

Search for Distant Hypervelocity Star Candidates Using RR Lyrae Stars

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ABSTRACT

Hypervelocity stars (HVSs) are stars with velocities exceeding their local escape velocities. Searching for HVSs and studying their origins can be an important way to study the properties of the Milky Way. In this paper, we utilize precise distances for RR Lyrae stars (RRLs) derived from the period-absolute magnitude-metallicity (PMZ) relation, along with proper motions from Gaia DR3, to conduct a large-volume search for HVSs. Our sample consists of a catalog with 8,172 RRLs with metallicity, distance and radial velocities estimated from SDSS and LAMOST spectroscopic data, and an extended catalog of 135,873 RRLs with metallicity and distance estimated from Gaia photometry. After careful quality cuts, 165 hypervelocity RRL candidates were found. We performed further checks on their light curves, and selected the most reliable 87 hypervelocity RRLs. All of them exceed the Milky Way’s escape velocity in the tangential component. Among them, 7 stars have tangential velocity over 800 km s^{−1}. We identified two spatially distinct distributions of hypervelocity RRLs: one concentrated toward the Galactic Center and another localized around the Magellanic Clouds, suggesting that their origins are likely associated with these regions through the Hills or other mechanisms. Furthermore, we detected a significant number of RRLs associated with dwarf galaxies that exceed the Milky Way’s escape velocity, likely ejected from their host systems. Future Gaia releases and spectroscopic follow-up observations will provide further insight into their ejection origin.

Keywords: Hypervelocity stars (776) — RR Lyrae variable stars (1410) — Milky Way dynamics (1051)
— Galaxy structure (622) — Distance indicators (394)

1. INTRODUCTION

Hypervelocity stars (HVSs) are stars whose velocities exceed the local escape velocity, making them gravitationally unbound from the Milky Way. Researches on high-velocity stars began in the 1920s, focusing on the proper motion of stars (van Maanen 1917). Subsequently, radial velocity measurements from spectroscopic observations revealed several OB-type stars in the Galactic halo with velocities up to 260 km s^{−1} (Greenstein & Sargent 1974). Owing to their youth and unusually high speeds—atypical of halo stars—they were inferred to have been ejected from their birthplaces into the halo, and were thus termed “runaway stars.”

In 1988, Hills first proposed a mechanism capable of accelerating stars to velocities of up to 1000 km s^{−1} or even faster (Hills 1988). When a binary system approaches the supermassive black hole (SMBH) at the Galactic Center (GC), the SMBH’s tidal force can disrupt the system. One of the binary companions can be captured by the SMBH, while the other one can be ejected at speeds reaching 1000 km s^{−1}, exceeding the escape velocity of the GC. In this scenario, the ejected stars are referred to as hypervelocity stars (HVSs). In this paper, we generally define HVSs as stars that are unbound from the Milky Way. Later, Brown et al. (2005) discovered the first HVS with a velocity of up to 700 km s^{−1} and a Galactocentric distance between 40 and 70 kpc, exceeding the local escape velocity. This

finding provided the first observational verification of the Hills mechanism. Their following surveys for HVSs in the Galactic halo are also consistent with GC origin (Brown et al. 2014), as well as these early-type HVSs discovered by LAMOST (Zheng et al. 2014; Huang et al. 2017; Li et al. 2018; Sun et al. 2025). Furthermore, a HVS with velocity of approximately 1700 km s^{-1} was discovered to be confidently traced back from the GC (Koposov et al. 2020).

Alternative ejection mechanisms, other than the Hills mechanism, can also explain the origin of HVSs. If they originate from the GC, they can also be produced by: (1) scattering by possible binary black hole at the GC (Yu & Tremaine 2003), (2) interactions between the SMBH and accreted globular clusters (Capuzzo-Dolcetta & Fragione 2015). In addition to originating from associations with the SMBH at the GC, HVSs can be produced by (1) type Ia supernovae in close binary systems (Blaauw 1961), especially for white dwarf (WD)–WD binaries (Shen et al. 2018) or binaries consisting of a WD and a non-degenerate star (Wang & Han 2009), which can eject HVS with velocity similar to the Hills mechanism, (2) scattering in dense stellar systems (Gvaramadze et al. 2009), (3) tidal disruption of Milky Way’s satellite galaxies (Abadi et al. 2009). Later searches for HVSs found supporting evidences for these scenarios. A hot subdwarf (Geier et al. 2015) and some white dwarfs (Shen et al. 2018; El-Badry et al. 2023) were found to be HVSs originating from type Ia supernovae explosions. Furthermore, some HVSs were found to originate from various substructures of the Milky Way, such as dwarf galaxies (Huang et al. 2021; Li et al. 2022). Most recent, a high-velocity star was found to originate from association with the intermediate-mass black hole (IMBH) at the center of a globular cluster (Huang et al. 2025).

Searching for HVSs and studying their origins provide valuable insights into the properties of the Milky Way. In particular, HVSs originating from the GC can help constrain the position and velocity of the Sun within the Milky Way (Hattori et al. 2018; Koposov et al. 2020), as well as refine our understanding of the distribution of stars and the parameter space of possible black hole companions around the GC (Evans et al. 2022). Additionally, HVSs serve as useful tracers for constraining the distribution and potential of the Milky Way’s dark matter halo (Gnedin et al. 2005).

In the search for HVSs, determining the distance and velocity of the stars is crucial to assess whether they can exceed their local escape velocity. However, the challenge lies in the fact that the extreme speeds of HVSs can result in them traveling significant distances from their origins, while the volume we search for HVSs is strongly constrained by accurate distance measurements.

Thus, one method for identifying HVSs is by selecting early-type stars with extreme radial velocities in spectroscopic surveys towards the Galactic halo, as is performed by Brown et al. (2014). These stars are bright and thus easy to observe at large volume. Additionally, early-type stars are not typically found in the Galactic halo, their presence suggests they may have been ejected from the Galactic disk or the GC, likely with high velocities. However, early-type massive stars represent only a small fraction of the stellar population, whereas the majority of stars are late-type, low-mass stars, according to the initial mass function. These stars are too faint to be observed at large distances in spectroscopic surveys, which makes detecting late-type HVSs based solely on extreme radial velocities a challenging task.

Another method to search for HVSs is selecting stars with high tangential velocity based on astrometric measurements. The Gaia satellite, launched in 2013, provides a huge number of accurate astrometric measurements, especially the recently released Gaia DR3 (Collaboration et al. 2022). Some HVSs have been discovered based on parallax and proper motion provided by Gaia DR3 (Liao et al. 2023; Marchetti et al. 2022). However, due to the limitation in parallax measurement, accurate distance data for faint, distant stars remains challenging. For instance, the median parallax uncertainties of Gaia DR3 are $0.02\text{--}0.03 \text{ mas}$ for $G < 15$; 0.07 mas at $G = 17$ and 0.5 mas at $G = 20$, corresponding to distance limits of $\sim 40, 14$ and 2 kpc respectively.

To address this issue, we utilize standard candles such as RR Lyrae variable stars to measure distances up to 100 kpc . Given the lack of precise radial velocities, we focus on stars with large tangential velocities. By incorporating accurate proper motion measurements from Gaia DR3, we can significantly expand the search volume for HVSs.

RR Lyrae variables (RRLs) are old, metal-poor, helium-burning giants located in the instability strip of the Hertzsprung-Russell (H-R) diagram. Their typical pulsation periods range from 0.2 to 1 day , with V-band amplitudes reaching up to 1.5 magnitudes . From their light curves, both metallicity and absolute magnitude can be derived (Drake et al. 2014; Li et al. 2023). As a result, their distances can be precisely measured for large samples, even when only time-domain photometry is available.

Previous work has used RRLs to search for HVSs (Prudil et al. 2022). Their sample has $6,187$ RRLs compiled from Gaia DR2 (Clementini et al. 2019) and the Catalina Sky Survey (Drake et al. 2014) with 3D velocity data. In this

paper, we utilize a sample of approximately 140,000 RRLs from Wang et al. (2022) and Li et al. (2023), combined with proper motion measurements from Gaia DR3, to conduct a large-scale search for hypervelocity RR Lyrae candidates (HV-RRLs), with a particular focus on those exhibiting high tangential velocities. The selection process of HV-RRL candidates will be shown in Section 2; we will show the results and find their possible origins by integrating their backward orbits in Section 3; we will discuss the RRLs as member stars of the Milky Way’s substructures in Section 4. Finally, a summary is presented in Section 5.

2. SAMPLE AND METHOD

2.1. Sample selection

In this study, we adopt two samples of RRL stars, which are introduced below.

Wang et al. (2022, hereafter W22) enlarged the RRL catalog derived by Liu et al. (2020), which is based on General catalog of Variable Stars (GCVS, Samus et al. 2009), Catalina sky survey (CSS, Drake et al. 2014) and other surveys. 8,172 RRLs are found to have low-to-medium resolution spectra collected by LAMOST Galactic spectroscopic surveys (Deng et al. 2012; Liu et al. 2014) and SDSS/SEGUE (Yanny et al. 2009). The metallicity and radial velocity of these RRLs are then estimated using the techniques developed in Liu et al. (2020).

Li et al. (2023, hereafter L23) calibrated the relation between RRL’s Fourier parameters of light curves and metallicity, based on spectroscopic metallicity estimates from Liu et al. (2020). Then, L23 applied this relation to a much larger RRL catalog based on Gaia DR3 time-series photometry derived by Clementini et al. (2022). As a result, 135,873 RRLs with precise photometric metallicity determination are selected.

Finally, after removing duplicates, their catalogs provide key parameters for a total of 138,857 RRLs, including right ascension (RA), declination (Dec), metallicity, distance, absolute magnitude, and period. The typical uncertainty in metallicity is approximately 0.3 dex, while distance uncertainty is approximately 10%.

We then cross-match our sample with Gaia DR3 to retrieve proper motion data (μ_α^* , μ_δ). The typical uncertainties are 0.02–0.04, 0.07–0.1, and 0.5–1.5 mas yr^{−1} for $G < 15$, $G \approx 17$, and $G \sim 20$ –21, respectively. Additionally, 8,561 RRLs in the catalogs have radial velocity measurements from LAMOST, SDSS spectroscopic data, or Gaia DR3. The typical radial velocity uncertainties range from 5 to 21 km s^{−1}. Additionally, to ensure data quality, we exclude radial velocity measurements of 19 RRLs with uncertainties greater than 30 km s^{−1}.

2.2. Data quality control

First, proper motion errors can introduce significant velocity uncertainties due to the large distances involved. Therefore, stringent astrometric cuts are necessary to exclude unreliable proper motion measurements. Following previous studies (Prudil et al. 2022; Marchetti et al. 2022), we apply the following selection criteria based on Gaia DR3 astrometric parameters (Lindgren et al. 2021):

- (1) `RUWE` < 1.4: this parameter reflects the quality of the single-star model fit to the astrometric observations;
- (2) `ipd_gof_harmonic_amplitude` < 0.4: this indicates the amplitude of changes in the goodness-of-fit in image parameter determination;
- (3) `ipd_frac_multi_peak` < 2: this indicates the amount of image asymmetry, to exclude possible binarity;
- (4) `astrometric_excess_noise_sig` ≤ 2.0: this indicates whether the object is astrometrically well-behaved;
- (5) `visibility_periods_used` ≥ 13: this ensures the selected variables are well-observed sources.

After applying these criteria, 110,823 RRLs remain. Fig. 1 presents the spatial distribution of the selected sample in Galactic Cartesian coordinates. Several substructures can be identified, as are marked in Fig. 1, including the Large Magellanic Cloud (LMC), the Small Magellanic Cloud (SMC), the stream of the Sagittarius spheroidal dwarf galaxy (Sgr), as well as three other dwarf galaxies that appear elongated due to distance uncertainties. The position of these dwarf galaxies are taken from Fritz et al. (2018).

Scholz (2024) conducted a stringent examination on astrometric quality and provided a comprehensive review on HVS candidates from Gaia DR2 and DR3, with a particular focus on sources exhibiting unusually large proper motions. To further ensure the astrometric quality of our sample, we applied the methodology outlined by Scholz (2024) to examine the astrometric flags and parameters provided by Gaia DR3 for each HV-RRL candidate. However, most

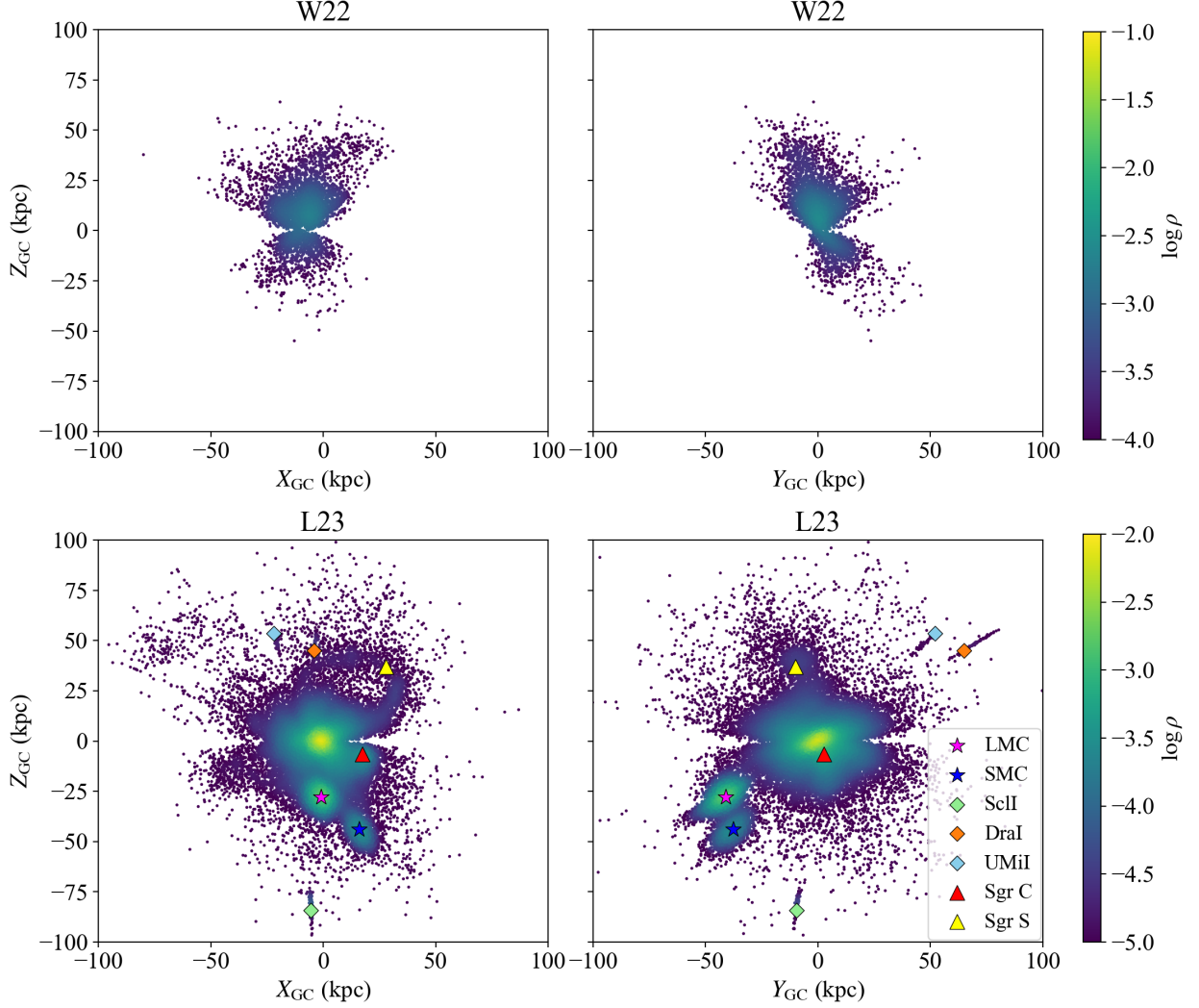


Figure 1. Spatial distribution of RRL samples from W22 (upper panels) and L23 (bottom panels) in the Galactic Cartesian coordinates. Left panels show X_{GC} – Z_{GC} distribution; right panels show Y_{GC} – Z_{GC} distribution. Color bar in the right side stands for number density in logarithmic scale. Magenta and blue stars denote the position of the LMC and SMC; Green, orange and skyblue diamonds denote the position of the Sculptor, Draco, and Ursa Minor dwarf galaxies (ScII, DraI, and UMiI); Yellow and Red triangles denote the Sgr core (C) and stream (S), respectively. The position of these dwarf galaxies are taken from Fritz et al. (2018).

stars in our sample with high tangential velocities exhibit relatively modest proper motions, with the large inferred velocities primarily driven by their substantial distances. As such, the criteria adopted by Scholz (2024) may not be fully applicable to our case. To facilitate further use and verification, our final online catalog includes a flag indicating whether each candidate satisfies the selection criteria defined by Scholz (2024).

2.3. HVS selection

To select hypervelocity RRL candidates, we calculate each RRL’s Galactocentric distance (R_{GC}) and total velocity in the Galactic rest frame (v_{GC}). The Sun’s coordinates in the Galactic rest frame are adopted as $R_{\odot} = 8.2$ kpc (Bland-Hawthorn & Gerhard 2016) and $Z_{\odot} = 20.8$ pc (Bennett & Bovy 2018). The Galactocentric distance, R_{GC} , is then calculated based on the RA, Dec, and distance D provided by Wang et al. (2022) and Li et al. (2023). The Sun’s peculiar motion relative to the Galactic rest frame is taken as $[U_{\odot}, V_{\odot}, W_{\odot}] = [11.1, 12.24, 7.25]$ km s $^{-1}$ (Schönrich

et al. 2010), with a circular velocity at the solar radius of $v_{c,R_0} = 234 \text{ km s}^{-1}$ (Zhou et al. 2023). Additionally, we tested alternative values for the solar peculiar motion (e.g., Huang 2015; Wang et al. 2021) and found that our results remain robust.

Next, we derive the total Galactic rest-frame velocity (v_{GC}) for RRLs with available radial velocity (v_r) measurements. For RRLs lacking radial velocity data, we compute only their tangential velocity in the Galactic rest frame ($v_{GC,t}$). If $v_{GC,t}$ exceeds the local escape velocity, then the total velocity v_{GC} must be even higher, allowing these stars to be classified as HVS candidates. The tangential velocity $v_{GC,t}$ is obtained by projecting both the star’s velocity and the Sun’s velocity perpendicular to the radial direction:

$$v_{GC,t} = \left| \vec{v}_{\text{obs},t} + \left[\vec{v}_{\odot} - (\vec{v}_{\odot} \cdot \hat{l}) \hat{l} \right] \right|, \quad (1)$$

where $\vec{v}_{\text{obs},t}$ is the observed tangential velocity, which equals to proper motion multiplying distance; $\vec{v}_{\odot} = (U_{\odot}, V_{\odot} + v_{c,R_0}, W_{\odot})$ is the velocity of the Sun in the Galactic rest frame and $\hat{l}$ indicates the unit vector along the line-of-sight.

We conducted 2000 Monte Carlo simulations, neglecting the uncertainties in RA and Dec, while assuming that the remaining parameters (μ_{α}^* , μ_{δ} , v_r , D) follow a multi-dimensional Gaussian distribution, with the corresponding covariance matrix provided by the original catalogs and Gaia DR3. It is important to note that the distances are derived from the period–metallicity relation of RRLs rather than from parallax, and are therefore uncorrelated with proper motions. The final values of R_{GC} and v_{GC} , along with their uncertainties ($\sigma_{R_{GC}}$, $\sigma_{v_{GC}}$), are determined from the 50th, 16th, and 84th percentiles of the 2000 Monte Carlo realizations.

To calculate the escape velocity (v_{esc}) of the Milky Way, we utilized `MWPotential2014` in python package `galpy` (Bovy 2015). It’s a potential distribution of the Milky Way consisting of a Miyamoto & Nagai disk potential (Miyamoto & Nagai 1975), a power-law bulge potential with an exponential cut-off and Navarro-Frenk-White spherical dark matter halo (Navarro et al. 1997). In this work, escape velocity is calculated by $v_{\text{esc}} = \sqrt{2(\Phi(\infty) - \Phi(r))}$, where Φ is the potential of the Milky Way. We then computed the probability (P_{unb}) that each RRL has a total Galactic rest-frame velocity (v_{GC}) exceeding the Milky Way’s escape velocity (v_{esc}). This was achieved by determining the fraction of samples where $v_{GC} > v_{\text{esc}}$ in 2000 times of Monte Carlo simulations. As a result, 8,090 RRLs with $P_{\text{unb}} > 0.5$ are found.

To ensure reliable velocity measurements, we exclude RRLs with large relative velocity uncertainties ($\sigma_{v_{GC}}/v_{GC} > 0.3$). A total of 6,838 RRLs meet this criterion. These RRLs are classified into two groups based on their potential association with Milky Way substructures, including the LMC, SMC, Sgr stream/core, other well-known dwarf galaxies, and star clusters. Guided by Cabrera Garcia et al. (2023), we identify stars associated with these substructures using the criteria detailed below:

- (1) Located within the tidal radii in angular separation and within 5 kpc in line-of-sight distance from 145 Galactic globular clusters (Harris 2010; Vasiliev 2019; Vasiliev & Baumgardt 2021a,b).
- (2) Within 10 half-light radii in angular separation and within 20 kpc in line-of-sight distance from the centers of 39 dwarf galaxies (Fritz et al. 2018).
- (3) The member stars of the LMC and SMC, which are defined by having close angular distances (16° and 12°) and small relative proper motions ($< \pm 15 \text{ mas yr}^{-1}$) comparing to the LMC and SMC. Meanwhile, the RRLs in the LMC and SMC should have expected apparent magnitude of $G > 18.5$ (Belokurov et al. 2016). The 6D data of the LMC and SMC is taken from Patel et al. (2020).
- (4) Belong to the sample of RRL candidates from the Sgr Stream and Sgr Core, as identified by Ramos et al. (2020).

As a result, we identified 6,673 unbound RRLs associated with various substructures of the Milky Way, constituting 97.6% of the unbound RRLs after the HVS selection. Similar to the main Galaxy, these substructures can also produce HVSs via various mechanisms, including supernova explosions, multi-body scattering and Hills mechanism. Boubert et al. (2017) conducted comprehensive simulations for the LMC and predicted that the runaway star production rate from the LMC could be as high as $3 \times 10^{-6} \text{ yr}^{-1}$. Recent simulations have also explored the ejection of HVSs from the LMC via the Hills mechanism. Evans et al. (2021) predicted that in future surveys, the number of observable HVSs ejected from the SMBH of the LMC will significantly exceed those originating from the GC, assuming a constant HVS

Table 1. Number of RRLs after data quality control and HVS selection

selection	W22	L23	total
original	8172	135873	144045
remove duplicates	7652	131205	138857
quality control	5138	105685	110823
$P_{\text{unb}} > 0.5$	23	8067	8090
$\sigma_{v_{\text{GC}}}/v_{\text{GC}} \leq 0.3$	19	6819	6838
not in substructure	19	146	165

ejection rate of 10^{-4} yr^{-1} . Furthermore, [Han et al. \(2025\)](#) proposed that the Leo overdensity of HVSs observed by [Brown et al. \(2014\)](#) can be attributed to the Hills mechanism in the LMC, with an ejection rate of $2 \times 10^{-6} \text{ yr}^{-1}$.

However, the selected unbound RRLs in these substructures may exceed the escape velocity simply due to additional velocity acquired from their host substructures, especially those already moving at high speeds in the Galactic rest frame. For instance, the LMC has an orbital velocity of approximately 330 km s^{-1} , while the escape velocity at its position is around 360 km s^{-1} . More importantly, some of these unbound RRLs are located in dense star fields, where Gaia’s astrometric precision necessitates further examination ([van Leeuwen et al. 2024](#)).

In this study, we first focus on the remaining unbound field stars that are not associated with any known substructures of the Milky Way, and subsequently discuss the unbound members associated with substructures in Section 4.3. As a result, we selected a final sample of 165 hypervelocity RR Lyrae (HV-RRL) candidates. The data cuts and selection criteria are summarized in Table 1.

2.4. Light curve examination

Although we have applied strict astrometric cuts to ensure reliable proper motion data from Gaia DR3, the reliability of distance measurements in RRL catalogs remains uncertain. The accuracy of RRL distance measurements is influenced by the quality of their light curves and the precision of Fourier parameter determination. Additionally, different types of RRLs have distinct relationships for deriving metallicity and distance. In the catalogs of W22 and L23, RRLs are classified into RRab and RRC subtypes. RRab stars exhibit asymmetric light curves with a faster rise and slower decline, whereas RRC stars have more symmetric light curves resembling sine waves. Incorrect identification or classification of RRLs and their subtypes could lead to inaccurate distance measurements. Therefore, it is crucial to carefully examine the light curves of RRLs in the catalogs of W22 and L23.

First, we verify whether these RRLs can be confidently identified as RRLs and accurately classified into RRab/RRC subtypes. To achieve this, we utilize light curves collected by Gaia DR3 ([Collaboration et al. 2022](#)), the Zwicky Transient Facility Public Data Release ([Masci et al. 2018](#)), and the Catalina Sky Survey ([Drake et al. 2009](#)). Our sample is cross-matched with these light curve catalogs, and we individually inspect the light curves of the selected RRLs. Focusing on light curve quality, we categorize the selected RRLs into three classes:

- (1) “Gold sample”: Contains at least one light curve observation that clearly matches the characteristic light curve pattern of an RRL subtype;
- (2) “Silver sample”: Contains light curves with larger dispersion or fewer data points;
- (3) “Bronze sample”: Difficult to confidently identify as an RRL or potentially misclassified. The unreliable light curves of bronze sample can lead to unrealistic metallicities, requiring cautious use. Three typical example of bronze sample light curves are shown in Fig. 2.

It is particularly important to note that, RRab stars should have periods of 0.3–1.2 days and amplitudes of 0.5–2 mag, while RRC stars have periods of 0.2–0.5 days and amplitudes of less than 0.8 mag ([Meylan & Burki 1986](#)). Additionally, periods provided by the catalogs should be consistent with the periods we derived from the light curves using Lomb-Scargle Periodograms. RRLs that fail to meet the period-amplitude criteria should be classified as part of the bronze sample. Fig. 3 shows the period-amplitude distribution of the final confirmed gold and silver HV-RRL samples.

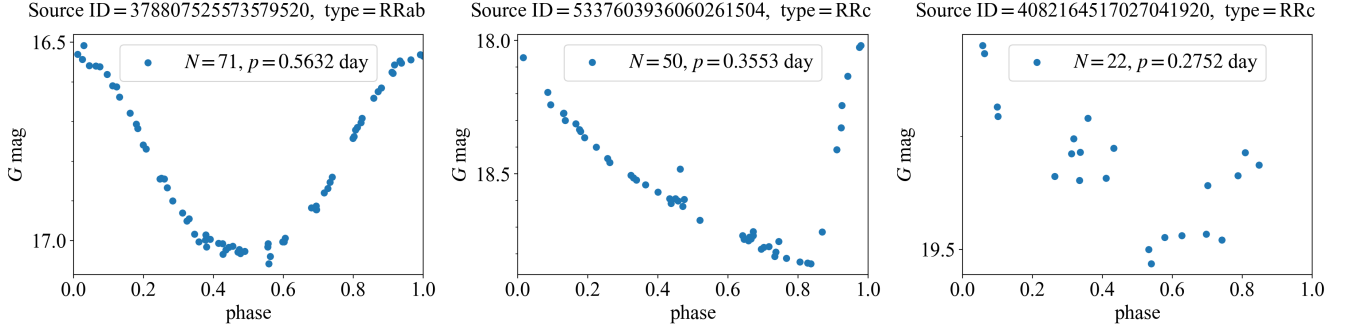


Figure 2. Three representative light curves provided by Gaia DR3

from the bronze sample are shown, which should be carefully used. The light curve in the left panel appears too symmetric to be consistent with a typical RR Lyrae star, yet it is classified as an R Rab. The middle panel shows a steep rise and an amplitude exceeding 0.8 mag, suggesting it should be classified as an R Rab rather than an RRc. The light curve in the right panel contains few and scattered data points, making it difficult to reliably identify as an RR Lyrae star.

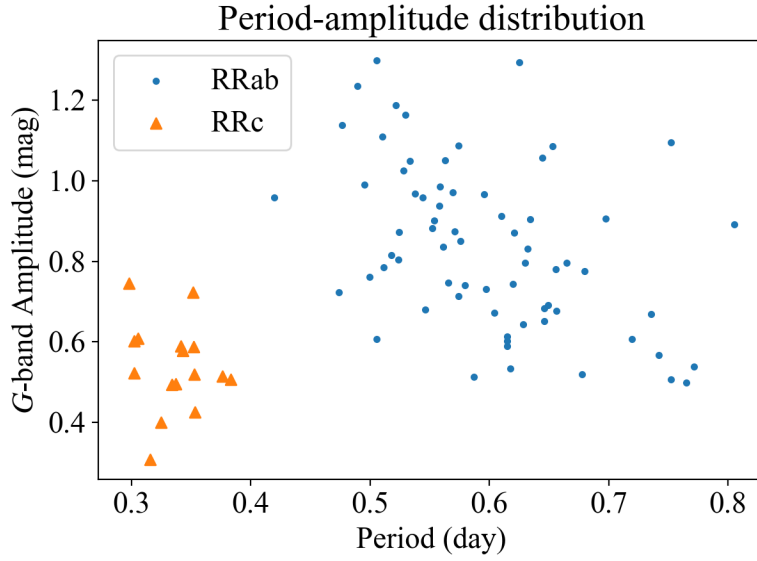


Figure 3. Period-amplitude distribution of the HV-RRL candidates for golden and silver samples. Blue circle dots are RRab types, orange triangles are RRc types.

To summarize the examinations above, we identified 64 “gold sample” HV-RRL candidates with reliable light curves, 23 “silver sample” HV-RRL candidates with moderately reliable light curves and 78 “bronze sample” HV-RRL candidates with doubtful light curves, which should be carefully used. A portion of the information for the selected 165 HV-RRL candidates is presented in Table 2.

3. RESULTS

3.1. Velocity distribution

After selection and further examination, the final HV-RRL candidates are presented in Fig. 4. Among the gold and silver samples, none of the HV-RRL candidates have measured radial velocities. Although many HV-RRL candidates

Table 2. Basic parameters for 165 HV-RRL candidates

Gaia ID	RA (deg)	Dec (deg)	$\mu_\alpha \cos \delta$ (mas yr ⁻¹)	μ_δ (mas yr ⁻¹)	D (kpc)	R_{GC} (kpc)	$v_{GC,t}$ (km s ⁻¹)	Ref.	Quality
378807525573579520	5.4851	37.9437	24.97 ± 0.06	-1.75 ± 0.06	14.1 ± 1.5	18.9 ± 1.3	1530.9 ± 171.5	L23	bronze
4918733303434183296	6.8229	-57.2477	1.29 ± 0.27	-1.78 ± 0.25	73.6 ± 7.8	71.4 ± 7.6	549.9 ± 127.1	L23	silver
4717299539114264320	22.8983	-58.8057	0.69 ± 0.28	-2.13 ± 0.31	69.7 ± 6.4	68.5 ± 6.4	574.8 ± 122.5	L23	gold
4910044167981920384	23.4723	-56.0680	1.18 ± 0.22	-1.36 ± 0.27	67.2 ± 6.7	66.2 ± 6.7	369.1 ± 99.4	L23	gold
4936275766641005312	30.3697	-52.8000	1.16 ± 0.23	-1.65 ± 0.24	68.7 ± 6.5	68.5 ± 6.4	462.0 ± 102.3	L23	gold
.....									
2004005081455404416	343.6118	56.4564	-1.94 ± 0.32	-1.79 ± 0.32	31.5 ± 3.6	34.9 ± 3.5	474.6 ± 67.7	L23	bronze
2644870582050682240	349.9803	-0.1865	11.48 ± 0.11	-9.32 ± 0.11	18.3 ± 1.3	19.3 ± 1.1	1092.5 ± 86.4	W22	bronze
2215178865230742912	351.7092	70.3796	0.92 ± 0.34	1.97 ± 0.35	48.1 ± 4.9	52.3 ± 4.9	410.8 ± 93.3	L23	gold
6522342764544281856	356.1458	-52.6550	0.89 ± 0.21	-2.11 ± 0.27	63.4 ± 6.2	60.8 ± 6.1	462.8 ± 111.4	L23	gold
6343475759127147008	356.6685	-85.9455	1.45 ± 0.15	-2.24 ± 0.19	43.9 ± 4.3	40.5 ± 4.2	383.9 ± 66.1	L23	gold

NOTE—The complete table is available online.

Table 3. Unbound probabilities P_{unb} for different potential models

Gaia ID	Bovy15	Cautun20	Monari18	McMillan17	Irrgang13I	Bovy15+LMC
378807525573579520	1.00	1.00	1.00	1.00	1.00	1.00
4918733303434183296	0.97	0.95	0.93	0.87	0.85	0.82
4717299539114264320	0.99	0.97	0.96	0.91	0.89	0.98
4910044167981920384	0.65	0.56	0.47	0.32	0.27	0.23
4936275766641005312	0.91	0.87	0.81	0.69	0.64	0.75
.....						
2004005081455404416	0.90	0.83	0.72	0.53	0.45	0.90
2644870582050682240	1.00	1.00	1.00	1.00	1.00	1.00
2215178865230742912	0.76	0.67	0.56	0.41	0.36	0.64
6522342764544281856	0.88	0.82	0.77	0.64	0.59	0.61
6343475759127147008	0.58	0.44	0.31	0.16	0.13	0.07

are located just above the Milky Way’s escape velocity curve, we identify seven candidates in the gold and silver samples with tangential velocities exceeding 800 km s^{-1} , including three with velocities surpassing 1000 km s^{-1} .

We also find that HV-RRL candidates in the bronze sample predominantly exhibit exceptionally high velocities with larger error bars. This suggests that the questionable light curves of these candidates contribute to the uncertainty in their velocity measurements. It is important to note that in the following sections, we present results only for the gold and silver samples, which we consider more reliable.

In addition to **MWPotential2014** (Bovy 2015), we also employed other potential models of the Milky Way to calculate the escape velocity, including: (1) **Cautun20** (Cautun et al. 2020), a mass model fitted to Gaia DR2 rotation curve of the Milky Way as measured by Eilers et al. (2019); (2) **Monari18** (Monari et al. 2018), a mass model fitted to the escape speed curve of the Milky Way based on the analysis of the velocity distribution of halo stars from the Gaia DR2; (3) **McMillan17** (McMillan 2017), which is an updated version of McMillan (2011), utilizing observation data such as terminal velocity curve, maser and etc. (4) **Irrgang13I** (model I from Irrgang et al. 2013), which is an updated version of Allen & Santillan (1991). These potentials all provided a higher escape velocity curve compared to **MWPotential2014**, as is displayed in Fig. 4.

Finally, to consider the influence of the LMC, we modeled the LMC potential by Hernquist profile (Hernquist 1990) with a total mass of $1.38 \times 10^{11} M_\odot$ (Erkal et al. 2019) and a scale radius of 16 kpc to ensure the mass enclosed at 8.7 kpc matches the measured value of $1.7 \times 10^{10} M_\odot$ (van der Marel & Kallivayalil 2014). As the fact that the LMC is

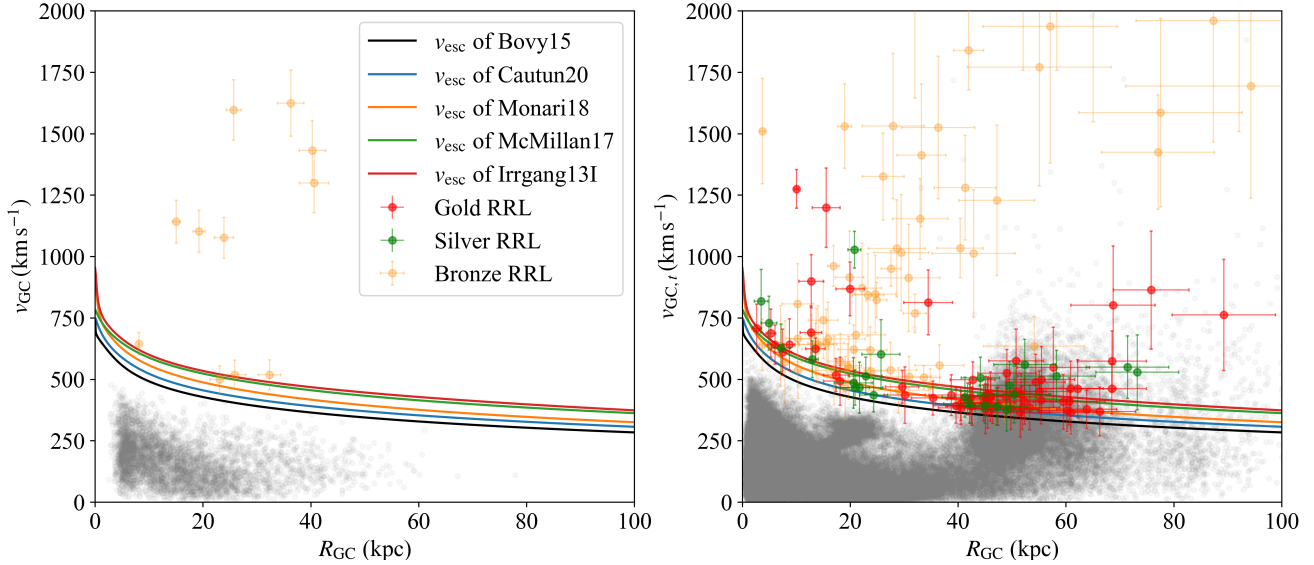


Figure 4. Velocity distribution of selected hypervelocity RRL candidates in the Galactic rest frame. Left panel shows RRLs with radial velocity; right panel shows RRLs without radial velocity. Red dots represent the HV-RRL candidates in the gold sample; green dots represent those in the silver sample; orange dots represent those in the bronze sample. Error bars are computed by Monte Carlo sampling. Grey dots depict the rest of the RRLs in the total sample. Black, blue, orange, green and red line denotes the escape velocity computed from Bovy (2015), Cautun et al. (2020), Monari et al. (2018), McMillan (2017) and Irrgang et al. (2013), respectively.

orbiting the Milky Way with high speed, the stars associated with the LMC should have relative velocity compared to the LMC above the escape velocity of the LMC potential to be truly unbound. The unbound probabilities (P_{unb}) under different potential models are summarized in Table 3.

3.2. Spatial distribution

The spatial distribution of HV-RRL candidates in the gold and silver sample is shown in Fig. 5. Notably, some HV-RRL candidates appear to cluster around the LMC and SMC.

Additionally, we present a Mollweide projection of the spatial distribution in the Galactic coordinates (l, b) in Fig. 6. In the upper panel, two distinct spatial distributions are evident: some HV-RRL candidates are concentrated toward the GC, while a larger number are localized around the LMC and SMC.

These distributions are consistent with the findings of Evans et al. (2021). By simulating the Hills mechanism originating from the SMBH at the GC and the center of the LMC, they demonstrated that HVs ejected from the GC tend to remain in close proximity to the GC on the sky and are largely confined to the Galactic mid-plane. In contrast, HVs ejected from the LMC will be a tight clump slightly leading the LMC’s orbit. Furthermore, the number of observable HVs from the LMC is predicted to be significantly higher than those from the GC, which is also consistent with our results.

However, it remains uncertain whether our HV-RRL candidates were ejected via the Hills mechanism. Other processes, such as tidal stripping from satellite galaxies or runaway stars produced by supernovae in binary systems, may also contribute to their origin. Boubert et al. (2017) studied the runaway stars from the LMC through N-body simulations. They found that unbound runaway stars from the LMC are also centered around the LMC, with a particularly large number of stars exceeding the Milky Way’s escape velocity within the LMC. In the lower panel of Fig. 6, approximately 7,000 unbound member stars of the LMC and SMC are included to illustrate a continuous density distribution. However, it should be noted that these unbound stars have not undergone light curve examination and may therefore be unreliable. To further distinguish between the Hills mechanism and the runaway scenario, ejection velocity distributions should be considered, necessitating follow-up observations to measure radial velocities.

3.3. Metallicity distribution

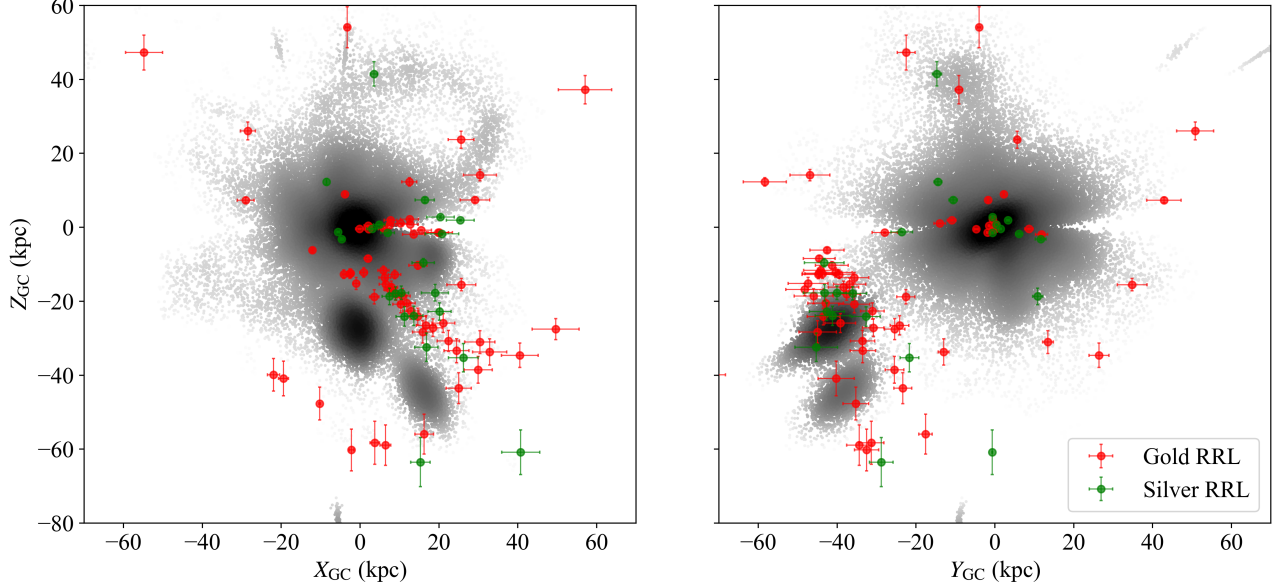


Figure 5. Spatial distribution of HV-RRL candidates in the gold and silver sample in the Galactic frame. Red dots represent the HV-RRL candidates in the gold sample; green dots represent in the silver sample. Error bars are computed by Monte Carlo sampling. Grey dots represent the rest of RRLs in the total sample, with depth of gray indicating logarithm of density.

To further investigate the metallicity distribution, the $[\text{Fe}/\text{H}]$ estimates of HV-RRL candidates are represented by the color of the dots in the upper panel of Fig. 6, while the $R_{\text{GC}}-[\text{Fe}/\text{H}]$ relation is shown in Fig. 7. HV-RRL candidates located within 30 kpc of the LMC and 20 kpc of the SMC are identified as neighbors of the Magellanic Clouds (MC neighbors) and are marked with black-edged circles. The MC neighbors and other candidates in the Galactic halo typically exhibit metallicities around $[\text{Fe}/\text{H}] \approx -2$, while HV-RRL candidates at smaller Galactocentric distances ($R_{\text{GC}} < 20$ kpc) tend to have higher metallicities, centered around $[\text{Fe}/\text{H}] \approx -1.5$. This modest difference in metallicity distributions may point to different origins for the two populations. Additionally, MC neighbors exhibit similar metallicities compared with the mean values of RRLs associated with the LMC (-1.67) and SMC (-1.95) as inferred from our RRL sample.

We further evaluate the impact of different selection criteria and gravitational potential models in Fig. 7. Increasing the adopted escape velocity (v_{esc}) reduces the overall number of HV-RRL candidates, but the two distinct spatial groupings remain clearly visible. Notably, Fig. 7(c), which includes the gravitational potential of the LMC, shows a significant reduction in the number of MC neighbors, while the rest of the HV-RRL population is largely unaffected. This implies that a substantial fraction of the initially identified MC neighbors are likely still gravitationally bound to the LMC.

3.4. Orbit integration

In addition to spatial and metallicity correlations, the most crucial approach to investigate the origin of HVs is to trace their backward orbits. For HV-RRL candidates with complete 6D data, we calculated the historical minimum distance (r_{min}) from the GC and Milky Way substructures, including 1,743 open clusters (Dias et al. 2021), 145 globular clusters (Harris 2010; Vasiliev 2019; Vasiliev & Baumgardt 2021a,b), 39 satellite galaxies (Fritz et al. 2018), as well as the LMC and SMC (Patel et al. 2020), with a total integration time of 50 Myr and a time step of 1 kyr (after a trial with total time of 1 Gyr and step of 100 kyr). We found one RRL (Gaia ID: 3745877687375105408) with a 19.0% probability of having reached a backward-integrated minimum distance within 1 kpc of the GC.

However, most of our HV-RRL candidates lack radial velocity data, making orbit integration impossible without complete 3D velocity information. To address this, we assume the radial velocity follows a Gaussian distribution with a mean of 0 km s^{-1} and different dispersions of:

- (1) 90 km s^{-1} , corresponding approximately to the standard deviation of radial velocity of 688 thick disk stars in our RRL sample, defined by $z_{\text{max}} < 4 \text{ kpc}$, eccentricity < 0.4 , and $L_z > 0$;

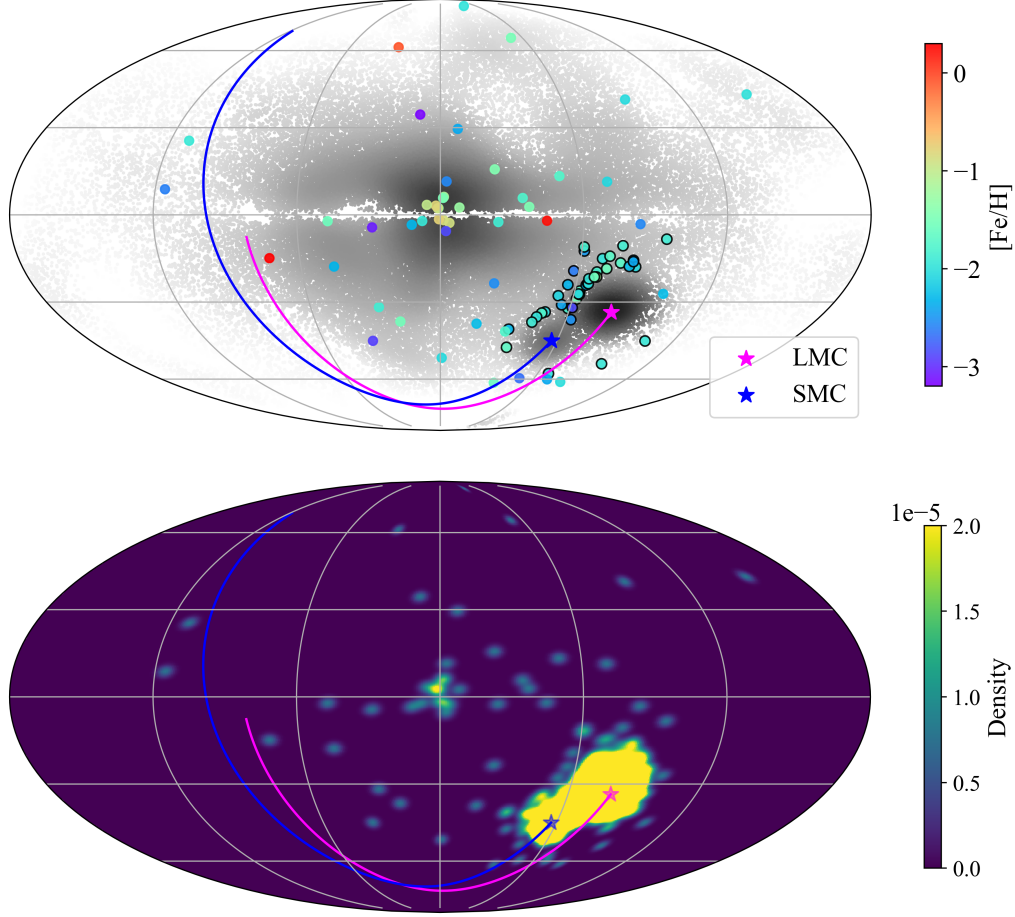


Figure 6. Spatial distribution of HV-RRL candidates in the Galactic coordinates using a Mollweide projection. In the upper panel, colors of the dots indicate the $[\text{Fe}/\text{H}]$ of the HV-RRL candidates, with black circles indicating they are neighbors of the LMC and SMC. Grey dots represent the rest of RRLs in the total sample, with depth of gray indicating logarithm of density. Magenta and blue stars and lines denote the current position and previous orbit of the LMC and SMC respectively. The lower panel displays the density of RRLs with velocity exceeding the Milky Way’s escape velocity, including the unbound member stars of the LMC and SMC.

- (2) 150 km s^{-1} , representing the standard deviation of radial velocity of 3,823 remaining halo-like stars in our RRL sample;
- (3) 300 km s^{-1} , reflecting the expectation that HVs originating from the GC may exhibit exceptionally high radial velocities.

It is important to emphasize that this is a rough approximation, and the true radial velocities may differ from the assumed distributions. Nevertheless, this method offers a useful first-order insight into the possible origins of these stars. Using this approach, we identified one RRL (Gaia ID: 4055929177457043840) whose backward-integrated minimum distance falls within the half-light radius of the Sgr (2.6 kpc; [Fritz et al. 2018](#)). The associated probabilities under the three assumed radial velocity scenarios are 41.9%, 40.9%, and 37.4%, respectively.

4. DISCUSSION

4.1. Radial velocity determination for J1300+0256

None of the HV-RRL candidates in the gold and silver samples have measured radial velocities by spectroscopic surveys. However, to further validate our HV-RRL candidates and determine their origins, obtaining additional radial velocity measurements is essential. Fortunately, we identified one candidate, J1300+0256 (Gaia ID:

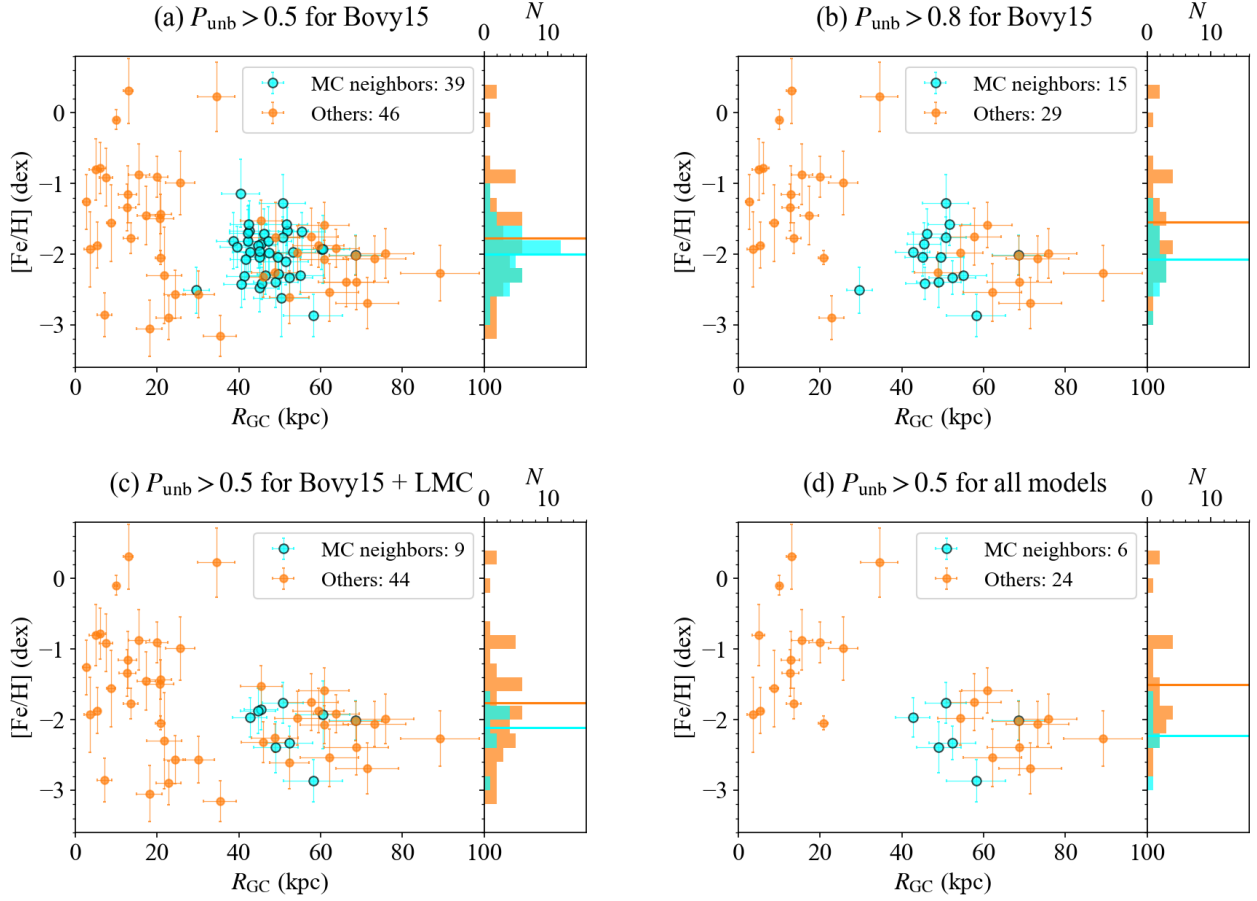


Figure 7. Galactocentric distance versus metallicity distribution of the selected HV-RRL candidates. Cyan points with black outlines and error bars represent candidates located near the Magellanic Clouds, while orange points with error bars denote other candidates. The right subpanel of each main panel shows the corresponding $[\text{Fe}/\text{H}]$ histogram, with horizontal lines marking the mean metallicity. Panels (a) through (d) illustrate the effects of varying selection criteria and gravitational potential models introduced in Section 3.1.

3692326965681261184), with a radial velocity measurement in the recent Data Release 1 of the Dark Energy Spectroscopic Instrument (DESI Collaboration 2025). J1300+0256 is an RRc-type star in the silver sample. Utilizing its metallicity of -1.22 ± 0.18 derived from the DESI spectrum with a mean SNR of 8.5, heliocentric distance is refined using the M_G - $[\text{Fe}/\text{H}]$ relation for RRc stars provided by Li et al. (2023).

The observed radial velocity of J1300+0256, derived from the $\text{H}\alpha$ absorption line in the DESI spectrum, is $163.6 \pm 12.2 \text{ km s}^{-1}$. However, due to the pulsation of RRLs, a correction is necessary to estimate the systematic radial velocity. To perform this correction, we employed the $\text{H}\alpha$ radial velocity template for RRc stars derived by Huang et al. (2024). Utilizing this template, the radial velocity curve of RRc stars can be reconstructed from Gaia G -band light curve amplitude and a single radial velocity measurement taken at a certain phase in the pulsation cycle. Accordingly, a correction of $29.1 \pm 4.5 \text{ km s}^{-1}$ is added to the observed radial velocity to derive the systematic radial velocity. Incorporating the corrected radial velocity, the total velocity of J1300+0256 in the Galactic rest frame reaches 441.1 km s^{-1} , exceeding the local escape velocity of 385.2 km s^{-1} at its position ($R = 39.50 \text{ kpc}$). With the full 3D velocity data, we integrated its past orbit but found no clear association with the GC. However, in 2000 Monte Carlo simulations, J1300+0256 can approach as close as 0.37 kpc to the globular cluster NGC 5824, which has a tidal radius of 0.25 kpc (Baumgardt et al. 2020; Vasiliev & Baumgardt 2021a).

4.2. Comparison with previous study

Prudil et al. (2022) also conducted a search for HVs using distances inferred from RRLs. Their sample consisted of 6,187 RRLs compiled from Gaia DR2 (Clementini et al. 2019) and the Catalina Sky Survey (Drake et al. 2014), all with 3D velocity measurements, from which they selected nine HV-RRL candidates. Three of their candidates overlap with our study, corresponding to Gaia source IDs 3942539665718239360, 3692326965681261184, and 2644870582050682240. In our classification, the three stars fall into the gold, silver, and bronze categories, respectively. Two of their candidates (Gaia IDs: 2471437298673558400 and 1018414089653402496) are not included in our initial sample. Compared to their study, we applied similar astrometric quality cuts to the Gaia data. Both studies used similar solar position and motion parameters and adopted the `MWPotential2014` model, with a selection criterion of $P_{\text{unb}} > 0.5$. However, they did not apply the relative velocity uncertainty cut $\sigma_{v_{\text{GC}}}/v_{\text{GC}} < 0.3$, resulting in the exclusion of three of their candidates from our final selection (Gaia IDs: 3903031502808975616, 674694939356598528, and 3661050979472106880). Additionally, one of their candidates (Gaia ID: 3664033198603611520) is identified as an unbound member star of the Sgr in Section 2.3. Therefore, it is not included in our final sample and will be discussed further in Section 4.3.

4.3. Member stars of the dwarf galaxies

In this section, we further investigate the velocity distribution of RRLs as member stars of dwarf galaxies, selected from the total sample described in Section 2. In the Galactic rest frame, we find that some RRLs within the substructures have velocities significantly exceeding the escape velocity. Notably, for the LMC and SMC, a substantial number of RRLs lie above the escape velocity, as shown in Fig. 8. This excess velocity may result from the high orbital velocities and tidal stripping near the pericenters of the dwarf galaxies’ orbits (Abadi et al. 2009).

To determine whether these stars are truly unbound from the dwarf galaxies and the Milky Way, we need to analyze their velocities in the rest frame of the dwarf galaxies. An example for RRLs in the rest frame of the LMC is shown in Fig. 9, indicating that numerous stars can be unbound from both the LMC and the Milky Way. Boubert et al. (2017) predicted there should be lots of stars escaping from the LMC through supernova in binary systems, with some also escaping the Milky Way’s gravitational potential. This aligns with our observed results displayed in Fig. 9.

Additionally, the Sculptor, Draco, and Ursa Minor dwarf galaxies (SclI, DraI, and UMiI) also exhibit a significant number of member stars with velocities exceeding the escape velocity, as shown in Fig. 8. This phenomenon may be attributed to tidal stripping, as previous studies have shown that these dwarf galaxies can host extended stellar halos or tidal debris (Qi et al. 2022; Tau et al. 2024). However, since these dwarf galaxies are currently far from their orbital pericenters, the contribution of tidal stripping to the production of HVs may be less significant, as discussed by Abadi et al. (2009). Furthermore, we highlight the possibility that these stars could be ejected via the Hills mechanism from central black holes within the dwarf galaxies. This is supported by the fact that some member stars exhibit velocities up to 800 km s^{-1} relative to the galaxy centers, which is comparable to the typical velocity produced by the Hills mechanism.

5. SUMMARY

Based on RRL catalogs from W22 and L23, combining astrometric measure by Gaia DR3, we identified 165 hyper-velocity RR lyrae (HV-RRL) candidates.

We’ve examined on their light curves, and categorized them into 64 “gold sample”, 23 “silver sample” and 78 “bronze sample” HV-RRL candidates to ensure we have reliable distance determination from RRL’s light curve. The 87 HV-RRL candidates in the gold and silver sample have relatively more reliable light curves, while the bronze sample should be carefully used. Among the gold and silver sample, all the HV-RRL candidates have no radial velocity measurements, exceeding the escape velocity of the Milky Way by their tangential velocity. Notably, 7 RRLs have tangential velocity exceeding 800 km s^{-1} , while 3 RRLs exceed 1000 km s^{-1} .

Spatially, two distinct distributions are evident: one group is concentrated toward the GC, while a larger number are clustered around the LMC and SMC. This pattern is consistent with the simulations presented by Evans et al. (2021) and Boubert et al. (2017). Moreover, we observe a clear metallicity distinction between these two groups of candidates.

By integrating their backward orbits with a prior on radial velocity, we identified some HV-RRL candidates that could originate from the GC or the Sagittarius spheroidal dwarf galaxy. In addition, we identified a substantial number of RRLs as member stars of dwarf galaxies that exceed the Milky Way’s escape velocity, likely ejected from their hosts through various mechanisms.

In the future, we plan to conduct spectroscopic observations of HV-RRL candidates lacking radial velocity measurements. With these data, we will be able to more accurately determine their origins.

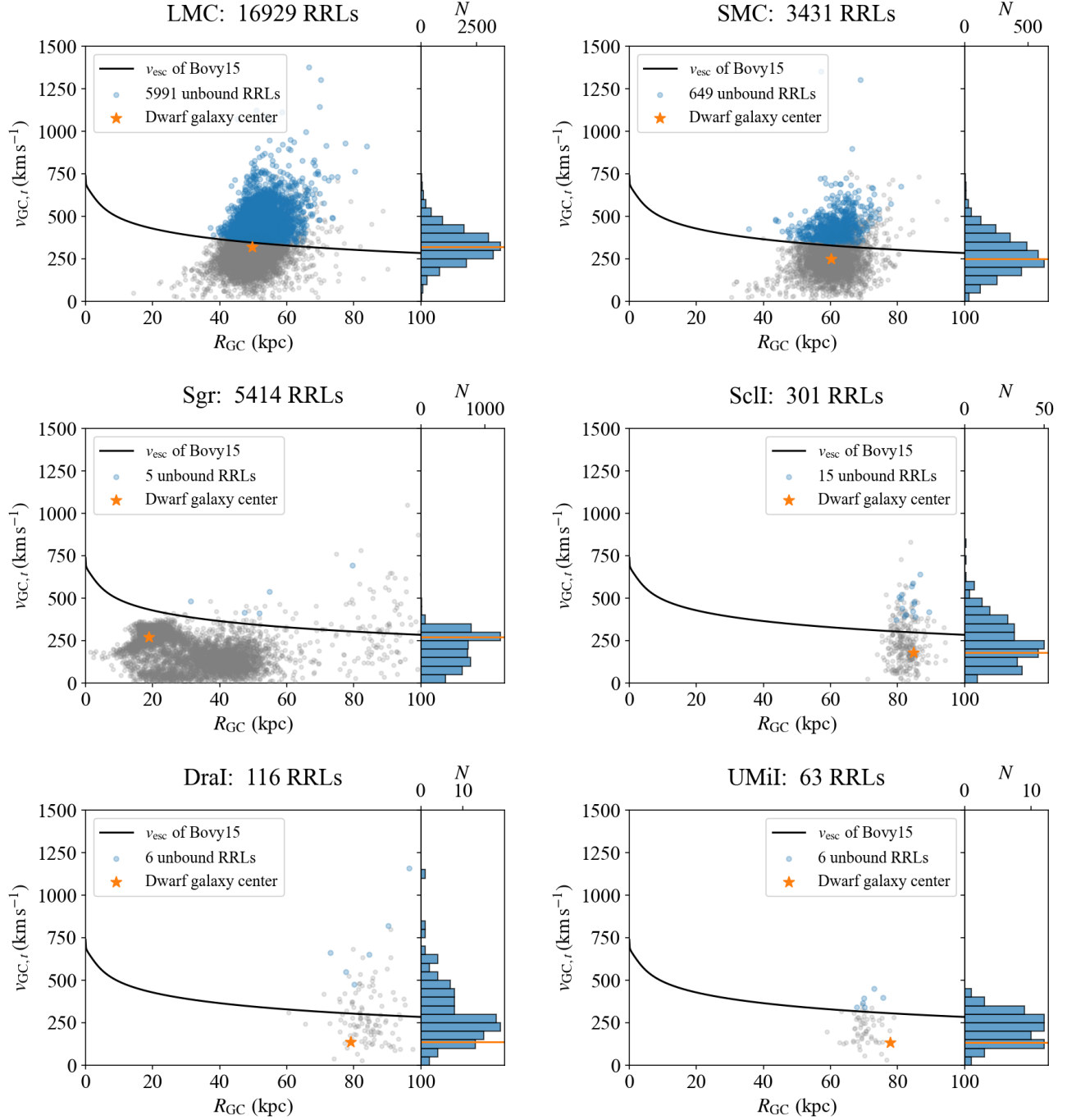


Figure 8. The velocity distribution of the RRLs as member stars of the dwarf galaxies in the Galactic rest frame. Blue dots represent the selected unbound candidates of the Milky Way, while grey dots represent other RRLs. Orange stars mark the position and velocity of the dwarf galaxies' centers.

ACKNOWLEDGMENTS

This work is supported by the National Key R&D Program of China No. 2024YFA1611903, the National Natural Science Foundation of China (NSFC grant Nos. 12090040, 12090044 and 12422303), Beijing Natural Science Foundation (no. 1242016) and the science research grants from the China Manned Space Project. This work was partially supported

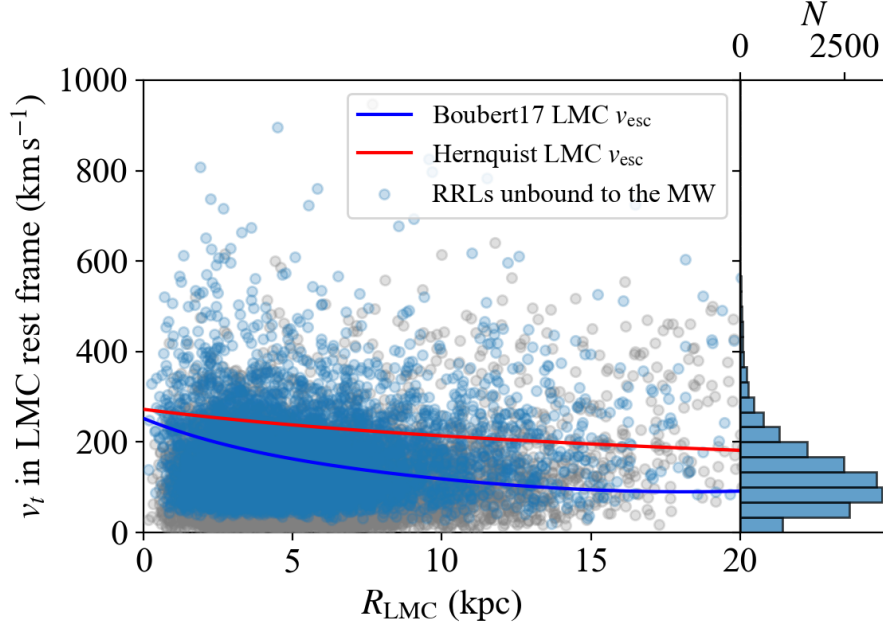


Figure 9. The velocity distribution of the RRLs as member stars of the dwarf galaxies in the LMC rest frame. Blue dots represent the selected unbound candidates of the Milky Way, while grey dots represent other RRLs. Blue line denotes the simulated LMC escape velocity in Fig. 4 from Boubert et al. (2017); Red line denotes the LMC escape velocity computed by Hernquist profile constructed in Section 3.1.

by Talents Program (24CE-YS-08) and the Popular Science Project (24CD012) of Beijing Academy of Science and Technology.

This work has made use of data from the European Space Agency (ESA) mission *Gaia* (<https://www.cosmos.esa.int/gaia>), processed by the *Gaia* Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the *Gaia* Multilateral Agreement.

This work has made use of data products from the Guo Shou Jing Telescope (the Large Sky Area Multi-Object Fibre Spectroscopic Telescope, LAMOST). LAMOST is a National Major Scientific Project built by the Chinese Academy of Sciences. Funding for the project has been provided by the National Development and Reform Commission. LAMOST is operated and managed by the National Astronomical Observatories, Chinese Academy of Sciences.

We thank Qingzheng Li and Xiangyu Li for their constructive assistance and appreciate Xinyi Li and Gaochao Liu for their guidance on data usage.

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