v_r$ (km s$^{-1}$) | $d$ (kpc) | $U$ (km s$^{-1}$) | $V$ (km s$^{-1}$) | $W$ (km s$^{-1}$) | $r_{min}$ (kpc) | $r_{max}$ (kpc) | $Z_{max}$ (kpc) | $e$ | $V_{GSR}$ (km s$^{-1}$) |
|----------|----------|---------------------|-----------|------------------|------------------|------------------|------------------|------------------|------------------|----|------------------------|
| J113102.87+665751.1 | 4 | -65.4 ± 3.2 | 1.14 | 24.6 ± 13.1 | -179.9 ± 30.2 | 14.1 ± 11.5 | 0.90 ± 0.65 | 8.71 ± 0.20 | 1.04 ± 0.26 | 0.83 ± 0.12 | 491 ± 17.8 |
| J064357.13+291410.0 | 7 | 9.6 ± 3.4 | 2.06 | 2.2 ± 3.6 | -32.1 ± 8.5 | 47.5 ± 5.4 | 8.56 ± 0.46 | 11.1 ± 0.64 | 0.65 ± 0.14 | 0.13 ± 0.04 | 187 ± 9.4 |
| J172630.60+075544.0 | 10 | 37.6 ± 3.9 | 3.35 | 42.0 ± 6.8 | -51.1 ± 9.5 | 84.4 ± 19.6 | 3.77 ± 0.54 | 7.02 ± 0.21 | 2.53 ± 0.57 | 0.41 ± 0.07 | 194 ± 4.9 |
| J095816.39+005224.4 | 15 | 3.2 ± 3.4 | 2.19 | 19.8 ± 8.4 | -3.8 ± 7.4 | -33.7 ± 8.3 | 8.36 ± 0.49 | 9.52 ± 0.34 | 1.67 ± 0.30 | 0.06 ± 0.01 | 206 ± 6.7 |
| J172728.94+185520.4 | 16 | 35.5 ± 3.0 | 3.71 | 21.3 ± 5.2 | 9.8 ± 5.7 | 33.2 ± 9.9 | 10.77 ± 0.71 | 12.70 ± 1.20 | 2.05 ± 0.67 | 0.06 ± 0.02 | 216 ± 4.6 |
| J064257.02+371604.2 | 17 | 17.3 ± 3.2 | 1.88 | 11.3 ± 2.9 | 23.4 ± 0.3 | 8.1 ± 1.8 | 8.20 ± 0.18 | 9.83 ± 0.37 | 0.56 ± 0.11 | 0.10 ± 0.03 | 197 ± 6.2 |

$v_r$ is the radial velocity, $U$, $V$, and $W$ velocities were calculated assuming $V_{LSR} = 220$ km s$^{-1}$ and ($-10.1, 4.0, 6.7$) km s$^{-1}$ of solar peculiar motion (Hogg et al. 2008). $V_{GSR}$ is the Galactic rest-frame velocity.
Figure 6. Projected orbits for our program stars over 2 Gyr from the present, in the planes of $Z$ and $R$ (left panels) and $X$ and $Y$ (right panels). $Z$ is the distance from the Galactic plane, while $R$ is the distance from the Galactic center projected onto the Galactic plane. $X$ and $Y$ are based on the Cartesian reference system, in which the center of the Galaxy is at the location at $(0, 0)$ kpc, and the Sun is located at $(X, Z) = (8.0, 0.0)$ kpc. The filled circle indicates the current location of each star.

disk, or halo component by calculating the probability of belonging to each component. In that process, we adopted the local stellar densities, velocity dispersions in $U$, $V$, and $W$, and the asymmetric drifts listed in Table 1 of Bensby et al. (2003).

Based on the computed probability of each program star, we derived a relative likelihood of being each component, by comparing the probability of being a member of a given component among the three, and assigned a star into a component with the higher likelihood. For example, if a star has a higher likelihood of being the thick disk relative to being the thin disk, that is $Pr(\text{Thick})/Pr(\text{Thin}) > 5$, this star is assigned the thick disk. On the other hand, the thin disk is assigned when a star has $Pr(\text{Thick})/Pr(\text{Thin}) < 0.5$.

The results of this test for our program stars revealed that only Pal14 IDs 4 and 10 have $Pr(\text{Thick})/Pr(\text{Thin})$ much larger than 5, and the rest of the stars have less than 0.05. The probability of being in the halo population is much less, $Pr(\text{Halo})/Pr(\text{Thick}) < 0.01$. Only one star with ID 4 has $Pr(\text{Halo})/Pr(\text{Thick}) \sim 0.9$, which is still too small to be a halo star. Thus, this exercise proves that our program stars belong to the thin or thick disk.

We also compared the Galactic rest-frame velocity ($V_{\text{GRF}}$) for each star with the local escape velocity to check on the probability that it is bound to the MW. A total of one million Monte Carlo realizations were carried out to calculate the Galactic rest-frame velocities after randomly resampling from a normal error distribution of the radial velocities, distances, and proper motions from Gaia DR2. The bound probability is defined by the fraction of the stars that exceed the local escape velocity to the total number of stars in the simulation. We found that all our samples are, as expected, bound to the MW.

To investigate the orbital characteristics of our program stars, we integrated the orbit of each star over 2
Figure 7. Abundance ratios of Mg, Si, Ca, Ti, Cr, and Ni, as a function of [Fe/H], for stars in the Galactic bulge (green triangles; Alves-Brito et al. 2010; Johnson et al. 2014), the thick disk (filled-blue circles; Alves-Brito et al. 2010; Bensby et al. 2003; Reddy et al. 2006), the thin disk (red circles; Alves-Brito et al. 2010; Bensby et al. 2003; Reddy et al. 2006), the halo (filled-orange squares; Alves-Brito et al. 2010; Reddy et al. 2006), and the LMC (black dots; Van der Swaelmen et al. 2013). Our program stars are displayed in red star symbols with the sample ID of Pal14.

Figure 6 shows the projected orbital trajectories of our program stars into the plane of Z and R (left panels) and X and Y (right panels). Z is the distance from the Galactic plane, and R is the distance from the Galactic center projected onto the Galactic plane. X and Y are based on the Cartesian reference system, in which the center of the Galaxy is at the location at (0, 0) kpc, and the Sun is located at (X, Z) = (8.0, 0.0) kpc. The filled circle indicates the current location of each star. In the figure, we clearly see that four objects (Pal14 IDs 7, 15, 16, and 17) spend most of their time on orbits outside the Solar circle (upper-left panel) with nearly circular orbits (upper-right panel), with eccentricities less than $e < 0.15$. Judging from the orbits and $U$, $V$, $W$ velocities, the Pal14 ID 7 and 17 stars are typical thin-disk stars, as they are confined to $|Z| < 0.7$ kpc, while Pal14 ID 15 and 16 stars appear to belong to the thick disk, as they exhibit excursions above $|Z| > 1.5$ kpc.

The bottom panels of Figure 6 indicate that the other two stars in our sample (Pal14 IDs 4 and 10) are mostly inside the Solar radius (lower-left panel), with relatively high eccentricity orbits (lower right): $e = 0.83$ for Pal14 ID 4 and $e = 0.41$ for Pal14 ID 10. Even though Pal14 ID 4 exhibits thick-disk kinematics, an external origin from a disrupted dwarf galaxy cannot be ruled out for this object, due to the high eccentricity.

4.2. Chemical Properties

Even though the kinematics provide valuable information on which Galactic component a given star is likely to be a member, the orbits of disk stars can change over the course of Galactic evolution due to the perturbations by transient spiral patterns or giant molecular clouds. However, since the abundance of a chemical element for dwarf stars is essentially invariant during its main sequence lifetime, this can provide additional information on its likely parent Galactic component, as
we explore in this section for our program HVS candidates.

Among the chemical elements, the so-called \( \alpha \)-elements such as Mg, Si, Ca, and Ti, are good indicators of the star-formation history (duration and intensity) of a stellar population (Tinsley 1979). These elements are produced by successive capture of \( \alpha \)-particles in massive stars, which explode as core-collapse supernova (CCSN) that enrich the surrounding interstellar medium (ISM) with these elements. At early times, the ISM of a stellar population is enriched by CCSNs, whereas at later times, by Type Ia SNe, which produce more iron-peak elements. Consequently, the large enhancements of the \( \alpha \)-elements relative to Fe in a stellar population indicates that it experienced rapid star formation, while the lower values of this ratio suggests slower, prolonged star formation.

Figure 7 exhibits the distributions of Mg, Si, Ca, Ti, Cr, and Ni abundances with respect to Fe, as a function of [Fe/H], for four different Galactic stellar populations – thin disk (red circle), thick disk (filled-blue circle), bulge (green triangle), and halo (filled-orange square), and LMC stars (black circles). Our program stars are represented by star symbols. The chemical abundances of each star in Galactic stellar populations are adopted from the following references: bulge stars from Alves-Brito et al. (2010); Johnson et al. (2014), halo stars from Alves-Brito et al. (2010); Reddy et al. (2006), thin and thick disk stars from Alves-Brito et al. (2010); Bensby et al. (2003); Reddy et al. (2006); the LMC stars are from Van der Swaalsen et al. (2013).

From inspection of Figure 7, the general trends for each population can be summarized as follows. The thick-disk and halo stars exhibit similar trends, as they are rich in \( \alpha \)-elements, but relatively lower in Cr and Ni. The thick-disk stars are mostly more metal-rich ([Fe/H] > –0.9) than the halo stars ([Fe/H] < –0.8). The bulge stars display a wide range of metallicity, with enhanced \( \alpha \)-elements in the metallicity region overlapping with the thick disk. The level of their \( \alpha \)-abundances diminishes with increasing metallicity, later joining the thin disk. However, one distinct pattern is that the Ca abundances (somewhat true for Ni as well) of the bulge stars are consistently higher than the thick- and thin-disk populations. Therefore, the Ca abundance plays a key role in distinguishing a bulge star from a disk star. The LMC stars exhibit systematically lower abundances for Mg, Si, Ca, and Ni elements than the other Galactic components, but overlap with other Galactic stars in Ti and Cr. We included the LMC stars in the figure because, as claimed by Boubert & Evans (2016), there is a possibility that runaway stars may come from the LMC. We also note that there is no clear distinction among the Galactic components in the Fe-peak element Cr. The Ni abundance of bulge stars are relatively higher in the range of –0.5 < [Fe/H] < 0.2 than any other Galactic populations. Our program stars, indicated with star symbols, all have metallicity larger than [Fe/H] = –0.7; none of them are likely halo stars.

Comparing the chemical characteristics of each Galactic component with those of each star in our program sample, while some of our program stars overlap with one or two Galactic stellar populations, most of our stars exhibit somewhat deviant abundances from comparison stellar populations. The Pal14 ID 16 star, which is the most-Fe rich object in our sample, appears to belong to the thin disk, because the Mg, Si, Ca, and Cr abundances agree with those of the thin-disk stars, although the Ti and Ni abundances are lower than the other thin-disk stars. Its chemistry is also overlapped with that of the bulge population. Pal 14 ID 17 is likely to be associated with the thin disk, as the level of most of elements is similar to that of the thin-disk stars, considering the error bars on Cr and Ni. Pal14 ID 4 is likely to be a bulge star because of the enhancement of all of its \( \alpha \)-elements. Pal14 ID 15 appears to be a metal-poor thin-disk star, as its \( \alpha \)-element abundances are lower than the thick disk, although the Cr abundance stands out with respect to the other elements. Pal14 ID 7 may be a thick-disk star, because its Mg, Si, and Ti are enhanced and the Ca abundance does not point to the bulge component, but rather the LMC. Taking into account the large error bar for Mg, Pal14 ID 10 appears to belong to the thick disk, with enhanced Si and Ti.

5. DISCUSSION

Even though our HVS stars turned out to be disk stars, based on the kinematic probabilistic membership assignment as described in Section 4.1, some of them have very distinct dynamical properties compared to the canonical disk stars, which we discuss below. In what follows, we consider a star with high eccentricity to be either an accreted or heated disk star, as stars from a disrupted dwarf galaxy are expected to exhibit high eccentricities, and dynamical heating mechanism can also produce high eccentricity stars. We regard stars with low eccentricity but comparatively large excursions from the Galactic plane to be possible runaway stars.

5.1. SDSS J113102.87+665751.1 (Pal14 ID 4)

As this star has [Fe/H] = –0.49, and a high value of \([\alpha/Fe] = 0.38\), one might consider this object to be a typical thick-disk star. However, the several individual \( \alpha \)-elements appear to be more enhanced with respect to the thick-disk population, and relatively closer to the bulge population, especially the Ca abundance, which is the key element to distinguish between the thick-disk and bulge stars. Thus, it is reasonable to infer that it is a bulge star.

The calculated orbital parameters for this star are \( Z_{\text{max}} = 1.04 \text{ kpc} \), \( e = 0.83 \), \( r_{\text{min}} = 0.90 \text{ kpc} \), and \( r_{\text{max}} = 8.71 \text{ kpc} \); hence its orbit spans from the near bulge through the Solar radius with a very high eccentricity. Note that our \( r_{\text{min}} \) value is rather smaller than that of Ziegerer et al. (2015) due to the slightly larger proper motions from Gaia DR2. These chemical and dynamical characteristics suggest that this star could be born in the bulge, and expelled to reach the current location by mechanisms such as dynamical ejection in high
stellar density environment or binary supernova ejection. However, its Galactic rest-frame velocity of $V_{\text{GRF}} = 49.1 \text{ km s}^{-1}$ is too small to consider that origin likely. Rather, its orbit points to it being a former member of a disrupted dwarf galaxy or a dynamically heated disk star.

5.2. SDSS J064337.13 + 291410.0 (Pal14 ID 7)
This star has [Fe/H] = –0.60 and [$\alpha$/Fe] = 0.22, properties associated with a typical thick-disk star. Looking into the individual $\alpha$-elements, the Mg and Ti abundances are relatively higher and the Ca abundance is lower than most stars of the thick-disk population. Only the Si and Ni abundances are close to those of other thick-disk stars.

The kinematic characteristics also suggests this object is a thick-disk star, as the obtained orbital parameters are $Z_{\text{max}} = 0.65$ kpc, $e = 0.13$, $r_{\text{min}} = 8.56$ kpc, and $r_{\text{max}} = 11.11$ kpc. Combining the chemical and kinematic characteristics, this star may be born in the outer disk, and now located close to the Solar circle.

5.3. SDSS J172630.60 + 075544.0 (Pal14 ID 10)
Given a metallicity of [Fe/H] = –0.69 and [$\alpha$/Fe] = 0.15, this object is also regarded as a likely thick-disk star. Yet, the abundances of four $\alpha$-elements exhibit a complex pattern; the Ca abundance is in the thick disk region, whereas the Si and Ti abundances are higher than the rest of the thick-disk population. The Ni abundance is also larger than the thick disk. Taking into account the large uncertainty of the Mg abundance, this object is considered as a thick-disk star.

Kinematically, however, this object has an eccentricity of $e = 0.41$ and $r_{\text{min}} = 3.77$ kpc, and its vertical height is as high as $Z_{\text{max}} = 2.53$ kpc. Combined with the chemical signatures, this object may be a dynamically heated disk star. It is also possible that this star may be a disk runaway star, originating from near the bulge, or a heated disk star, as it reaches a comparatively large vertical height. The high eccentricity also indicates a possible external origin from a dissolved dwarf galaxy, but the extent of its orbit (only exploring 2 kpc away) appears to be too small to be commensurate with an accreted origin.

5.4. SDSS J095816.39 + 005224.4 (Pal14 ID 15)
The metallicity of [Fe/H] = –0.55 and [$\alpha$/Fe] = –0.05 for this star indicate a metal-poor thin-disk star. The chemical abundances of individual elements agree with those of the thin-disk population within the error bars, except the lower Ti and higher Cr abundances than those of any Galactic population.

The derived orbital parameters of $r_{\text{min}} = 8.36$ kpc, $Z_{\text{max}} = 1.67$ kpc, and $e = 0.06$ also suggest a thin-disk star. As this star reaches up to $Z = 1.67$ kpc, this is a good candidate for a disk runaway star ejected by a SNe explosion in a binary system. As Bromley et al. (2009) simulated, some runaway stars exhibit similar kinematics to the disk or halo stars.

5.5. SDSS J074728.84 + 185520.4 (Pal ID 16)
This object has the highest metallicity in our sample, [Fe/H] = 0.27, and its [$\alpha$/Fe] value is –0.20. All six elements show relatively lower abundance ratios than the Sun, which mimic the patterns of a metal-rich thin-disk star. Hence, one may consider this to belong to the thin disk.

The orbital parameters of $r_{\text{min}} = 10.77$ kpc, $Z_{\text{max}} = 2.05$ kpc, and $e = 0.06$ also imply a thin-disk star. As can be seen from Figure 6, this object resides in the outer disk and undergoes large excursions, with a small eccentricity, above the Galactic plane. Thus, it is more plausible to infer that this object is a runaway star from the thin-disk population.

5.6. SDSS J064257.02 + 371604.2 (Pal ID 17)
Pal14 ID 17 is a metal-rich ([Fe/H] = –0.12) star with an essentially Solar alpha ratio ($[$\alpha$/Fe] = –0.02). The abundances of the individual $\alpha$-elements are overlapped with those of the thin-disk population, whereas the iron-peak elements appear more consistent with the bulge. Its orbital parameters ($r_{\text{min}} = 8.20$ kpc, $Z_{\text{max}} = 0.56$ kpc, and $e = 0.10$) also point to a typical thin-disk star.

### Table 6
Possible origin of our program stars

| SDSS ID          | Pal14 ID | Galactic component | Possible origin(s) |
|------------------|----------|--------------------|--------------------|
| J113102.87 + 665751.1 | 4        | Bulge              | Accreted or heated |
| J064337.13 + 291410.0 | 7        | Thick              | ...               |
| J172630.60 + 075544.0 | 10       | Thick              | Runaway or heated  |
| J095816.39 + 005224.4 | 15       | Thin               | Runaway            |
| J074728.84 + 185520.4 | 16       | Thin               | Runaway            |
| J064257.02 + 371604.2 | 17       | Thin               | ...               |

### Summary and Conclusions
We have presented a chemodynamical analysis of six low-mass dwarf stars, alleged to be HVSs by Pal14, in order to determine from which Galactic component they originate. Based on kinematic analysis using accurate Gaia DR2 proper motions, we confirm that all six objects are bound to the MW, as noted previously by Ziegerer et al. (2015). Our conclusion is also upheld by the recent study by Boubert et al. (2018), who performed a detailed investigation of late-type HVS candidates with proper motions from Gaia DR2, and found that almost all known late-type HVS candidates are
bound to the Galaxy. The HVS status for the low-mass stars identified by Pal14 is mainly due to the incorrect assignment of the proper motions.

Nonetheless, we have attempted to characterize the parent Galactic stellar components and origins of our program stars by taking into account a comparison of their abundance patterns with various Galactic stellar components and their orbital properties simultaneously. We note that the kinematic probabilistic assignment of their membership to the Galactic component has revealed that our program stars belong to the thin or thick disk. However, since four of the six stars exhibit distinct dynamical properties and chemical characteristics compared to the canonical disk stars, we cannot rule out exotic origins such as runaway, disk heating, and accretion from dwarf galaxies as discussed in the previous section, and summarize below and in Table 6.

We identify two typical disk stars (Pal14 IDs 7 and 17); Pal14 ID 7 is a typical thick disk star, while Pal ID 17 is a typical thin-disk star, as these stars have similar abundance patterns to stars of Galactic thick and thin disks, respectively, and have nearly circular orbits.

One star (Pal14 ID 4) may originate from the Galactic bulge, as its orbit passes close to the bulge with a high eccentricity. Moreover, the abundances of the α-elements for this star all agree with those of other Galactic bulge stars. One may think that this star may be ejected from the bulge by dynamical ejection or SNe ejection mechanism. However, its V_{hel} is too small to consider such an origin likely. Rather, its high-eccentricity orbit suggests an accreted origin from a disrupted dwarf galaxy, or dynamical heating.

Pal14 ID 10 may be a runaway or heated disk star, as it reaches as high as 2.53 kpc from the Galactic plane during its orbit, and most of the chemical abundances within the derived uncertainties are similar to the thick-disk population.

Pal14 ID 15 appears to be a runaway from the Galactic disk, because it exhibits very large excursion ($Z_{\text{max}} = 1.67$ kpc) from the Galactic plane with small eccentricity ($e = 0.06$) in an orbit reaching beyond the Solar radius. The similar chemical abundance pattern to other metal-poor thin-disk stars support the idea as well.

Finally, Pal14 ID 16, which has the highest metallicity in our sample, exhibits similar chemical abundances to a very metal-rich thin-disk star, while its orbit exhibits a large excursion ($Z_{\text{max}} = 2.05$ kpc) from the Galactic plane at a location beyond $R = 11$ kpc. We consider this star as a runaway star from the Galactic disk.

Although all of our spectroscopically observed candidate HVSs turned out to be bound to the Galaxy, and not even particularly fast-moving objects, some of our program stars exhibit exotic orbits. Thus, future higher resolution spectroscopic follow-up observations for these curious stars may be of interest, and provide a better understanding of their origin.

ACKNOWLEDGMENTS

We thank anonymous referees for their careful review of this manuscript, and for pointing out a number of places where we could improve the clarity of the presentation.

This research has made use of the VizieR catalogue access tool, CDS, Strasbourg, France. This work has made use of data from the European Space Agency (ESA) mission Gaia\textsuperscript{5}, processed by the Gaia Data Processing and Analysis Consortium (DPAC)\textsuperscript{6}. Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement.

Funding for SDSS-III was provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy Office of Science. The SDSS-III Web site is http://www.sdss3.org/.

Y.S.L. acknowledges support from the National Research Foundation (NRF) of Korea grant funded by the Ministry of Science and ICT (No.2017R1A5A1070354 and NRF-2018R1A2B6003961). T.C.B. acknowledges partial support for this work from grant PHY 14-30152; Physics Frontier Center/JINA Center for the Evolution of the Elements (JINA-CEE), awarded by the US National Science Foundation.

REFERENCES

Abadi, M. G., Navarro, J. F., & Steinmetz, M. 2009, An Alternative Origin for Hypervelocity Stars, ApJ, 691, L63

Allende Prieto, C., Sivarani, T., Beers, T. C., et al. 2008, The SEGUE Stellar Parameter Pipeline. III. Comparison with High-Resolution Spectroscopy of SDSS/SEGUE Field Stars, AJ, 136, 2070

Alves-Brito, A., Meléndez, J., Asplund, M., et al. 2010, Chemical similarities between Galactic bulge and local thick disk red giants: O, Na, Mg, Al, Si, Ca, and Ti, A&A, 513, 35

Battistini, C., & Bensby, T. 2015, The origin and evolution of the odd-Z iron-peak elements Sc, V, Mn, and Co in the Milky Way stellar disk, A&A, 577, 9

Beers, T. C., Carollo, D., Ivezić, Z., et al. 2012, The Case for the Dual Halo of the Milky Way, ApJ, 746, 34

Beers, T. C., Chiba, M., Yoshii, Y., et al. 2000, Kinematics of Metal-poor Stars in the Galaxy. II. Proper Motions for a Large Nonkinematically Selected Sample, AJ, 119, 2866

Bensby, T., Feltzing, S., Lundstrom, I. 2003, Elemental abundance trends in the Galactic thin and thick disks as traced by nearby F and G dwarf stars, A&A, 410, 527

Bensby, T., Feltzing, S., Lundstrom, I. 2005, α-, r-, and s-process element trends in the Galactic thin and thick disks, A&A, 433, 185

Blaauw, A. 1961, On the origin of the O- and B-type stars with high velocities (the "run-away" stars), and some related problems, BAN, 15, 265

Boeche, C., & Grebel, E. K. 2016, SP_Ace: a new code to derive stellar parameters and elemental abundances, A&A, 587, 2

\textsuperscript{5}https://www.cosmos.esa.int/gaia

\textsuperscript{6}https://www.cosmos.esa.int/web/gaia/dpac/consortium
Tauris, T. M., Takens, R. J. 1998, Runaway velocities of stellar components originating from disrupted binaries via asymmetric supernova explosions, A&A, 330, 1047
Tetzlaff, N., Neuhäuser, R., & Hohle, M. M. 2011, A catalogue of young runaway Hipparcos stars within 3 kpc from the Sun, MNRAS, 410, 190
Tinsley, B. M. 1979, Stellar lifetimes and abundance ratios in chemical evolution, ApJ, 229, 1046
Van der Swaelmen, M., Hill, V., Primas, F., et al. 2013, Chemical abundances in LMC stellar populations. II. The bar sample, A&A, 560, A44.
Venn, K. A., Irwin, M., Shetrone, M. D., Tout, C. A., Hill, V., Tolstoy, E. 2004, Stellar Chemical Signatures and Hierarchical Galaxy Formation, AJ, 128, 1177
Watkins, L. L., Evans, N. W., & An, J. H. 2010, The masses of the Milky Way and Andromeda galaxies, MNRAS, 406, 264
Xue, X. X., Rix, H. W., Zhao, G., et al. 2008, The Milky Way’s Circular Velocity Curve to 60 kpc and an Estimate of the Dark Matter Halo Mass from the Kinematics of 2400 SDSS Blue Horizontal-Branch Stars, ApJ, 684, 1143
Yanny, B., Rockosi, C., Newberg, H. J., et al. 2009, SEGUE: A Spectroscopic Survey of 240,000 Stars with g = 14-20, AJ, 137, 4377
York, D. G., Adelman, J., Anderson, J. E., Jr., et al. 2000, The Sloan Digital Sky Survey: Technical Summary, AJ, 120, 1579
Yu, Q., & Tremaine, S. 2003, Ejection of Hypervelocity Stars by the (Binary) Black Hole in the Galactic Center, ApJ, 599, 1129
Zhong, J., Chen, L., Liu, C., et al. 2014, The Nearest High-velocity Stars Revealed by LAMOST Data Release 1, ApJL, 789, L2
Ziegeler, E., Volkert, M., Heber, U., et al. 2015, Candidate hypervelocity stars of spectral type G and K revisited, A&A, 576, 14