

A SYSTEMATIC SURVEY FOR HYPERVELOCITY RUNAWAYS FROM THERMONUCLEAR SUPERNOVAE

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ABSTRACT

The explosion of a white dwarf (WD) in a close binary can launch a surviving runaway star at velocities of $\gtrsim 1000 \text{ km s}^{-1}$. Such runaways provide a direct probe of thermonuclear supernovae (SNe) in double-degenerate binaries. Several candidate runaways are known, but their evolutionary states and the demographics of the broader population are uncertain. To enable robust population inference, we carry out a systematic survey for hypervelocity runaways with a simple selection function, selecting candidates based on large *Gaia*-inferred tangential velocities and blue colors. We classify 100% of the resulting 92 candidates using a combination of spectroscopic follow-up and archival data. The search yields ten suspected D⁶ stars and three LP 40-365 stars. Three D⁶ stars are new discoveries, including two hot ($T_{\text{eff}} \gtrsim 50,000 \text{ K}$) objects and one cool ($T_{\text{eff}} \approx 7,000 \text{ K}$) object. We forward-model our survey under several proposed D⁶ star evolutionary models, coupling each to a Galactic model and the survey selection function. No single model reproduces the observed diversity of D⁶ stars, which likely reflects a range of remnant masses, ages, and heating mechanisms. Models in which runaway companions are heated by SN shocks alone are too faint and short-lived to explain most of the observed sample, while fully reheated models are too luminous and long-lived. Models with intermediate heating, as occurs in some simulations of violent mergers and partially disrupted remnants, best match the observed magnitude, distance, and kinematic-age distributions. The inferred D⁶ star birth rate is model dependent, but the models that best match the observed population require rates of only a few percent of the Galactic SN Ia rate, perhaps implying that most SNe Ia result from WD binaries in which both components explode. If most SNe Ia do produce surviving runaways, these must be fainter or shorter-lived than the currently known runaways.

Subject headings: white dwarfs – binaries: close – stars: chemically peculiar

1. INTRODUCTION

Several classes of progenitor models for Type Ia supernovae (SNe Ia) and related thermonuclear transients begin with the gravitational wave-driven inspiral of two white dwarfs (WDs) in a close binary (e.g. [Webbink 1984](#); [Iben & Tutukov 1984](#)). In some models, only one of the WDs explodes. The other – suddenly free of its companion’s gravity – is predicted to escape with a velocity comparable to its orbital velocity, which is typically $(1000 - 2000) \text{ km s}^{-1}$.

Over the last decade, searches using wide-field photometric and spectroscopic surveys have identified more than a dozen high-velocity stars suspected to have been ejected from thermonuclear explosions in WD binaries ([Geier et al. 2015](#); [Vennes et al. 2017](#); [Shen et al. 2018b](#); [Raddi et al. 2019](#); [El-Badry et al. 2023](#); [Hollands et al.](#)

[2025](#); [Bhat et al. 2026a](#)). Most of these stars fall between the main sequence and WD cooling track in the color-magnitude diagram (CMD). The objects with space velocities $\gtrsim 1000 \text{ km s}^{-1}$ have been dubbed “D⁶ stars”, after a theoretical model for their formation (“dynamically driven, double-degenerate, double-detonation” SNe; [Shen et al. 2018a](#)). Some recent works have proposed progenitor models for these objects that are distinct from the D⁶ scenario ([Pakmor et al. 2025](#); [Bhat et al. 2026b](#); [Glanz et al. 2025](#)), in which a violent WD merger leads to detonation of the primary and partial disruption of the secondary. In this case, the hypervelocity star can reach lower masses and somewhat higher velocities than in the D⁶ scenario. We refer to the observed runaway stars with velocities $\gtrsim 1000 \text{ km s}^{-1}$ as D⁶ stars in this work for consistency with the previous literature, but we are agnostic of the precise mechanism that detonated the SNe from which they were ejected.

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The observed sample of thermonuclear-runaway candidates also includes LP 40-365 stars (Vennes et al. 2017; Raddi et al. 2019; Bhat et al. 2026a), of which eight are currently known (Section 5.2), and runaway helium stars, of which one is known (e.g. Geier et al. 2015; Neunteufel et al. 2022; Geier et al. 2024). LP 40-365 stars have lower inferred ejection velocities, typically $\sim 600 \text{ km s}^{-1}$, and neon + oxygen dominated atmospheres polluted with partially burned SN ash. They have been associated with failed or peculiar thermonuclear explosions, such as SNe Iax (Foley et al. 2013), in which the observed star is the remnant of a partially burned ONe WD rather than the surviving donor. While both LP 40-365 stars and D⁶ stars are likely products of thermonuclear SNe in close binaries containing a WD, they likely trace different outcomes: partially burned primaries for LP 40-365 stars, and surviving donors or donor fragments for D⁶ stars. Like D⁶ stars, runaway helium stars are likely surviving donors, but they are ejected from WD + helium star binaries rather than WD + WD binaries and thus have lower velocities.

The eight suspected D⁶ stars published to date have radii of $(0.02 - 0.2) R_{\odot}$, significantly larger than ordinary WDs. They span a wide range of temperatures, from $\sim 7000 \text{ K}$ to $\sim 100,000 \text{ K}$ (Chandra et al. 2022; Werner et al. 2024a; Hollands et al. 2025). Seven have hydrogen-free atmospheres, likely because their envelopes were stripped by mass transfer prior to their companions’ detonation. Most appear to have atmospheres dominated by carbon and oxygen, together with enhancements in metals such as iron, nickel, and silicon (El-Badry et al. 2023; Werner et al. 2024a,b; Hollands et al. 2025). At least one has a helium-rich surface (Werner et al. 2024a); the same object has hydrogen detected in its atmosphere, the origin of which is uncertain.

The masses of the known D⁶ stars are in most cases poorly constrained. Their inferred ejection velocities span $(1000 - 3000) \text{ km s}^{-1}$. It is possible to infer the stars’ masses from their velocities if they were semi-detached donors that were launched from Keplerian pre-SN orbits (Bauer et al. 2021; Braudo & Soker 2024), but such constraints could be biased if the stars were partially disrupted during or just prior to their ejection (e.g. Wong & Bildsten 2025; Bhat et al. 2026b; Pakmor et al. 2025). Masses can in principle be measured directly from constraints on the stars’ radii and surface gravities (e.g. Hollands et al. 2025), but uncertainties in atmospheric models in most cases limit the robustness of such constraints.

One cool D⁶ star is on a trajectory that traces back to a SN Ia remnant (Shen et al. 2018b; Chandra et al. 2022). Assuming this association is physical and not a chance alignment, the object’s kinematic age is $\sim 0.1 \text{ Myr}$. Tracing the trajectories of the other stars back to the Galactic plane suggests typical kinematic ages of $\sim 1 \text{ Myr}$, though the stars’ uncertain birth locations lead to uncertainty in this value (El-Badry et al. 2023). The evolutionary state of D⁶ stars is uncertain. Several models have been explored to explain their inflated radii and wide range of temperatures (Zhang et al. 2019; Bauer et al. 2019; Bhat et al. 2025; Yamaguchi et al. 2025; Wong et al. 2024; Wong & Bildsten 2025; Bhat et al. 2026b; Shen 2025). While some models have succeeded in matching the observed temperatures, luminosities, velocities, and ages of

individual D⁶ stars, none reproduce the diversity of physical properties in the observed population. For the cool D⁶ stars ($T_{\text{eff}} \lesssim 10,000 \text{ K}$), the models that currently appear most promising are those in which the donors lost significant mass during or just prior to their companions’ explosions (Shen 2025; Wong & Bildsten 2025; Bhat et al. 2026b), such that the stars have lower masses than would be inferred when their ejection velocities are interpreted as pre-explosion orbital velocities. The hotter objects appear to be more massive than the cool objects. Most models have struggled to explain why the hot objects remain inflated at relatively old ages.

If most SNe Ia arise from WD+WD mergers in which one component survives, then the birth rate of D⁶ stars should be similar to the SNe Ia rate ($\mathcal{R}_{\text{Ia}} \approx 0.005 \text{ yr}^{-1}$ in the Milky Way; Li et al. 2011; Maoz et al. 2014). On the other hand, if most SNe Ia arise from other channels – such as WD+WD mergers in which both stars explode (e.g. Pakmor et al. 2022; Boos et al. 2024; Pollin et al. 2024; Prust et al. 2026; Mehta et al. 2026), or binaries containing a WD and a nondegenerate star (e.g. Whelan & Iben 1973) – the birth rate of D⁶ stars should be much lower. Observationally constraining the birth rate of D⁶ stars is thus a promising avenue to constrain the dominant progenitor channel for SNe Ia.

In this paper, we present results of a systematic search for D⁶ stars using astrometry from *Gaia* and spectroscopic follow-up. Our search is designed to have a simple selection function, making it amenable to population modeling. Early discoveries from the search were presented by El-Badry et al. (2023, hereafter E23); here, we present the complete survey and several new discoveries. We also compare the survey’s yield to several classes of evolutionary models for SN survivors developed in the last few years.

The remainder of this paper is organized as follows. Section 2 describes how we select candidate D⁶ stars based on *Gaia* astrometry and photometry. Section 3 details our spectroscopic follow-up, while Section 4 presents our newly discovered D⁶ star candidates. We integrate the stars’ orbits in Section 5 and compare their demographics to simulated populations in Section 6. We summarize our main results in Section 7.

2. CANDIDATE SELECTION

Following E23, we select candidate hypervelocity runaways using cuts on astrometric tangential velocity, proper motion, color, and apparent magnitude.

2.1. Tangential velocity and proper motion

Given a total proper motion μ and parallax ϖ , the implied tangential velocity is

$$v_{\perp} = 4.74 \text{ km s}^{-1} \times \left(\frac{\mu}{\text{mas yr}^{-1}} \right) \left(\frac{\varpi}{\text{mas}} \right)^{-1}. \quad (1)$$

We select sources with $v_{\perp} > 600 \text{ km s}^{-1}$. This threshold is large enough to exclude most bound halo stars while including a majority of D⁶ stars. Sources on near-radial trajectories will be missed by this selection; blind spectroscopic searches may discover them in the future.

For the sources of interest to our search, the uncertainty in $v_{\perp}$ is always dominated by parallax uncertainty. Many distant sources with small, noise-

dominated parallaxes and relatively low proper motions satisfy $v_{\perp} > 600 \text{ km s}^{-1}$ because parallax inversion overestimates their distances. We reduce contamination from such sources using two cuts. First, we require a minimum proper motion, $\mu > 50 \text{ mas yr}^{-1}$, which effectively limits the search to sources with distances $d \lesssim 4.22 \text{ kpc} \times [v_{\perp, \text{true}} / (1000 \text{ km s}^{-1})]$ for a true tangential velocity $v_{\perp, \text{true}}$. Second, we define $v_{\perp, \text{lower}} = 4.74\mu / (\varpi + \sigma_{\varpi})$ as a rough proxy for the 1σ lower limit on $v_{\perp}$, and we require $v_{\perp, \text{lower}} > 400 \text{ km s}^{-1}$. Here σ_{ϖ} is the parallax uncertainty.

Reducing the thresholds of $v_{\perp}$, $v_{\perp, \text{lower}}$, and μ increases the number of candidates, improving the search’s sensitivity to sources at larger distances and sources on more radial trajectories. However, it also dramatically increases the number of contaminants. We have found that the adopted thresholds provide a reasonable compromise between completeness and purity. The adopted thresholds are accounted for in our modeling (Section 6), so their precise values are ultimately unimportant as long as spectroscopic follow-up can reliably distinguish between D⁶ stars and contaminants.

In addition to the above cuts, we require `ruwe` < 1.4, since sources with larger `ruwe` generally have problematic astrometric solutions affected by binarity or blending with nearby sources (Lindgren 2018; Belokurov et al. 2020; El-Badry 2025). This cut is expected to exclude only a small fraction of true D⁶ stars, which should not be in binaries and are usually detected in regions that are not particularly crowded.

2.2. Color

All currently known D⁶ stars – as well as related classes of SN survivors such as LP 40-365 stars – have relatively blue intrinsic colors. To reduce contamination from main-sequence halo stars, we require $G_{\text{BP}} - G_{\text{RP}} < 0.5$. This dramatically reduces the number of contaminants: removing it increases the number of candidates by a factor of 400. The price to pay is that our search is not sensitive to red objects, including both intrinsically red sources with $T_{\text{eff}} \lesssim 6500 \text{ K}$ (some of which have been proposed to exist; e.g. Shen 2025; Wong & Bildsten 2025) and intrinsically blue sources with significant foreground extinction.

We explored selections based on extinction-corrected color, which could in principle make our search sensitive to more sources in the Galactic plane. Because most of our candidates have noisy parallaxes, we found that obtaining robust extinctions for all of them using 3D dust maps is currently impractical. Moreover, since most known D⁶ stars are already near the faint magnitude limit of our search (Section 2.3) and extinction makes sources both redder and fainter, our simulations in Section 6 predict that the number of otherwise promising D⁶ stars our search misses due to extinction is modest. Thus, our selection is based on observed color without extinction corrections.

2.3. Apparent magnitude

We adopt a magnitude limit of $G < 20.5$, just above the *Gaia* faint limit of $G \simeq 20.7$. Although only 23% of sources in *Gaia* DR3 have $G > 20.5$, removing this faint limit increases the number of candidates by a factor

of 2.8. This reflects the fact that sources near the faint limit have the largest parallax uncertainties and are most likely to have spurious colors or astrometry.

2.4. ADQL query

The cuts described above are implemented through the following ADQL query, which can be executed in the *Gaia* archive.

```
select * from gaiadr3.gaia_source
where phot_g_mean_mag < 20.5
and bp_rp < 0.5
and pm > 50
and ruwe < 1.4
and ( (4.74*pm/parallax > 600 and
      4.74*pm/(parallax + parallax_error) > 400) or
      parallax < 0 )
```

The query is similar to the one employed by E23, with the main difference being that the magnitude limit is $G = 20.5$ here and was $G = 20.0$ in that work. We also remove the cut of `parallax_over_error` < 5 adopted by E23, which results in the addition of a few relatively bright candidates not considered in that work.

The query returns 92 sources, of which 25 were already considered by E23. We provide a complete log of the candidates and our follow-up in Appendix B. We have characterized all 92 candidates via a combination of our own spectroscopic follow-up and analysis of archival data. Because the classifications and radial velocities (RVs) require spectroscopic information, we summarize the outcome of the survey after describing the follow-up data in Section 3.4.

3. FOLLOW-UP

We obtained dedicated follow-up spectroscopy of all candidates, except in cases where archival data could rule out a source as a viable supernova survivor. All spectra from this follow-up program are published together with this paper.¹ We describe our observations and analysis of survey data below.

3.1. Instruments

3.1.1. MagE

We observed 4 sources using the Magellan Echellette spectrograph (MagE; Marshall et al. 2008) on the 6.5 m Magellan Baade telescope at Las Campanas Observatory. All observations were carried out with the 0.7''-wide slit, yielding a spectral resolution $R \approx 5500$ and wavelength coverage of 3500–11,000 Å.

We reduced the spectra using PyPeIt (Prochaska et al. 2020), which performs bias and flat-field correction, cosmic-ray removal, wavelength calibration, sky subtraction, extraction of 1D spectra, merging of spectral orders, and heliocentric RV corrections.

3.1.2. LRIS

We observed 25 sources using the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995) on the 10 m Keck-I telescope on Maunakea. Some of the observations used the 600/7500 grating on the red side and the

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600/4000 grism on the blue side, resulting in a full width at half-maximum intensity (FWHM) of $4.7 \text{ \AA}$ on the red side and $4.0 \text{ \AA}$ on the blue side, or a typical resolution $R \approx 1500$. Other observations used the 400/8500 grating on the red side and the 400/3400 grism on the blue side, resulting in $\text{FWHM} \approx 6.9 \text{ \AA}$ on the red side and $6.5 \text{ \AA}$ on the blue side, or a typical resolution $R \approx 1000$. LRIS is equipped with an atmospheric dispersion corrector.

We reduced the data using the LRIS automated reduction pipeline (LPIPE; Perley 2019), which performs bias and flat-field corrections, cosmic-ray removal, wavelength calibration and flexure corrections using night-sky lines, extraction of 1D spectra, telluric corrections, and flux calibration using a standard star.

3.1.3. GMOS

We observed 6 sources using the Gemini Multi-Object Spectrograph (GMOS; Hook et al. 2004) on the 8.1 m Gemini-South telescope at Cerro Pachón (programs GS-2023A-FT-107, GS-2023B-Q-139, and GS-2026A-FT-204). We used the B1200_G5321 grating with a $0.75''$ -wide slit and central wavelength of $4500 \text{ \AA}$, leading to wavelength coverage from 3700 to $5300 \text{ \AA}$ and resolution $R \approx 3000$. We obtained a spectrum of a CuAr comparison lamp for wavelength calibration on-sky immediately after each 900 s science exposure. The data were reduced using PyPeIt.

3.1.4. SOAR

We observed 32 sources with the Goodman Spectrograph (Clemens et al. 2004) on the SOAR telescope. All SOAR observations used a $1.2''$ slit and a 400 line mm^{-1} grating, giving an approximate wavelength coverage of 4000 – $7850 \text{ \AA}$ with a FWHM resolution of $\sim 6.6 \text{ \AA}$. For each candidate we obtained a single exposure of length 1200 – 1800 s , using longer exposures for fainter targets. All spectra were reduced and optimally extracted in the standard manner. The wavelength calibration was performed with comparison-lamp spectra obtained immediately after each science exposure.

3.1.5. DBSP

We observed 2 sources with the Double Spectrograph (DBSP; Oke & Gunn 1982) on the 5 m Hale telescope at Palomar Observatory. The 600/4000 grating was used on the blue side and the 316/7500 grating on the red side, together with the D55 dichroic. We employed the $1.0''$ or $1.5''$ slit, depending on the seeing, yielding an average resolution $R \approx 1500$ and wavelength coverage of 3000 – $10,700 \text{ \AA}$.

We reduced the spectra using PyPeIt (Prochaska et al. 2020) with the DBSP_DRP wrapper (Mandigo-Stoba et al. 2022). This performs bias and flat-field corrections, cosmic-ray removal, wavelength calibration, extraction of 1D spectra, telluric corrections, and flux calibration using a standard star.

3.1.6. X-shooter

We observed 5 sources using the X-shooter spectrograph (Vernet et al. 2011) on the 8.2 m UT3 telescope at the VLT on Cerro Paranal (program 115.27UU.001). We used the 0.8, 0.9, and 0.6 arcsec slits on the UVB,

VIS, and NIR arms. This setup yielded a resolution of $R \approx 9,700$ in the UVB arm, $R \approx 18,400$ in the VIS arm, and $R \approx 11,600$ in the NIR arm, with near-continuous wavelength coverage from 3100 – $24000 \text{ \AA}$. We reduced the data using the ESO Reflex pipeline (Freudling et al. 2013) with standard calibrations.

3.1.7. ESI

We observed 3 sources with the Echellette Spectrograph and Imager (ESI; Sheinis et al. 2002) on the 10 m Keck-II telescope on Maunakea. We used the $0.5''$ -wide slit, yielding a resolution $R \approx 8000$, with a useful wavelength coverage of 3900 – $10,000 \text{ \AA}$. We reduced the data using the Mauna Kea Echelle Extraction (MAKEE) pipeline, which performs bias subtraction, flat fielding, wavelength calibration, and sky subtraction. The pipeline also carries out a linear shift to the wavelength solution using night-sky emission lines.

3.1.8. Gaia XP

We identified 7 bright candidates ($G \lesssim 16$) as A and F-type stars based on the presence of strong Balmer lines in their Gaia XP spectra (De Angeli et al. 2023; we visualize these using the GaiaXP tool with `truncation = true`). The sources have well-measured parallaxes and fall on the main sequence of the CMD. These sources could be hypervelocity stars launched by the Hills (1988) mechanism (e.g. Brown 2015; Koposov et al. 2020), ejection from binaries in core-collapse supernovae (e.g. Blaauw 1961; Renzo et al. 2019), or dynamical interactions in dense clusters (e.g. Leonard 1991), or they could be ordinary halo stars in the tail of the $v_{\perp}$ distribution for objects bound to the Milky Way. In either case, the presence of strong hydrogen lines in their spectra makes them unlikely to be survivors of double-degenerate supernovae.

3.1.9. Other surveys

A few sources were also observed by SDSS spectroscopic surveys (e.g. Yanny et al. 2009; Kleinman et al. 2013), by the LAMOST survey (Cui et al. 2012), and by other works targeting halo stars (e.g. Brown et al. 2008).

3.2. Classification and RV measurements

We visually inspected all spectra, comparing them to templates for normal stars, WDs of several spectral types, and known D⁶ and LP 40-365 stars. Results of this classification are listed in Table 4.

We measured RVs from pseudo-continuum normalized spectra by minimizing χ^2 between the data and Doppler-shifted template spectra. For main-sequence contaminants, we used synthetic spectra from the BOSZ grid (Bohlin et al. 2017) calculated with ATLAS and SYNTH (Kurucz 1993). For DA WD contaminants, we used templates from Koester (2010); for DB WDs, we used templates from Cukanovaite et al. (2021). For D⁶ and LP 40-365 stars, we used the C/O-dominated atmosphere library described by E23; these are tailored to hydrogen-free, metal-rich D⁶ atmospheres calculated with ATLAS and SYNTH.

We applied barycentric corrections using the mid-exposure times and target coordinates. For SOAR and DBSP spectra, we correct for flexure by measuring a

residual wavelength zero-point offset using telluric absorption lines centered on the atmospheric A band (e.g. Griffin 1973; Nagarajan et al. 2023). We adopted minimum RV uncertainties of 50 km s^{-1} for the SOAR, DBSP, and LRIS spectra. For most objects, this exceeds the formal RV uncertainty and is meant to account for possible shifts in the wavelength solution due to flexure. Most of our confirmed hypervelocity runaways were followed-up with more stable, higher-resolution spectrographs, allowing us to measure more precise RVs.

3.3. Contaminants

We summarize the several classes of false positives we rejected below.

3.3.1. Normal WDs and hot subdwarfs

The most common contaminants are WDs and hot subdwarfs (“sdO/B” stars). While some of these could conceivably also be thermonuclear SN runaways, they have comparatively low RVs, and are most likely bound halo objects with underestimated parallaxes and overestimated $v_{\perp}$. We label these objects according to their spectral type in Table 4.

3.3.2. Main-sequence K dwarfs

Spectroscopic follow-up showed some candidates to be main-sequence K dwarfs, usually low-metallicity halo stars. While such sources normally should fall redward of our color cut, noisy *Gaia* colors for faint sources cause some redder sources to scatter into the sample. Such sources are labeled “MS” in Table 4.

3.3.3. Main-sequence A and F stars

About a dozen candidates are relatively bright ($G = 10 - 16$) and have well-constrained parallaxes. Most of these sources have spectra from archival surveys and did not require additional follow-up. Their spectra show Balmer lines characteristic of A and F-type stars, consistent with their position on the main sequence of the *Gaia* CMD. The sources’ CMD positions and hydrogen-dominated spectra make it unlikely that these sources are runaways from WD+WD binaries, though some may still be high-velocity runaways launched through other channels. Such sources are also labeled “MS” in Table 4.

3.3.4. Blended sources

Several candidates are faint sources within a few arcseconds of a much brighter source. Since such sources are overrepresented in our candidate sample relative to the full *Gaia* catalog and there is no astrophysical reason to expect thermonuclear runaways to be preferentially found near a bright companion, we suspect that they have spurious colors and/or astrometry due to blending (e.g. El-Badry et al. 2021; Rybizki et al. 2022). Such sources are marked “blended” in Table 4; in most cases, we did not follow them up spectroscopically.

3.3.5. Wide binaries

A few candidates have a comparably bright companion within a few arcsec with near-identical high proper motion, making them very likely halo wide binaries. In some cases, the colors and astrometry are likely affected

TABLE 1
Candidate accounting for the *Gaia* search.

Category	Number
Sources returned by ADQL query	92
Previously studied by E23	25
Spectroscopically confirmed runaways	13
D ⁶ stars	10
LP 40-365 stars	3
False positives	79
WDs and hot subdwarfs	45
Main-sequence stars	20
Blends and wide binaries	14

NOTE. — Confirmed runaways are classified based on follow-up spectroscopy. False positives are candidates rejected through our follow-up, archival spectra, or inspection of the *Gaia* astrometry. A detailed log is provided in Table 4.

by blending; in others, the companion is distant enough that blending is unlikely to be very important. The high accelerations involved in launching hypervelocity runaways would unbind any wide binaries. These sources are marked “WB” in Table 4 and were not followed-up.

3.4. Results

Table 1 summarizes our classifications. The sample of 92 candidates yields 13 confirmed thermonuclear SN runaways and 79 false positives. Seven of the confirmed runaways were already recovered by E23, including six objects discovered in that work and one previously discovered by Shen et al. (2018b). Three of the remaining six are new discoveries, while the other three were discovered by Shen et al. (2018b) and Raddi et al. (2019) but not recovered by E23.

Figure 1 shows basic properties of sources in both groups. Both false positives and confirmed runaways are found primarily at high latitude relative to the bulk of the *Gaia* catalog; this is mainly due to our requirement of $G_{BP} - G_{RP} < 0.5$, which sets an effective maximum extinction of $A_V \lesssim 2$ mag. Confirmed runaways are still found at lower latitude on average than false positives, reflecting the fact that they are launched primarily from the Galactic disk and remain bright for at most a few Myr (Section 6). In contrast, most of the false positives are halo stars, which are distributed more isotropically.

The false positives separate into two broad groups in color-magnitude space. The bright group is dominated by A- and F-type main-sequence stars with well-measured positive parallaxes and tangential velocities just above the 600 km s^{-1} threshold. These objects are likely metal-poor halo stars or main-sequence binary runaways. The faint group is dominated by WDs and faint halo stars with large parallax uncertainties. Noisy parallaxes can scatter ordinary halo objects in this group into the high- $v_{\perp}$ selection, and such contaminants become increasingly prevalent at faint magnitudes.

Confirmed runaways have systematically larger absolute RVs than false positives, though some still have RVs close to zero. All the LP 40-365 stars detected by our search have $|RV| < 100 \text{ km s}^{-1}$; this reflects the fact that LP 40-365 stars are ejected with typical velocities of $\sim 600 \text{ km s}^{-1}$, so any sources satisfying our cut of $v_{\perp} > 600 \text{ km s}^{-1}$ (Section 6) must necessarily have low RVs. We can approximately estimate the fraction of sources missed due to our tangential velocity cut as follows. For randomly oriented trajectories, the ratio

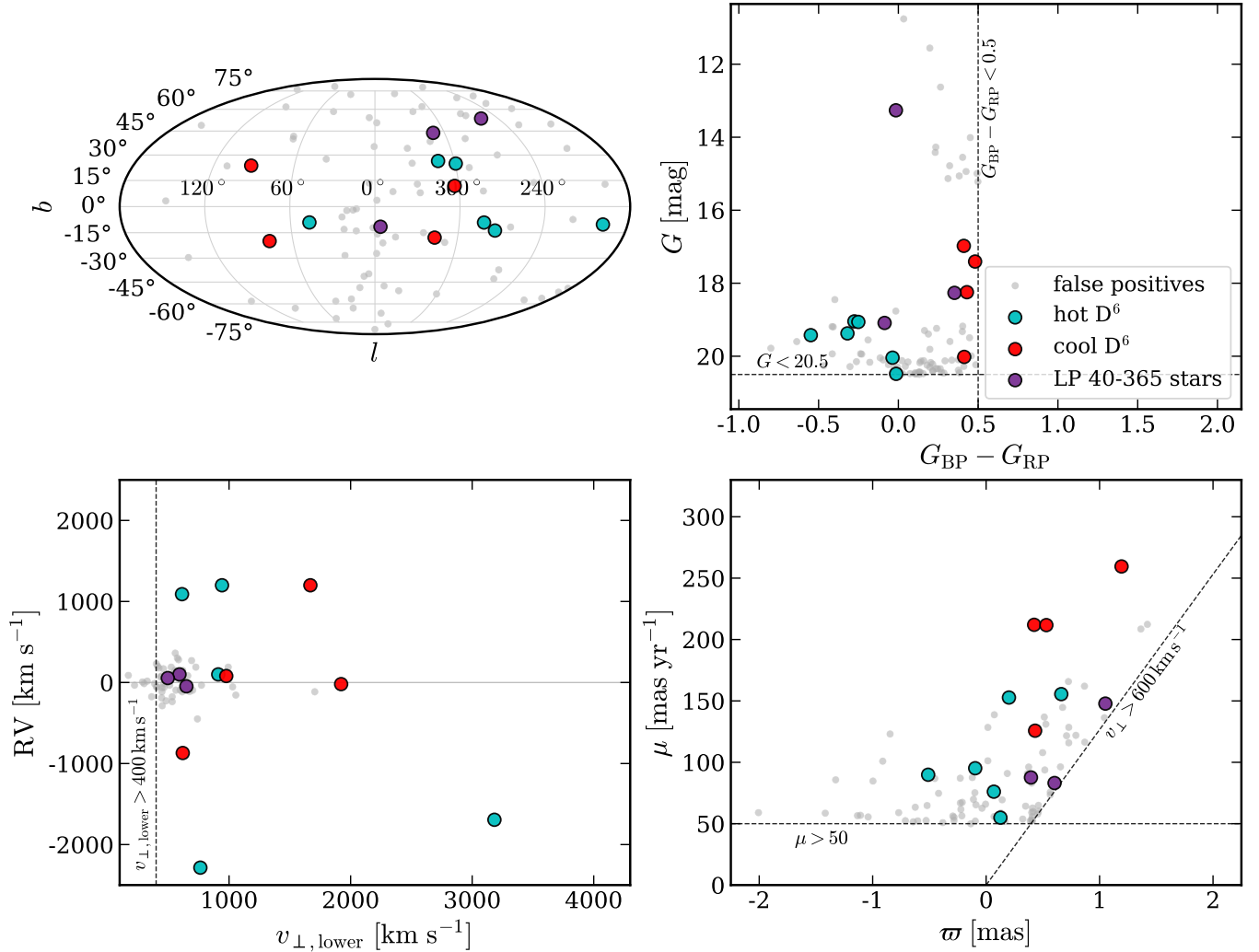


FIG. 1.— Basic properties of the 92 candidates returned by our *Gaia* search. Gray points show false positives, while colored points show different classes of spectroscopically confirmed runaways: hot D⁶ stars (cyan), cool D⁶ stars (red), and LP 40-365 stars (purple). Panels show sky positions, the *Gaia* color–apparent magnitude diagram, radial velocity as a function of the 1σ tangential-velocity lower limit $v_{\perp, \text{lower}} = 4.74\mu/(\varpi + \sigma_{\varpi})$, and the parallax–proper-motion plane. The RV panel includes only sources with measured RVs. Dashed black lines show our selection cuts on color, magnitude, proper motion, and tangential velocity. The confirmed runaways are found at lower Galactic latitudes, brighter apparent magnitudes, and higher RV amplitudes. The LP 40-365 stars are found at lower velocities than the D⁶ stars.

$x = v_{\perp}/v_{3D}$ is distributed as $p(x) = x/\sqrt{1-x^2}$ (Notale & Chamaraux 2018). This implies that populations with true velocities of 650, 1000, and 2000 km s⁻¹ would have approximately 62%, 20%, and 5% of their members with $v_{\perp} < 600 \text{ km s}^{-1}$, respectively. This simplified estimates neglects effects of Galactic rotation and our additional cut on $v_{\perp, \text{lower}}$, but the basic conclusion is that projection effects will cause our search to miss only a small fraction of high-velocity D⁶ stars, but an order-unity fraction of lower-velocity LP 40-365 stars. We refer to Raddi et al. (2019) for further discussion of this issue.

A few candidates – all of which turned out to be false positives – have $v_{\perp, \text{lower}} < 400 \text{ km s}^{-1}$ in the lower-left panel; these are sources with negative measured parallaxes, which satisfy the final “or parallax < 0” branch of the ADQL query.

4. NEW DISCOVERIES

Our search yielded three new D⁶ stars, whose properties we discuss below.

4.1. J1251-5059

J1251-5059 (*Gaia* DR3 6078434976557457536) is a cool D⁶ star with a spectrum very similar to the three cool D⁶ stars discovered by Shen et al. (2018b). We first identified the source as a likely D⁶ star based on a SOAR spectrum and subsequently obtained higher-resolution spectra with GMOS and X-shooter.

The source’s zeropoint-corrected *Gaia* DR3 parallax, $\varpi = 0.45 \pm 0.53$, is not particularly constraining, but it rules out distances $d < 1.0 \text{ kpc}$ ($d < 0.7 \text{ kpc}$) at the 1σ (2σ) level. The 3D dust map of Wang et al. (2025) predicts $E(B - V) = 0.15 \pm 0.02$ across this distance range, while the Schlegel et al. (1998) map predicts $E(B - V) = 0.18$ at infinity. The best-fit intrinsic color of $(G_{BP} - G_{RP})_0 = 0.20 \pm 0.10 \text{ mag}$ is slightly bluer than the three D⁶ stars from Shen et al. (2018b), but the

source’s color is consistent with the colors of all three systems within 2σ . The color uncertainty is dominated by photon noise.

The three cool D⁶ stars from Shen et al. (2018b) – which have better-constrained parallaxes than J1251-5059 – have intrinsic *G*-band absolute magnitudes ranging from 7.2 to 5.8. Requiring J1251-5059 to fall within this absolute magnitude range would require a distance between 3.0 and 5.7 kpc, while any distance below 3.0 kpc would make J1251-5059 the least luminous cool D⁶ star discovered so far.

Comparing the X-shooter spectrum to Kurucz models, we measure an RV of $-870 \pm 5 \text{ km s}^{-1}$. The source’s proper motion implies a tangential velocity $v_{\perp} = 1788 \text{ km s}^{-1} \times [d/(3 \text{ kpc})]$. Although the source’s total velocity is uncertain, it thus seems likely that it has a total velocity of $\gtrsim 1500 \text{ km s}^{-1}$. Our kinematic modeling (Section 5) leads to an inferred ejection velocity of $1508^{+838}_{-413} \text{ km s}^{-1}$.

In Figure 2, we compare the X-shooter spectrum of J1251-5059 to an X-shooter spectrum of the star D6-1. That spectrum was obtained on July 11, 2018 (program 0101.C-0646), and will be subject to a detailed abundance analysis in future work. Both spectra are shifted to rest frame. We have rescaled the spectrum of D6-1 by a factor of 0.1 so that the fluxes of the two sources are on the same scale; this corresponds to moving D6-1 to a 3.16 times larger distance at fixed radius.

The spectrum of J1251-5059 is very similar to that of D6-1. Both stars have spectra dominated by metal lines, including Mg, Si, Ca, O, and Na. The objects’ similar spectra suggest that they have both similar atmospheric parameters and compositions. The most important difference between the two objects’ spectra is in the strength of two broad absorption features near 4700 and 5150 Å. These are very likely the Swan bands due to molecular carbon (C₂), which are often observed in the spectra of cool WDs with carbon in their atmospheres (e.g. Schmidt et al. 1995). As discussed by Werner et al. (2024a) and Hollands et al. (2025), the ratio of carbon to oxygen in the atmospheres of known D⁶ stars varies by an order of magnitude. Systems with higher carbon abundances have stronger C₂ bands, implying that J1251-5059 contains less carbon relative to oxygen than D6-1.

J1251-5059 was flagged as a variable star by the *Gaia* DR3 variability processing pipeline (Eyer et al. 2023). We retrieved the source’s *G*-band light curve from the DR3 DataLink server. It contains 49 usable flux measurements taken over a period of 998 d. The source appears variable at the 0.1 mag level, with scatter of about twice the amplitude of the typical per-epoch uncertainties. This variability is reminiscent of the rotational modulation observed in D6-2 (Chandra et al. 2022). We are unable to unambiguously identify a variability period from the light curve, but it may be possible to identify a rotation period for the source with a light curve from *Gaia* DR4 or Rubin/LSST.

4.2. J0812-5943

J0812-5943 (*Gaia* DR3 5290552672404889984) is a blue D⁶ star with a spectrum more similar to the hot objects discovered by E23 than to the cool objects from Shen et al. (2018b). We identified the source as a promising

candidate from a SOAR spectrum and subsequently obtained several higher-SNR spectra with GMOS.

The source’s zeropoint-corrected *Gaia* DR3 parallax, $\varpi = -0.40 \pm 0.57$, favors large distances; $d < 1.6 \text{ kpc}$ is ruled out at the 2σ level. The 3D dust map of Wang et al. (2025) predicts $E(B - V) = 0.17 \pm 0.02$ across 1.5 – 5 kpc, while the Schlegel et al. (1998) map predicts $E(B - V) = 0.20$ at infinity. These predictions lead to a predicted intrinsic color of $(G_{\text{BP}} - G_{\text{RP}})_0 \approx -0.25 \pm 0.23$, with the uncertainty dominated by shot noise in the BP and RP fluxes.

Among the currently known D⁶ stars, the spectrum of J0812-5943 is most similar to J0927-6335, a source with an inferred absolute magnitude of $6 \lesssim M_{G,0} \lesssim 7$ (E23). J0812-5943 would fall in this absolute magnitude range for distances of 4 – 6 kpc. At these distances, the source’s proper motion implies a tangential velocity $v_{\perp} = 1704 \text{ km s}^{-1} \times [d/(4 \text{ kpc})]$. We measure a radial velocity of $-1210 \pm 10 \text{ km s}^{-1}$. These velocities are again suggestive of a high space velocity of order 2000 km s^{-1} but are subject to significant uncertainties due to the source’s poorly constrained parallax. Our kinematic modeling (Section 5) leads to an inferred ejection velocity of $1924^{+674}_{-459} \text{ km s}^{-1}$.

To obtain rough constraints on the source’s temperature and surface gravity, we compared the spectrum of J0812-5943 to the C/O-dominated atmosphere models calculated by E23 for hot D⁶ stars. Those models were computed with the Kurucz ATLAS/SYNTH machinery, using hydrogen-free, C/O-rich compositions with enhanced metal abundances motivated by the observed spectra of D⁶ stars. E23 calculated a library of models spanning effective temperatures $15,000 < T_{\text{eff}}/\text{K} < 150,000$ and surface gravities $6 < \log [g/(\text{cm s}^{-1})] < 8$; J0812-5943 is best-matched by the model with $T_{\text{eff}} = 49,000 \text{ K}$ and $\log [g/(\text{cm s}^{-1})] = 7.4$.

Figure 3 compares the coadded GMOS spectrum to this model. The right panel shows the RV constraint from the individual exposures and from a joint analysis of all exposures. The model contains most of the strong lines present in the observed spectrum, allowing a robust measurement of the star’s RV and supporting our classification of it as a hot D⁶ star. The star is very likely cooler than J0927-6335 – the source’s closest spectral cousin among the currently known D⁶ stars – because its O III and C III lines are significantly stronger relative to O IV and C IV. For J0927-6335, Werner et al. (2024a) found $T_{\text{eff}} = 60,000 \text{ K}$.

We adopt $T_{\text{eff}} = 49,000 \text{ K}$ as our best estimate of the star’s temperature, but this should be interpreted with caution until a full analysis with bespoke atmospheric models is possible. Our Kurucz atmosphere models are suitable for identifying the dominant species and measuring RVs, but they are LTE models computed with a code that is not well tested for sources with atmospheric parameters and compositions like the hot D⁶ stars. It is clear from Figure 3 that the model is an imperfect fit to the data. This was also true for the objects studied by E23 and likely reflects both limitations of the model spectra and a mismatch between the true and assumed abundance patterns. We also experimented with fitting the spectrum with NLTE models produced with the TMAP code (see Section 4.3), but we found that the

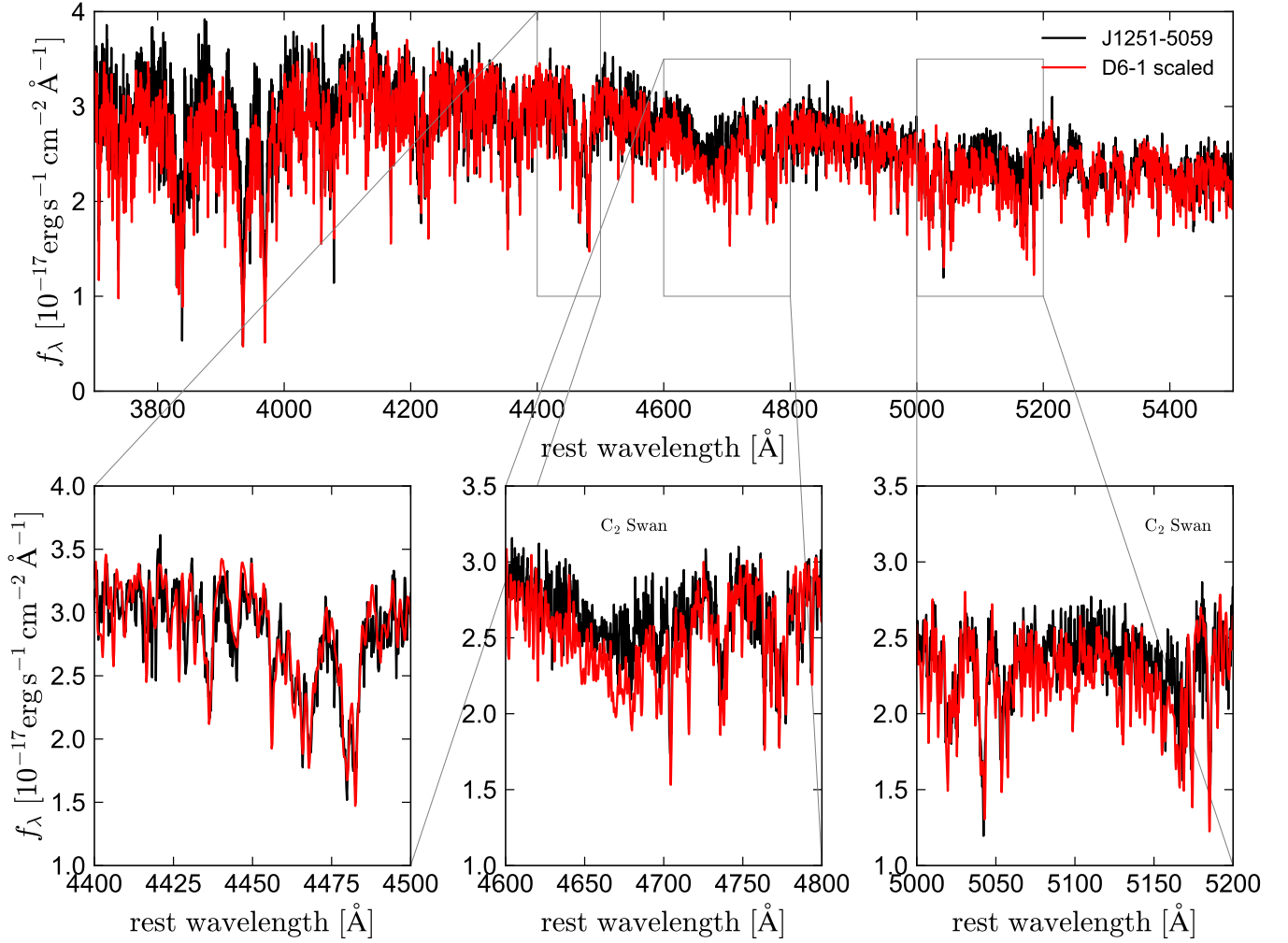


FIG. 2.— Comparison of the X-shooter spectra of J1251-5059, a new D⁶ star discovered by our search (black) and D6-1, a brighter and nearer source discovered by Shen et al. (2018b). The spectrum of D6-1 is multiplied by 0.1 so that the flux scales of the two sources are consistent. Overall, the two stars have extremely similar spectra after this rescaling, indicating that they have similar temperatures and surface compositions. However, there are two broad absorption features that are significantly deeper in D6-1 than in J1251-5059. These are likely Swan bands due to molecular carbon, implying that J1251-5059 has a lower carbon abundance than D6-1.

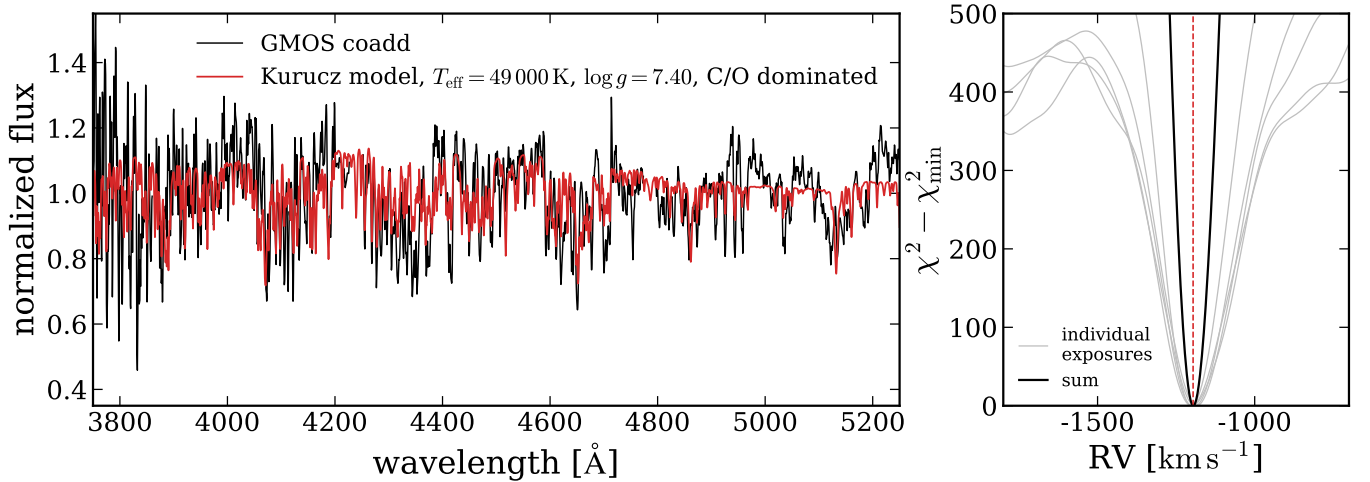


FIG. 3.— GMOS spectrum and RV constraints for J0812-5943, a new hot D⁶ star discovered by our search. Left: coadded, normalized GMOS spectrum (black) compared to a normalized Kurucz model with $T_{\text{eff}} = 49,000$ K, $\log g = 7.40$, and a C/O-dominated composition (red). Right: $\chi^2 - \chi_{\text{min}}^2$ as a function of radial velocity. Gray curves show the individual exposures, while the black curve shows their sum. The best-fit radial velocity is $RV = -1210 \pm 10 \text{ km s}^{-1}$.

Kurucz code produces a significantly better fit for this star, likely because the line list used for the TMAP analysis lacks many of the O III and O IV lines present in the Kurucz model.

4.3. J1949+0745

J1949+0745 (*Gaia* DR3 4298029440184716160) is another hot D⁶ star. The source’s zeropoint-corrected *Gaia* DR3 parallax, $\varpi = 0.20 \pm 0.59$, favors large distances, ruling out $d < 1.3$ kpc ($d < 0.7$ kpc) at the 1σ (2σ) level. The 3D dust map of Wang et al. (2025) predicts $E(B - V) = 0.25 \pm 0.01$ across $1.5 - 5$ kpc, while the Schlegel et al. (1998) map predicts $E(B - V) = 0.27$ at infinity. These predictions lead to a predicted intrinsic color of $(G_{\text{BP}} - G_{\text{RP}})_0 \approx -0.37 \pm 0.12$, consistent with the Rayleigh-Jeans tail of a hot star. The source’s proper motion implies a tangential velocity $v_{\perp} = 2172 \text{ km s}^{-1} \times [d / (3 \text{ kpc})]$. The RV is relatively low, with a best-fit value of $\text{RV} = 100 \pm 20 \text{ km s}^{-1}$.

Figure 4 shows the LRIS spectrum of J1949+0745, coadded across three exposures. The spectrum resembles that of a PG 1159 star, being dominated by lines of C IV and He II (e.g. Werner & Herwig 2006). Among the known sample of D⁶ stars, it is most similar to J0927-6335. It is likely hotter than J0812-5943, with stronger C IV relative to C III. Unlike J0927-6335 and J0812-5943, it also shows He lines.

Figure 4 compares the normalized spectrum to a NLTE atmosphere model calculated with TMAP (Werner et al. 2003). The model is He-dominated (He = 0.58, C = 0.25, O = 0.17, mass fractions), with $T_{\text{eff}} = 65,000 \text{ K}$, $\log g = 8.5$.

Cooler models produce He I lines that are too strong (the strongest being He I $\lambda 5876 \text{ \AA}$), while hotter models lose the observed C III features. Lower surface gravities overpredict the cores of the higher He II series lines.

The strongest tension in this model is in the C IV features near $4440 \text{ \AA}$ and $5802/5812 \text{ \AA}$, which are stronger than observed. Reducing the carbon abundance could improve those lines but would underpredict the C-rich absorption trough near $4650\text{--}4660 \text{ \AA}$. There is evidence for oxygen: The strongest feature predicted by the model is a O III line blend around $3750 \text{ \AA}$, but it is not strong enough to fit the observation. Models with higher O abundances or lower temperatures would fit this feature better. However, higher O abundances cause other O III lines to become too strong (in particular $\lambda 3962 \text{ \AA}$), while lower temperatures lead to a poorer fit to the He I lines. The spectrum therefore suggests that J1949+0745 may be a He-dominated PG 1159 star, perhaps representing systems like the source J1332-3541 (Werner et al. 2024a) but with a different mass or evolutionary phase. Test models show that the hydrogen abundance in J1949+0745 must be lower than 10 %, otherwise the H β /He II $\lambda 4860$ line blend would be significantly too strong in the model. We consider it unlikely that J1949+0745 is an ordinary PG 1159 star with an underestimated parallax, because a normal WD with the star’s parameters would have already crossed the wind limit and transitioned to become a DO WD (e.g. Unglaub & Bues 2000; Bédard et al. 2022; Mackensen et al. 2025).

5. KINEMATIC MODELING

We jointly infer distances, velocities, and kinematic ages of all objects discovered by our search, and for other D⁶ and LP 40-365 stars from the literature, following the procedure described by E23. For each source, we sample the posterior over absolute magnitude, proper motion, and RV using the measured *Gaia* astrometry, RV, their uncertainties, and the *Gaia* astrometric covariance matrix; we also apply the *Gaia* parallax zeropoint correction. Our fiducial distance prior is flat in absolute magnitude, M_G . This is equivalent to a distance prior $p(d) \propto 1/d$, downweighting large distances and velocities. We also adopt a prior that the total ejection velocity cannot exceed 3000 km s^{-1} . Sensitivity to the adopted distance prior is explored by E23. For US 708, we adopt a Gaussian distance prior of $d = 8.5 \pm 1 \text{ kpc}$ following Geier et al. (2015).

For each posterior sample, we transform the heliocentric phase-space coordinates to a Galactocentric frame and compute the current height above the Galactic plane and total velocity. We then integrate the orbit in the MWPotential2014 Galactic potential using galpy (Bovy 2015). This is an improvement over the treatment of E23, who neglected the gravitational potential and assumed straight-line orbits. We integrate backward or forward in time, depending on the sign of the initially inferred midplane-crossing time, and identify the most recent or next crossing of the disk midplane. We define the ejection velocity, v_{ejection} , by subtracting the local circular velocity of the Galactic potential at this crossing. For most objects, this potential-integrated treatment changes the inferred ejection velocity and midplane-crossing time only modestly relative to the straight-line approximation used by E23, but the difference is non-negligible for the longest flight-time systems. Most notably, the inferred ejection velocity of US 708 increases from $743^{+19}_{-15} \text{ km s}^{-1}$ when the potential is neglected to $802^{+14}_{-13} \text{ km s}^{-1}$ when it is accounted for.

Table 2 reports the results of applying this modeling to all known high-velocity runaways likely associated with thermonuclear supernovae. We discuss the population further in Section 5.2.

5.1. Newly discovered objects

J0812-5943 has an inferred distance of $d = 3.68^{+1.91}_{-1.64} \text{ kpc}$. Accounting for extinction, this corresponds to $M_{G,0} \approx 7.2$, with an uncertainty of about 1 mag dominated by the distance uncertainty. This places it at the faint end of the hot D⁶ population, likely with a lower luminosity than J0927-6335 and J0546+0836. Its inferred 3D velocity is $v_{\text{tot}} = 2144^{+659}_{-446} \text{ km s}^{-1}$, and its inferred ejection velocity is $v_{\text{ejection}} = 1924^{+674}_{-459} \text{ km s}^{-1}$, reflecting a likely boost of $\sim 220 \text{ km s}^{-1}$ due to Galactic rotation. J0812-5943 is below the midplane ($z = -0.86^{+0.39}_{-0.45} \text{ kpc}$) and moving away from it. It has a well-constrained midplane crossing time of $t_{\text{midplane}} = 1.09^{+0.42}_{-0.12} \text{ Myr}$.

J1949+0745 has a fiducial distance of $d = 2.15^{+1.26}_{-0.93} \text{ kpc}$, implying $M_{G,0} \approx 7.7$. It is therefore similarly luminous to J0812-5943 and J1332-3541. We infer a total velocity of $v_{\text{tot}} = 1733^{+912}_{-657} \text{ km s}^{-1}$ and ejection velocity $v_{\text{ejection}} = 1529^{+913}_{-657} \text{ km s}^{-1}$, both with large uncertainties dominated by distance uncertainty. J1949+0745 is below the midplane ($z = -0.32^{+0.15}_{-0.20} \text{ kpc}$) and moving

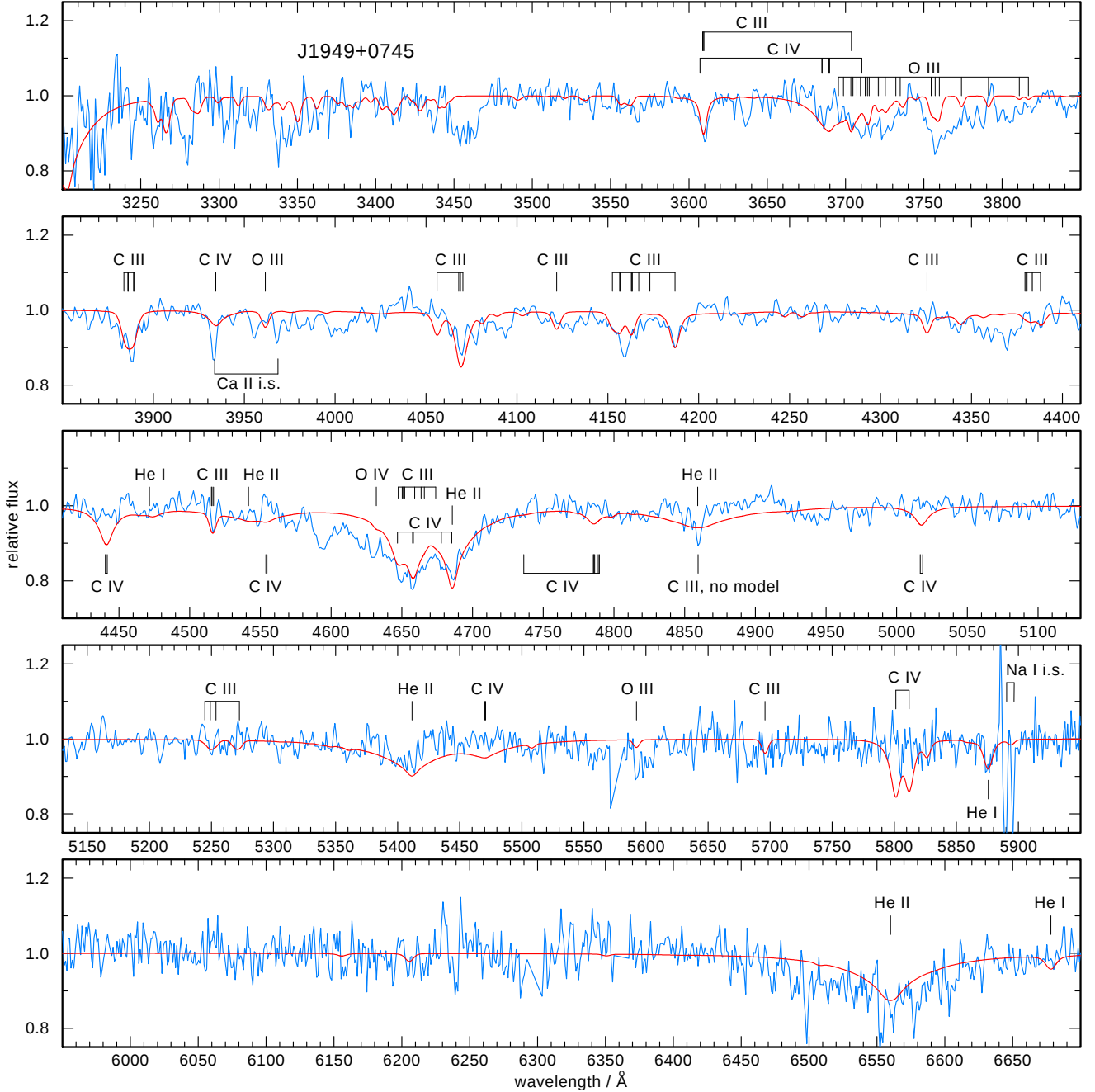


FIG. 4.— Normalized spectrum of J1949+0745 compared to a He-dominated NLTE atmosphere model calculated with TMAP. The model has $T_{\text{eff}} = 65,000$ K, $\log g = 8.5$, and abundances He = 0.58, C = 0.25, and O = 0.17 (mass fractions). It reproduces most of the strongest lines, supporting classification of J1949+0745 as a hot D⁶ star, but the model does not fully match all features in the spectrum. In particular, the C IV lines near 4440 Å and 5802/5812 Å are stronger in the model than in the data.

away from it. It has a well-constrained midplane crossing time of $1.86^{+0.09}_{-0.16}$ Myr. Its likely launch site is in the disk, of order 5 kpc from the Galactic center.

J1251-5059 has a fiducial distance of $d = 2.16^{+1.67}_{-1.00}$ kpc, corresponding to $M_{G,0} \approx 7.9$ after extinction correction. This implies a lower luminosity than the three cool D⁶ stars from Shen et al. (2018b), consistent with the expectation from Section 4 that J1251-5059 is likely the least

luminous known member of the cool D⁶ sequence. Its inferred total velocity is $v_{\text{tot}} = 1563^{+826}_{-364}$ km s⁻¹, and its inferred ejection velocity is $v_{\text{ejection}} = 1508^{+838}_{-413}$ km s⁻¹. Unlike J0812-5943 and J1949+0745, J1251-5059 is above the Galactic plane and moving nearly parallel to it. At a distance of $z = 0.46^{+0.34}_{-0.20}$ kpc above the midplane, its formal travel time to the disk is $-4.11^{+2.48}_{-11.32}$ Myr. This

Name	<i>Gaia</i> DR3 Source ID	G [mag]	$G_{BP} - G_{RP}$ [mag]	RV [km s ⁻¹]	d [kpc]	v_{tot} [km s ⁻¹]	$v_{ejection}$ [km s ⁻¹]	z [kpc]	$t_{midplane}$ [Myr]
Suspected D ⁶ stars									
D6-1	5805243926609660032	17.4	0.48	1200 ± 40	1.91 ^{+0.29} _{-0.22}	2045 ⁺²⁵⁵ ₋₁₉₀	2260 ⁺²⁵³ ₋₁₈₉	-0.57 ^{+0.07} _{-0.09}	0.63 ^{+0.04} _{-0.04}
D6-2	1798008584396457088	17.0	0.41	80 ± 10	0.84 ^{+0.59} _{-0.04}	1152 ⁺⁶² ₋₅₃	1059 ⁺⁶² ₋₅₆	-0.27 ^{+0.02} _{-0.02}	-0.72 ^{+0.01} _{-0.01}
D6-3	2156908318076164224	18.2	0.43	-20 ± 80	2.25 ^{+0.36} _{-0.36}	2237 ⁺³⁵⁹ ₋₃₅₄	2402 ⁺³⁹⁵ ₋₃₉₀	0.93 ^{+0.14} _{-0.14}	2.22 ^{+0.19} _{-0.16}
J1235	6156470924553703552	19.0	-0.28	-1694 ± 10	4.07 ^{+1.01} _{-1.18}	2672 ⁺³⁴⁰ ₋₃₄₈	2471 ⁺³⁵³ ₋₃₄₅	1.73 ^{+0.42} _{-0.49}	1.87 ^{+0.83} _{-0.25}
J0927	5250394728194220800	19.4	-0.32	-2285 ± 20	4.60 ^{+2.20} _{-1.77}	2764 ⁺²⁷⁸ ₋₁₅₇	2560 ⁺²⁸⁹ ₋₁₆₈	-0.71 ^{+0.28} _{-0.35}	-1.34 ^{+0.42} _{-0.42}
J0546	3335306915849417984	19.1	-0.25	1200 ± 20	4.12 ^{+2.23} _{-1.77}	1725 ⁺⁶⁷² ₋₄₁₄	1886 ⁺⁶⁷⁷ ₋₄₃₅	-0.71 ^{+0.31} _{-0.39}	0.61 ^{+0.05} _{-0.08}
J1332	6164642052589392512	19.4	-0.55	1090 ± 50	1.64 ^{+1.23} _{-0.69}	1474 ⁺⁷⁶⁴ ₋₃₃₉	1632 ⁺⁷³⁵ ₋₃₃₁	0.75 ^{+0.54} _{-0.31}	0.64 ^{+0.14} _{-0.14}
J1251	6078434976557457536	20.0	0.41	-870 ± 5	2.16 ^{+1.67} _{-1.00}	1563 ⁺⁸²⁶ ₋₃₆₄	1508 ⁺⁸³⁸ ₋₄₁₃	0.46 ^{+0.34} _{-0.20}	-4.11 ^{+2.48} _{-11.32}
J0812	5290552672404889984	20.5	-0.01	-1210 ± 10	3.68 ^{+1.91} _{-1.64}	2144 ⁺⁶⁵⁹ ₋₄₄₆	1924 ⁺⁶⁷⁴ ₋₄₅₉	-0.86 ^{+0.39} _{-0.45}	1.09 ^{+0.42} _{-0.12}
J1949	4298029440184716160	20.0	-0.04	100 ± 20	2.15 ^{+1.26} _{-0.93}	1733 ⁺⁹¹² ₋₆₅₇	1529 ⁺⁹¹³ ₋₆₅₇	-0.32 ^{+0.15} _{-0.20}	1.86 ^{+0.09} _{-0.16}
J1637	1327920737357113088	20.3	-0.13	384 ± 6	3.10 ^{+3.17} _{-1.62}	1188 ⁺⁹⁴⁰ ₋₄₀₇	1058 ⁺¹¹⁵⁵ ₋₄₄₅	2.09 ^{+2.11} _{-1.08}	3.67 ^{+1.07} _{-1.21}
Suspected LP 40-365 stars									
LP 40-365	1711956376295435520	15.6	0.23	498 ± 5	0.61 ^{+0.01} _{-0.01}	837 ⁺⁶ ₋₆	627 ⁺⁵ ₋₅	0.43 ^{+0.01} _{-0.01}	4.66 ^{+0.33} _{-0.29}
J1603	5822236741381879040	17.8	0.16	-480 ± 5	2.08 ^{+0.48} _{-0.33}	835 ⁺⁶² ₋₃₉	605 ⁺⁷¹ ₋₄₂	-0.35 ^{+0.06} _{-0.09}	1.56 ^{+0.12} _{-0.10}
J0905	688380457508503040	19.6	0.24	300 ± 50	4.60 ^{+7.43} _{-2.84}	536 ⁺¹⁰⁹⁹ ₋₂₈₅	660 ⁺¹⁰⁶⁸ ₋₂₂₇	2.97 ^{+4.76} _{-1.82}	-13.63 ^{+29.14} _{-12.78}
J1825	6727110900983876096	13.3	-0.02	-47 ± 5	0.95 ^{+0.03} _{-0.02}	429 ⁺¹⁹ ₋₁₇	668 ⁺¹⁹ ₋₁₇	-0.17 ^{+0.01} _{-0.01}	1.59 ^{+0.02} _{-0.02}
J1311	3507697866498687232	18.3	0.35	55 ± 10	1.87 ^{+1.07} _{-0.50}	949 ⁺⁴²² ₋₁₉₅	809 ⁺⁴⁵⁴ ₋₂₁₁	1.31 ^{+0.74} _{-0.35}	3.83 ^{+0.20} _{-0.20}
J1109	3804182280735442560	19.1	-0.09	100 ± 10	2.84 ^{+2.30} _{-1.19}	1357 ⁺⁹⁴⁹ ₋₄₉₃	1155 ⁺⁹⁸³ ₋₄₈₉	2.31 ^{+1.84} _{-0.96}	3.88 ^{+0.28} _{-0.37}
J1022	5446737753669901568	19.0	-0.22	-390 ± 20	7.52 ^{+7.25} _{-4.00}	1300 ⁺⁹⁴⁵ ₋₄₅₀	1208 ⁺⁹⁹⁷ ₋₅₁₉	2.50 ^{+2.39} _{-1.32}	2.79 ^{+0.53} _{-0.19}
J1240	1682129610835350400	18.4	-0.29	-177 ± 10	0.42 ^{+0.02} _{-0.02}	240 ⁺²¹ ₋₁₉	395 ⁺¹⁷ ₋₁₆	0.35 ^{+0.02} _{-0.02}	-13.30 ^{+3.57} _{-5.36}
Suspected runaway helium star donors									
US 708	815106177700219392	18.9	-0.44	835 ± 10	8.38 ^{+1.02} _{-0.99}	920 ⁺¹³ ₋₁₂	802 ⁺¹⁴ ₋₁₃	6.17 ^{+0.75} _{-0.73}	12.51 ^{+2.00} _{-1.85}

TABLE 2

Known high-velocity objects suspected to be runaways from thermonuclear supernovae. Uncertainties are 1σ (middle 68%). Distances and velocities are inferred with a flat- M_G prior. We distinguish between v_{tot} , the current 3D space velocity in a Galactocentric frame, and $v_{ejection}$, the assumed velocity with which the star was launched, assuming it was on a circular orbit in the Galactic disk at the time. $t_{midplane} = z/v_z$ represents the time since the most recent midplane crossing. Objects in bold are new discoveries. We also list previously known D⁶ stars (Shen et al. 2018b) and LP 40-365 stars (Raddi et al. 2019), as well as the one known high-velocity helium star US 708 (Geier et al. 2015).

prevents a reliable kinematic measurement of the star’s age.

5.2. The known thermonuclear-runaway population

Figure 5 shows basic observed and inferred properties of all the objects in Table 2. The three new discoveries presented in this work are marked with black outlines. There are now 20 suspected runaways from thermonuclear SNe, including 11 D⁶ stars, 8 LP 40-365 stars, and one runaway sdB. The sample of D⁶ stars includes the ten objects recovered by our search as well as the D⁶ star J1637 discovered by Raddi et al. (2019) and recently characterized by Hollands et al. (2025). The sample of LP 40-365 stars includes three objects recovered by our search (J1311, J1109, and J1825), as well as LP 40-365 itself (Vennes et al. 2017), J1603 and J0905 (Raddi et al. 2019), J1022 (Bhat et al. 2026a), and J1240 (Kepler et al. 2016; Gänsicke et al. 2020).

We also include US 708, the only confirmed hypervelocity hot subdwarf, in Table 2 and Figure 5. As described in Appendix A, reanalysis of archival and new Keck/ESI spectra gives an updated RV of 835 ± 10 km s⁻¹, lower than the value of 917 ± 7 km s⁻¹ reported by Geier et al. (2015). With this RV, we infer an ejection velocity of 802^{+14}_{-13} km s⁻¹, bringing US 708 in better agreement with expectations for a helium star donor runaway (e.g. Bauer et al. 2019; Rajamuthukumar et al. 2025).

In the CMD, all sources except J1240 fall between the WD cooling track and the main sequence, with absolute magnitudes $9 \lesssim M_{G,0} \lesssim 3$ and colors $(G_{BP} - G_{RP})_0 <$

0.5. The sources’ blue colors are in part due to selection effects, since our search used an explicit cut of $bp_{rp} < 0.5$. However, removing this cut and considering only sources with well-constrained parallaxes still yields only blue sources (e.g. Shen et al. 2018b), implying that red hypervelocity runaways are rarer than their blue counterparts at fixed optical luminosity. Consistent with this interpretation, the sources discovered by Raddi et al. (2019) through a color-blind search of SDSS spectra also satisfy $(G_{BP} - G_{RP})_0 < 0.5$.

The upper right panel of Figure 5 shows inferred temperatures and luminosities, with dashed lines showing lines of constant radius. The adopted temperatures are the most recent spectroscopic estimates available in the literature. In cases where no spectroscopic estimate is available (primarily cool D⁶ stars), we estimate temperatures by SED fitting, using the library of C/O-dominated spectral models described by E23. We estimate luminosities by SED fitting, using a spectroscopic temperature prior when spectroscopic temperature estimates exist. We use the distance samples from our kinematic modeling (Section 5).

The population spans at least a factor of ~ 20 in effective temperature and 1000 in luminosity. Most of the observed sources are very likely inflated relative to a mass-radius relation for degenerate objects (although their masses are not well constrained). The only exceptions are J1240, which has $R \approx 0.016 R_\odot$, consistent with predictions for a normal $\approx 0.4 M_\odot$ WD, and perhaps J1332 and J1949, which have poorly constrained distances but

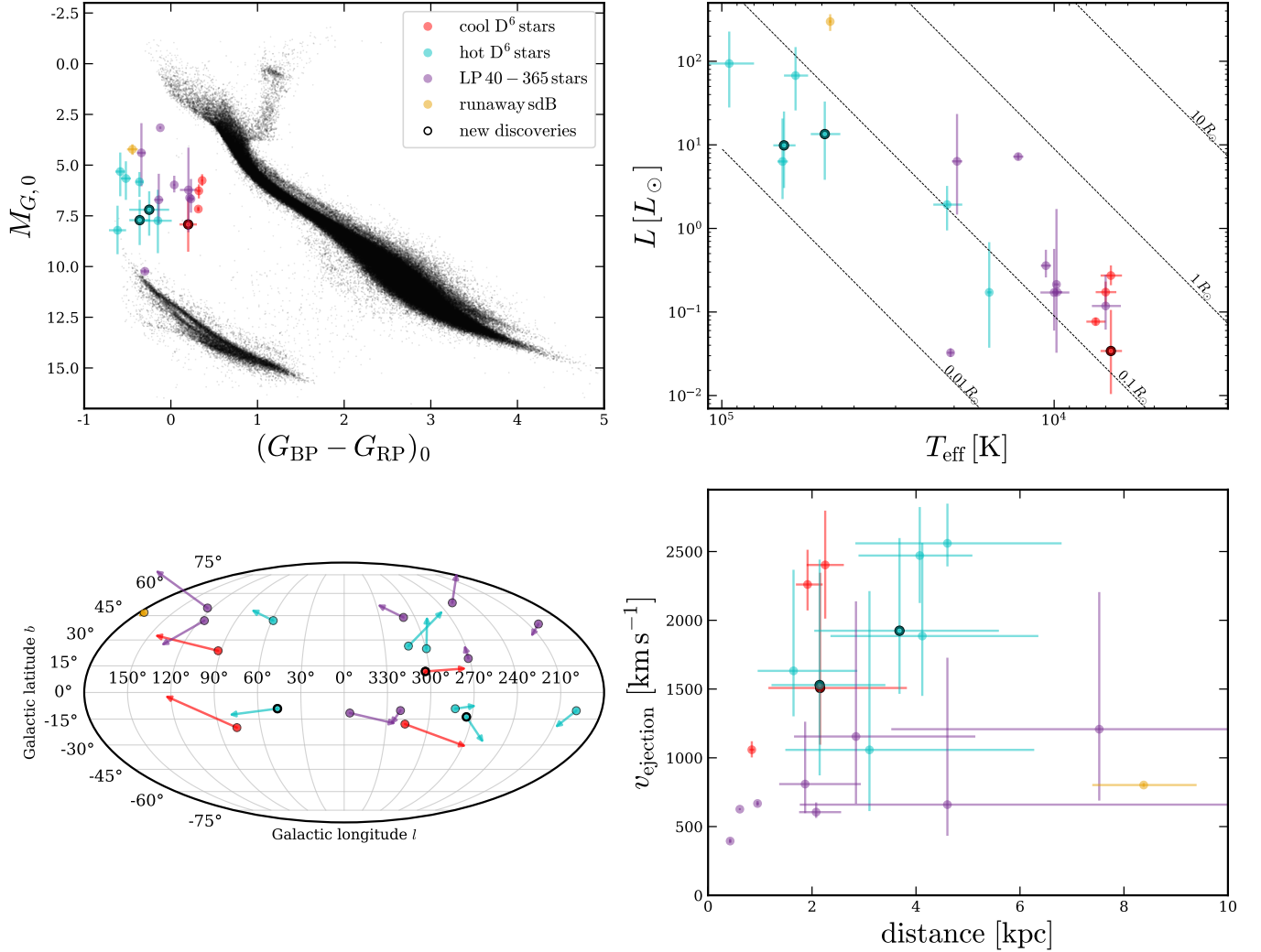


FIG. 5.— Summary of the known population of hypervelocity WDs and related objects. In each panel, we show suspected hot and cool D^6 stars in cyan and red, LP 40-365 stars in purple, and the runaway sdB US 708 in yellow. The three new discoveries presented in this work are shown with a black outline. Top left: color-magnitude diagram, with the *Gaia* 100 pc sample shown for context. Top right: HR diagram. Bottom left: sky distribution. Arrows show proper motions, with length scaled to show motion over 0.7 Myr. Bottom right: inferred distances and ejection velocities.

could have radii of $\lesssim 0.02 R_\odot$ at their closest possible distances. The hot objects are generally more luminous but smaller than the cool ones. Most of the LP 40-365 stars have temperatures intermediate between hot and cool D^6 stars, but two hot D^6 stars – J1637 and J1235 – have temperatures overlapping with the LP 40-365 stars.

The temperature distribution of the known D^6 stars appears bimodal, with one group at $T_{\text{eff}} \lesssim 10,000$ K, another at $T_{\text{eff}} \gtrsim 50,000$ K, and comparatively few objects at intermediate temperatures. Because the sample is still small and heterogeneous, we do not attempt to quantify the significance of the bimodality, but we note that it is unlikely to be a product of our sample selection: our color cuts are sensitive to sources with $T_{\text{eff}} \gtrsim 6,000$ K and should not preferentially remove objects at intermediate temperatures.

The lower left panel of Figure 5 shows the objects’ location in the sky. Arrows show proper motions in angular units. Few objects are found at low Galactic latitudes. As expected, most sources are moving away from the disk. However, some objects in all three classes are mov-

ing towards the disk. Since all the D^6 stars and at least some of the LP 40-365 stars are unbound from the Milky Way, this suggests that the objects are relatively young and were launched from a kinematically warm population. Our simulations in Section 6 suggest a progenitor population with a height of $h_z \approx 0.3$ kpc.

The lower right panel shows inferred distances and ejection velocities. Most D^6 stars have inferred ejection velocities of order 2000 km s^{-1} , while the LP 40-365 stars and US 708 cluster at lower ejection velocities. The two nearest objects are the LP 40-365 stars J1240 and LP 40-365 itself. This suggests that the local space density of LP 40-365 stars is likely higher than that of D^6 stars. It would be a mistake, however, to conclude that LP 40-365 stars have a higher birth rate than D^6 stars: LP 40-365 stars remain detectable for longer, since (a) they have typical ejection velocities ~ 3 times lower than D^6 stars and thus remain detectable longer, and (b) some LP 40-365 stars remain bound to the Milky Way and thus can remain within a plausibly detectable volume indefinitely.

The nearest object, J1240, has an inferred cooling age of ~ 40 Myr (Gänsicke et al. 2020), more than an order of magnitude larger than the kinematically-inferred ages of D⁶ stars.

6. POPULATION MODELING OF D⁶ STARS

Our search for hypervelocity WDs is complete within the selection limits discussed in Section 2. In total, the query detects 10 of the 11 known D⁶ stars in Table 2.² To constrain the intrinsic population of D⁶ stars, we perform Monte Carlo simulations of their birth and evolution and compare these to the population recovered by our search.

6.1. Evolutionary models

Several works have presented long-term evolutionary models for D⁶ stars and other classes of temporarily inflated SN runaways. All the models we consider are 1D calculations performed with MESA (Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023); in several cases, the initial conditions are motivated by 3D hydrodynamic simulations.

The temperatures, luminosities, and evolutionary timescales predicted by these models differ by multiple orders of magnitude. The evolutionary state of the observed stars is not well understood, and so their inferred birth rate depends significantly on the assumed detectable lifetime. We forward-model our survey under the assumption of several different evolutionary models. Comparison of the observed and simulated population constrains the birth rate required to produce the observed population under any one model and can rule out models that make predictions inconsistent with observations. We begin by summarizing the evolutionary models under consideration.

6.1.1. WDs shocked by SN ejecta

Bhat et al. (2025) modeled the evolution of WDs whose outer layers have been inflated by interaction with a SN shock from an exploding companion. Their initial conditions were based on a hydrodynamic double-detonation simulation from Pakmor et al. (2022), in which the accreting WD exploded but the donor survived. Only the outer layers of the surviving donor expand, so these models contract and return to the WD cooling sequence within $\lesssim 10^4$ yrs. Bhat et al. (2025) conclude that these models cannot explain the bulk of the observed population, but propose that they may explain the object J1332.

Wong & Bildsten (2025) calculated related models for surviving helium WDs shocked by SN ejecta, including the effects of mass loss and subsequent thermal relaxation. These models are useful because they provide a set of shocked-donor tracks with lower bound-remnant masses than the models from Bhat et al. (2025). Like the Bhat et al. (2025) tracks, they heat the survivor relatively superficially compared to the fully convective models discussed below, though the lowest-mass models are heated more deeply. They therefore fade rapidly and are primarily detectable at young ages. Given the low initial

² The only known D⁶ star not recovered by our search is J1637 (Hollands et al. 2025): our initial *Gaia* query does not capture it because at $v_{\perp, \text{lower}} = 393 \text{ km s}^{-1}$, it narrowly fails our cut of $v_{\perp, \text{lower}} = 400 \text{ km s}^{-1}$. This object was discovered via a template search in SDSS spectra by Raddi et al. (2019).

donor masses in these models, they are unlikely to produce runaways with velocities larger than $\sim 1600 \text{ km s}^{-1}$.

6.1.2. Fully convective C/O stars

Shen (2025) modeled the evolution of hot, fully convective, C/O-dominated stars. He calculated models with masses ranging from $0.1 M_{\odot}$ to $0.5 M_{\odot}$, as might be produced if a CO WD is partially disrupted and heated during a violent merger. The models contract along an analog of the Hayashi (1961) track until their cores become radiative, after which they heat up and become more luminous, until they eventually become degenerate and evolve down the WD cooling track. Because the cores – not just the outer layers – are heated, the models’ evolutionary timescales are much longer than those of Bhat et al. (2025). Shen (2025) suggested that the low-mass ($\sim 0.1 M_{\odot}$) tracks may be suitable for cool D⁶ stars. He also speculated that the higher-mass tracks might be able to explain hot D⁶ stars, but noted that it would be difficult to heat such a massive (and thus, dense) WD enough for it to become fully convective.

6.1.3. Partially disrupted runaways from violent mergers

We consider two models based on simulations of violent mergers in which the donor WD is partially disrupted but a bound remnant survives. One model is taken from Glanz et al. (2025), who simulated a merger of $0.62 M_{\odot}$ and $0.69 M_{\odot}$ hybrid “HeCO” WDs (i.e., CO WDs with unusually thick He envelopes). In this model, a CO-dominated $0.49 M_{\odot}$ remnant, formed from the partially disrupted donor, is ejected with a velocity of 2061 km s^{-1} . Because the donor is partially disrupted during the merger and is closer to the exploding WD than in models where it barely fills its Roche lobe, the companion’s ejecta is able to shock and heat its deep interior rather than just its surface. Consequently, the remnant cools significantly more slowly than the intact companions such as modeled in Bhat et al. (2025).

We also consider a model from Bhat et al. (2026b), which is based on the violent merger simulation from Pakmor et al. (2025). In this calculation, the merger of a $0.7 M_{\odot}$ and a $1.1 M_{\odot}$ CO WD results in the ejection of a bound remnant with a mass of only $0.16 M_{\odot}$ at a velocity of 2800 km s^{-1} . The remnant is heated during the merger, and Bhat et al. (2026b) show that its long-term evolution may produce low-mass, C/O-rich hypervelocity stars with parameters similar to the cool D⁶ stars, J1637, and J1235.

6.1.4. Partially reheated WDs

Zhang et al. (2019) produced evolutionary models for partially reheated WDs with a range of masses and heating depths. These models were designed to describe survivors of SNe Ia; in this sense, they are likely more applicable to LP 40-365 stars than to D⁶ stars. However, they provide a useful phenomenological comparison set: they varied both mass and a parameter f_{env} , which controls how much of the WD envelope is heated, allowing tracks intermediate between superficial shock heating and the more deeply heated fully convective models. We consider three of these models, all with a mass of $0.3 M_{\odot}$, but with three different values of f_{env} : 0.1, 0.5, and 0.9.

6.2. Forward-model of the Galactic population

We assume a constant Galactic birth rate of D^6 stars, adjusting the rate such that each evolutionary model produces roughly the total number detected by our search (10), or the number of observed runaways that could plausibly be explained by each model. We report this rate relative to the Galactic SNe Ia rate, $\mathcal{R}_{\text{Ia}} \approx 5 \times 10^{-3} \text{ yr}^{-1}$ (e.g. Maoz et al. 2014). We simulate only objects launched within the last 20 Myr, since D^6 stars travel ~ 2 kpc per Myr and thus escape the Galaxy within $\lesssim 10$ Myr.

We sample birth positions from a simple Galactic model consisting of an exponential disk with radial scale length $h_R = 2.6$ kpc and vertical scale height $h_z = 0.3$ kpc, and a spherical bulge component with an exponential density profile of scale length 0.5 kpc (e.g. Bland-Hawthorn & Gerhard 2016). We assume 5% of runaways are launched from the bulge. This implies a specific SNe Ia rate that is ~ 5 times lower in the bulge than in the disk, reflecting the bulge’s old stellar population and the falling delay time distribution of SNe Ia (e.g. Maoz et al. 2012, 2014).

We assume runaways are launched isotropically in the rest frame of the binary. We assume a Gaussian distribution of ejection velocities centered on 2000 km s^{-1} with a dispersion of 500 km s^{-1} . While this is a simplification, our results are only weakly sensitive to the exact launching velocity assumed, as long as most D^6 stars have $v_{\text{ejection}} \gtrsim 1000 \text{ km s}^{-1}$.

We assign disk progenitors the local circular velocity, while bulge progenitors are assigned an isotropic ve-

locity dispersion of 100 km s^{-1} . We then integrate the launched stars in the same MWPotential2014 Galactic potential used for the observed sources using *galpy* (Section 5) to obtain their present-day positions and velocities relative to the Sun. We assign temperatures and luminosities as a function of age using the evolutionary tracks from each model; we calculate absolute magnitudes in the *Gaia* bands using bolometric corrections derived from the Kurucz models for C/O dominated atmospheres with $\log g \approx 6$. We assign extinctions to each object based on the 3D dust map of Wang et al. (2025), assuming a Cardelli et al. (1989) extinction law. For simulated sources beyond the distance limit of the 3D map (typically a few kpc, depending on sightline), we add $A_V = 1 \text{ mag kpc}^{-1}$ for any additional path length while the source remains close to the Galactic disk ($|z| < 1 \text{ kpc}$). We predict parallax and proper motion uncertainties in *Gaia* DR3 as a function of G -band apparent magnitude following the empirical relations reported by Lindegren et al. (2021), and we perturb the mock-observed astrometry according to these uncertainties. We similarly predict G_{BP} and G_{RP} -band flux uncertainties as a function of apparent magnitude in these bands, use these to calculate uncertainties in $G_{\text{BP}} - G_{\text{RP}}$ colors, and perturb the predicted colors by these uncertainties. Finally, we pass the simulated population through the selection function of our search (Section 2.4), marking objects as “detected” if they pass all the cuts in our *Gaia* DR3 ADQL query.

6.3. Results

TABLE 3
Forward-model results for several classes of evolutionary models.

Model	Required birth rate (10 detected stars)	d (kpc)	$M_{G,0}$ (mag)	t_{midplane} (Myr)	G (mag)	$(G_{\text{BP}} - G_{\text{RP}})_0$ (mag)
<i>Shocked donors</i>						
$0.64 M_{\odot}$, Bhat et al. (2025)	$0.11 \mathcal{R}_{\text{Ia}}$	$1.38^{+2.13}_{-0.41}$	$8.98^{+1.02}_{-3.17}$	$0.76^{+1.15}_{-0.87}$	$19.57^{+0.59}_{-1.14}$	$-0.52^{+0.03}_{-0.14}$
$0.85 M_{\odot}$, Bhat et al. (2025)	$0.15 \mathcal{R}_{\text{Ia}}$	$1.41^{+2.77}_{-0.54}$	$7.19^{+3.14}_{-2.49}$	$0.47^{+0.92}_{-0.34}$	$19.15^{+0.92}_{-1.12}$	$-0.53^{+0.06}_{-0.05}$
$0.95 M_{\odot}$, Bhat et al. (2025)	$0.18 \mathcal{R}_{\text{Ia}}$	$2.07^{+2.32}_{-1.04}$	$7.43^{+1.88}_{-3.08}$	$0.42^{+0.43}_{-0.45}$	$18.44^{+1.62}_{-0.38}$	$-0.53^{+0.05}_{-0.03}$
$0.45 M_{\odot}$, Wong & Bildsten (2025)	$0.11 \mathcal{R}_{\text{Ia}}$	$1.21^{+0.30}_{-0.25}$	$9.24^{+0.12}_{-0.07}$	$1.23^{+1.41}_{-0.87}$	$19.74^{+0.58}_{-0.80}$	$-0.50^{+0.05}_{-0.09}$
$0.25 M_{\odot}$, Wong & Bildsten (2025)	$0.069 \mathcal{R}_{\text{Ia}}$	$1.50^{+0.69}_{-0.49}$	$8.47^{+0.30}_{-0.69}$	$1.12^{+1.29}_{-0.69}$	$19.55^{+0.71}_{-0.94}$	$-0.38^{+0.07}_{-0.10}$
$0.054 M_{\odot}$, Wong & Bildsten (2025)	$0.13 \mathcal{R}_{\text{Ia}}$	$2.28^{+1.63}_{-0.80}$	$6.78^{+0.88}_{-1.16}$	$0.45^{+0.22}_{-0.27}$	$18.98^{+0.86}_{-1.24}$	$0.20^{+0.09}_{-0.11}$
<i>Fully convective models (Shen 2025)</i>						
$0.2 M_{\odot}$	$0.032 \mathcal{R}_{\text{Ia}}$	$5.14^{+1.56}_{-1.69}$	$5.21^{+0.53}_{-0.56}$	$6.18^{+2.71}_{-2.20}$	$18.77^{+1.06}_{-1.19}$	$0.37^{+0.07}_{-0.26}$
$0.3 M_{\odot}$	$0.0057 \mathcal{R}_{\text{Ia}}$	$5.31^{+2.21}_{-1.96}$	$3.92^{+1.44}_{-0.77}$	$3.79^{+2.38}_{-1.18}$	$17.94^{+1.35}_{-1.19}$	$-0.30^{+0.31}_{-0.16}$
$0.5 M_{\odot}$	$0.0064 \mathcal{R}_{\text{Ia}}$	$4.72^{+2.57}_{-2.05}$	$5.35^{+0.84}_{-3.19}$	$1.58^{+1.04}_{-0.69}$	$18.58^{+1.21}_{-2.21}$	$-0.51^{+0.18}_{-0.07}$
<i>Partially reheated models (Zhang et al. 2019)</i>						
Partially reheated $0.30 M_{\odot}$, $f_{\text{env}} = 0.1$	$0.091 \mathcal{R}_{\text{Ia}}$	$1.37^{+0.33}_{-0.38}$	$8.83^{+0.26}_{-0.21}$	$1.11^{+1.30}_{-0.61}$	$19.54^{+0.67}_{-0.60}$	$-0.46^{+0.09}_{-0.07}$
Partially reheated $0.30 M_{\odot}$, $f_{\text{env}} = 0.5$	$0.027 \mathcal{R}_{\text{Ia}}$	$2.29^{+1.01}_{-0.89}$	$7.67^{+0.43}_{-1.36}$	$1.31^{+2.54}_{-1.09}$	$19.70^{+0.57}_{-1.49}$	$-0.52^{+0.09}_{-0.09}$
Partially reheated $0.30 M_{\odot}$, $f_{\text{env}} = 0.9$	$0.0044 \mathcal{R}_{\text{Ia}}$	$4.69^{+2.38}_{-1.81}$	$4.84^{+1.36}_{-0.75}$	$1.68^{+1.90}_{-0.89}$	$18.94^{+0.95}_{-1.15}$	$-0.40^{+0.10}_{-0.10}$
Partially reheated $0.60 M_{\odot}$, $f_{\text{env}} = 0.5$	$0.030 \mathcal{R}_{\text{Ia}}$	$2.81^{+2.00}_{-1.44}$	$6.31^{+1.78}_{-1.72}$	$0.68^{+1.47}_{-0.53}$	$19.30^{+0.65}_{-1.31}$	$-0.54^{+0.05}_{-0.05}$
<i>Violent mergers</i>						
Violent merger $0.16 M_{\odot}$, Bhat et al. (2026b)	$0.0060 \mathcal{R}_{\text{Ia}}$	$4.03^{+1.71}_{-1.50}$	$5.86^{+0.90}_{-0.98}$	$1.68^{+2.58}_{-0.95}$	$19.39^{+0.74}_{-1.33}$	$-0.20^{+0.08}_{-0.08}$
HeCO merger $0.49 M_{\odot}$, Glanz et al. (2025)	$0.059 \mathcal{R}_{\text{Ia}}$	$1.66^{+2.05}_{-0.63}$	$7.94^{+0.22}_{-1.95}$	$0.74^{+1.49}_{-0.54}$	$19.45^{+0.38}_{-0.80}$	$-0.53^{+0.05}_{-0.10}$
<i>Observed sources</i>						
Observed (all)	...	$2.20^{+1.90}_{-0.44}$	$6.72^{+1.13}_{-1.02}$	$0.64^{+1.23}_{-0.99}$	$19.22^{+0.81}_{-0.73}$	$-0.30^{+0.62}_{-0.25}$
Observed (hot only)	...	$3.88^{+0.34}_{-1.83}$	$6.51^{+1.30}_{-0.92}$	$0.87^{+0.99}_{-0.64}$	$19.40^{+0.73}_{-0.34}$	$-0.44^{+0.11}_{-0.15}$
Observed (cool only)	...	$2.03^{+0.17}_{-0.68}$	$6.72^{+0.86}_{-0.71}$	$-0.04^{+1.50}_{-2.44}$	$17.83^{+1.34}_{-0.64}$	$0.32^{+0.02}_{-0.06}$

Note. Comparison of the properties of observed D^6 stars recovered by our search (bottom) to predictions of several different evolutionary models (Section 6). For each model, we report the Galactic birth rate required to produce 10 runaways detectable with our search; this is expressed relative to the Galactic SNe Ia rate, $\mathcal{R}_{\text{Ia}} = 5 \times 10^{-3} \text{ yr}^{-1}$. Ranges show the median and middle 68% of several properties of simulated objects detectable with our search for each model.

We summarize the results of these simulations in Table 3 and Figures 6–10. The Galactic birth rate required to produce 10 detectable D⁶ stars varies by a factor of ~ 40 across models, with the shocked-donor models requiring birth rates of order $0.1 \mathcal{R}_{\text{Ia}}$ and the more deeply heated models from Shen (2025) requiring birth rates of $\lesssim 0.01 \mathcal{R}_{\text{Ia}}$. These differences are primarily due to differences in the models’ predicted observable lifetimes: models that remain bright in the optical for a long time require a smaller intrinsic rate than models that are faint or short-lived. None of the models we considered imply birth rates close to the SNe Ia rate. The observable properties of detectable D⁶ stars predicted by each model also vary significantly across models, as we discuss below. In each column of Figures 6–10, we compare the ten D⁶ stars detected by our search to a random sample of ten detectable sources simulated with a different evolutionary model.

6.3.1. Shocked donor models

Figure 6 shows predictions for the shocked helium-WD donor models from Wong & Bildsten (2025). The $0.45 M_{\odot}$ and $0.25 M_{\odot}$ tracks are generally fainter than the observed D⁶ stars when they satisfy our color and magnitude cuts. The detected simulated sources are therefore typically nearby, with smaller distances and larger proper motions than the bulk of the observed sample. The lowest-mass model – which is produced from a $0.10 M_{\odot}$ donor that loses significant mass after interaction with the companion’s ejecta – is cooler and redder, and overlaps the observed cool D⁶ stars in the color-magnitude and temperature-magnitude planes. It is likely most applicable to D6-2, whose low velocity is most readily explained by a low-mass donor. Producing 10 detections with these models requires birth rates of order $(0.07\text{--}0.13) \mathcal{R}_{\text{Ia}}$.

Figure 7 shows the shocked models from Bhat et al. (2025), which have higher masses than the models from Wong & Bildsten (2025). These tracks behave similarly in that they are short-lived, although their detectable phases are hotter and bluer than the Wong & Bildsten (2025) models. They can overlap some observed hot D⁶ stars, especially J1332. However, because the models fade rapidly, producing a sample of 10 detections requires a high birth rate, $\approx 0.1\text{--}0.2 \mathcal{R}_{\text{Ia}}$, and predicts many nearby, high-proper-motion detections. This makes the shocked-donor models unlikely to explain the full observed population, though they may be appropriate for a few individual systems.

6.3.2. Fully convective models

Figure 8 shows predictions for three models of different masses from Shen (2025) that begin as fully convective C/O dominated stars. These models are too red to be detected by our search until after they develop radiative cores. The $0.2 M_{\odot}$, $0.3 M_{\odot}$, and $0.5 M_{\odot}$ models reach $G_{\text{BP}} - G_{\text{RP}} < 0.5$ at ages of 4 Myr, 1.7 Myr, and 0.6 Myr, respectively. The temperature reached during the radiative stage increases with mass, with the three models reaching a maximum T_{eff} of 20 kK, 36 kK, and 77 kK. In the CMD, the $0.2 M_{\odot}$ model predicts some sources with parameters similar to the observed cool D⁶ stars, while the $0.3 M_{\odot}$ and $0.5 M_{\odot}$ models predict sources re-

sembling some of the hot observed stars. All three models also predict some detectable sources that are more luminous than any of the observed objects.

Because these models only become detectable at relatively late times, they predict t_{midplane} values systematically larger than observed. This tension is modest for the $0.5 M_{\odot}$ model and relatively severe for the $0.2 M_{\odot}$ and $0.3 M_{\odot}$ models. It is even more severe for the $0.15 M_{\odot}$ model (not shown here), which only becomes blue enough to be detected by our search at an age of 8 Myr. Shen (2025) found that the $0.15 M_{\odot}$ model could match the properties of observed cool D⁶ stars at ages of order 1 Myr, in apparent tension with our results. The reason for this tension is that Shen (2025) did not include a cut of $G_{\text{BP}} - G_{\text{RP}} < 0.5$ when modeling detectability, and the models under consideration are too cool to pass this cut when they are fully convective. That being said, the models predict temperatures only slightly too cool to pass this color cut and enter our search, so changing the assumed opacities or atmosphere models could improve agreement with observation without significantly changing the underlying physical model. If we arbitrarily increase the temperatures of the $0.15 M_{\odot}$ track by 500 K, it crosses our color cut after only ≈ 0.2 Myr rather than ≈ 9 Myr. With this shift, that model would require a birth rate of $0.017 \mathcal{R}_{\text{Ia}}$ for 10 detections (or $0.007 \mathcal{R}_{\text{Ia}}$ for 4) and would produce a population with colors and magnitudes similar to the observed cool D⁶ stars.

In order to produce 10 detectable sources, the $0.2 M_{\odot}$, $0.3 M_{\odot}$, and $0.5 M_{\odot}$ models respectively require birth rates of $0.032 \mathcal{R}_{\text{Ia}}$, $0.006 \mathcal{R}_{\text{Ia}}$, and $0.006 \mathcal{R}_{\text{Ia}}$. Since each of these models are likely to be applicable to at most four of the observed objects, the implied fraction of SNe Ia that produce a D⁶ star under these models is $\sim 0.1\text{--}1\%$.

6.3.3. Partially reheated models

Figure 9 shows partially reheated $0.30 M_{\odot}$ models from Zhang et al. (2019) with three choices of f_{env} . This isolates the effect of heating depth at fixed remnant mass. The shallowest-heated model, $f_{\text{env}} = 0.1$, produces faint detections at close distances and requires a relatively high birth rate, $0.091 \mathcal{R}_{\text{Ia}}$, to yield 10 objects in our search. Increasing the heated envelope fraction makes the detectable phase brighter and longer-lived: the required birth rate falls to $0.027 \mathcal{R}_{\text{Ia}}$ for $f_{\text{env}} = 0.5$ and $0.0044 \mathcal{R}_{\text{Ia}}$ for $f_{\text{env}} = 0.9$. The $f_{\text{env}} = 0.5$ and 0.9 models overlap parts of the observed distribution in color, magnitude, and temperature, but the deepest-heated model tends to predict larger distances and more luminous objects than most of the observed systems. The model with $f_{\text{env}} = 0.5$ thus best matches the observed population.

The left column of Figure 10 shows a partially reheated model with $f_{\text{env}} = 0.5$ and a higher mass of $0.60 M_{\odot}$. It produces hot, blue detections and requires a birth rate of $0.030 \mathcal{R}_{\text{Ia}}$. Its detections overlap the observed hot D⁶ stars in color and magnitude but predict somewhat higher temperatures than found in the observed population.

6.3.4. Violent-merger remnants

The center and right columns of Figure 10 show violent-merger remnant models. The $0.49 M_{\odot}$ HeCO-merger remnant from Glanz et al. (2025) matches the

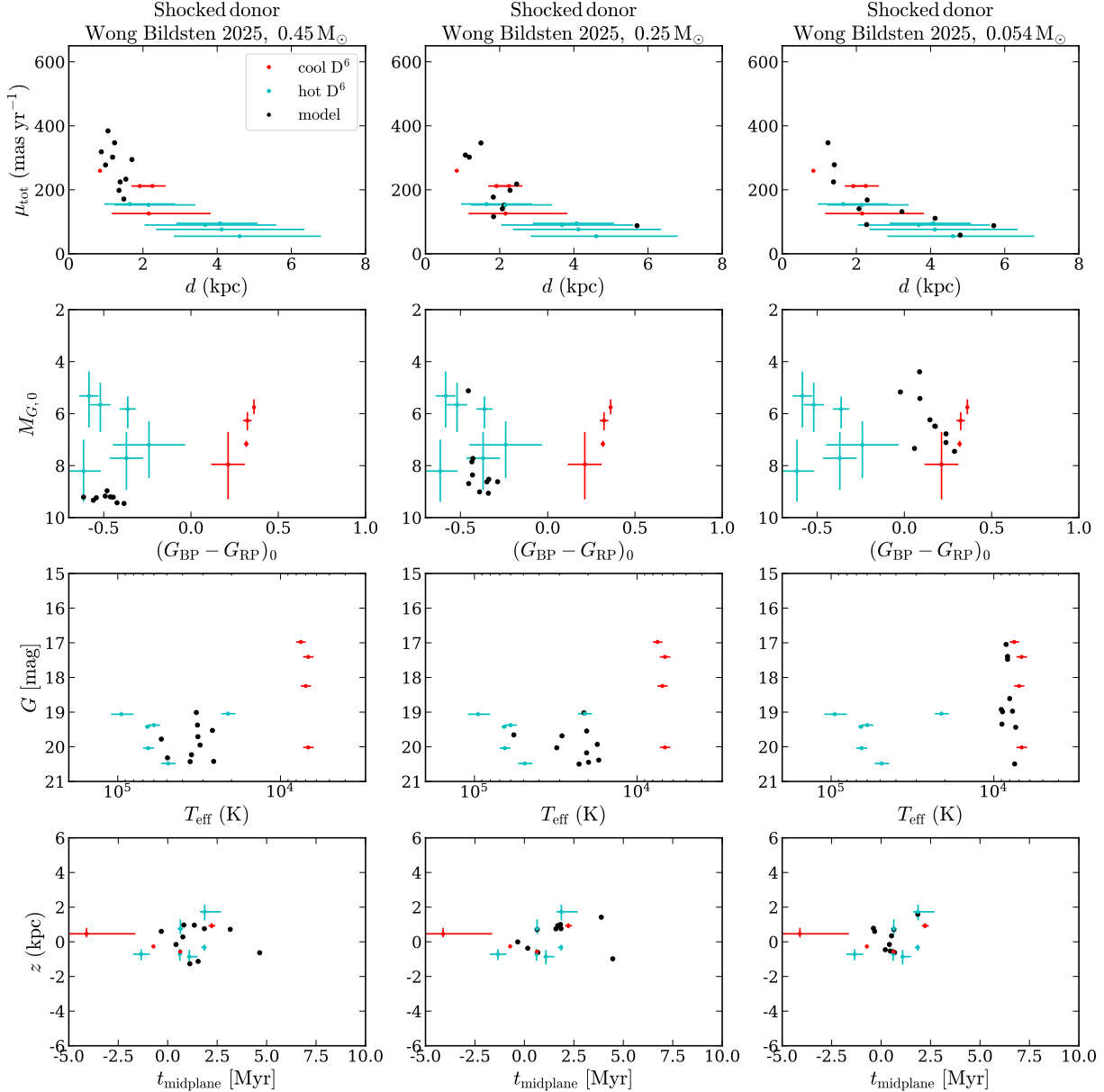


FIG. 6.— Comparison of observed D⁶ stars recovered by our search (red and cyan) with simulated populations (black) for shocked-donor models from [Wong & Bildsten \(2025\)](#). Each column shows a different model, labeled by the mass of the runaway star. In this and the following population-comparison figures, the simulated points show a random subset of 10 detectable sources after scaling the model birth rate to produce 10 detections (Table 3). Rows show distance and proper motion, intrinsic color and absolute magnitude, spectroscopic temperature and apparent G magnitude, and height above the Galactic plane as a function of midplane-crossing time. These shocked-donor models generally predict sources that are fainter, and therefore detected at smaller distances, than the observed systems. The lowest-mass remnant model produces cooler and redder detections than the more massive models, including some objects with properties similar to the observed cool D⁶ stars.

properties of observed hot D⁶ stars well, including their distances, proper motions, luminosities, temperatures, and t_{midplane} distribution. To predict 10 detections, this model requires a birth rate of $0.059 \mathcal{R}_{\text{Ia}}$. The $0.16 M_{\odot}$ remnant from [Bhat et al. \(2026b\)](#) predicts colors and magnitudes intermediate between the observed hot and cool D⁶ stars, and some of the sources predicted to be detectable have physical parameters similar to J1235. Its required birth rate is much lower, about $0.006 \mathcal{R}_{\text{Ia}}$, because the model remains detectable for a relatively long time. These violent-merger calculations effectively produce partial reheating: the survivor is heated more

deeply than in the superficially shocked donor models, but it is not reset to the fully convective initial states assumed by [Shen \(2025\)](#). In this sense, their thermal evolution is qualitatively similar to the intermediate-heating behavior captured phenomenologically by the [Zhang et al. \(2019\)](#) models.

6.4. Selection effects and future surveys

The birth rates in Table 3 describe the rate of all run-aways in a given evolutionary model, not only the rate of objects that satisfy our search criteria. Figure 11 illustrates this distinction for the HeCO violent-merger model

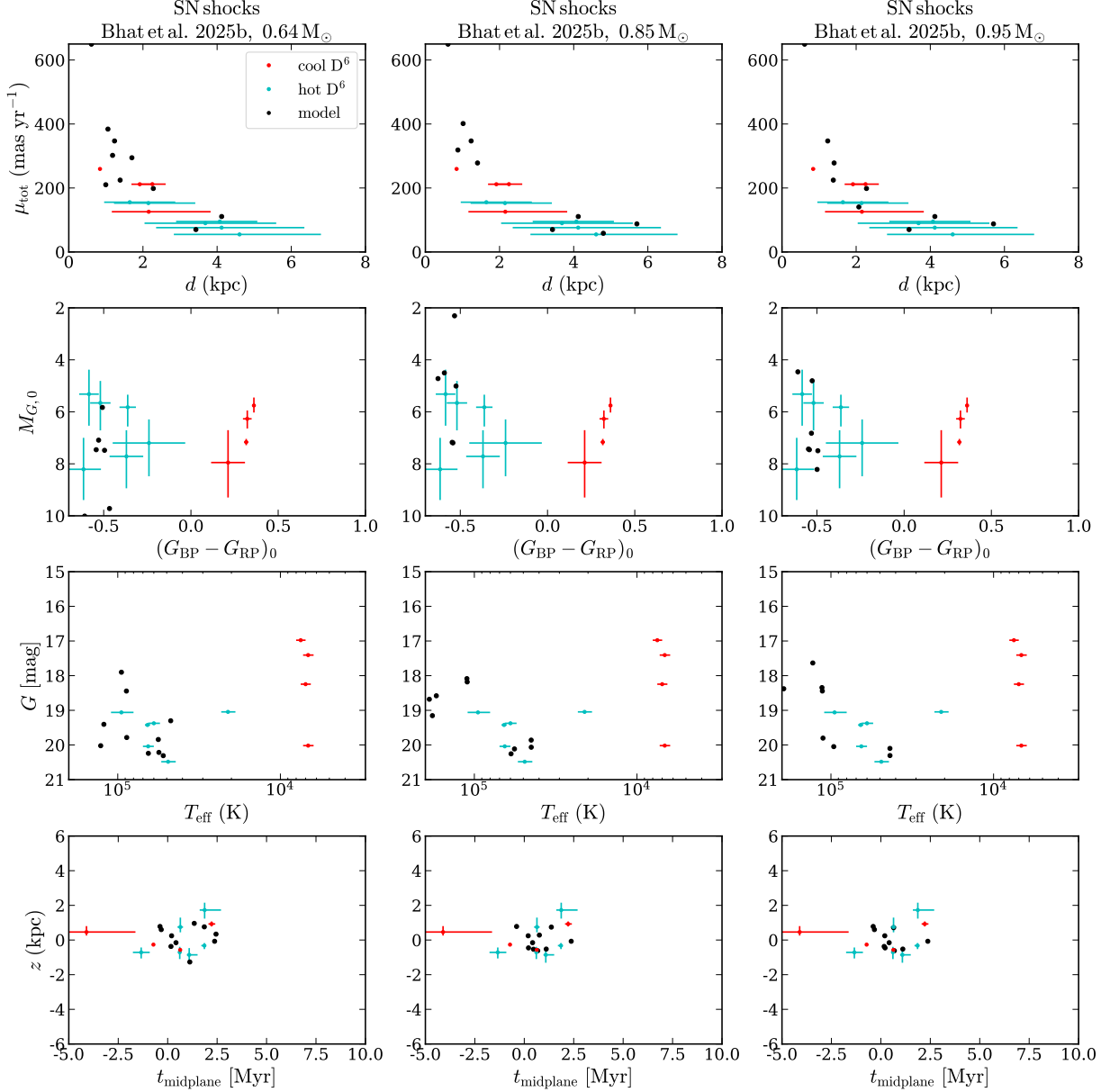


FIG. 7.— Same as Figure 6, but comparing to the shocked-donor models from Bhat et al. (2025). The three columns show surviving donor masses of $0.64 M_{\odot}$, $0.85 M_{\odot}$, and $0.95 M_{\odot}$. These models are short-lived because only the outer layers of the surviving donor are inflated by the SN shock. Their detectable phases are hot and blue, but they fade rapidly and therefore require high birth rates to produce 10 detections.

from Glanz et al. (2025). After re-normalizing this model to produce 10 detections with our current search, it predicts of order 3000 runaways younger than 10 Myr in the Galaxy. Most of these objects are not recovered by our search because they are too faint.

This modeling provides a simple way to forecast the yield of future searches. Under the Glanz et al. (2025) evolutionary models, extending the magnitude limit of our search from $G < 20.5$ to $G < 21.5$ (which is fainter than the *Gaia* limit and thus currently infeasible) would increase the expected yield from 10 to ≈ 19 detections. In contrast, relaxing the color cut from $G_{BP} - G_{RP} < 0.5$ to < 1.0 adds only about one object for this model, because the detectable HeCO-merger remnants are already blue. The population predicted to exist at low latitude and

reddened beyond our search’s color limits is predicted to be modest, since D^6 stars move ~ 1 kpc away from the Galactic midplane within 0.5 Myr. These conclusions are, of course, model dependent: redder evolutionary tracks, such as those predicted for lower-mass models, would benefit more from a relaxed color cut. Similarly, models with short evolutionary lifetimes predict larger gains from searching at low Galactic latitudes, since in those models few objects leave the Galactic plane before fading beyond detectability.

Future searches will likely struggle to extend this census to much larger distances. Rubin/LSST and other deep imaging surveys will identify high-proper-motion blue sources below the *Gaia* magnitude limit, but without precise parallaxes it will be difficult to distinguish

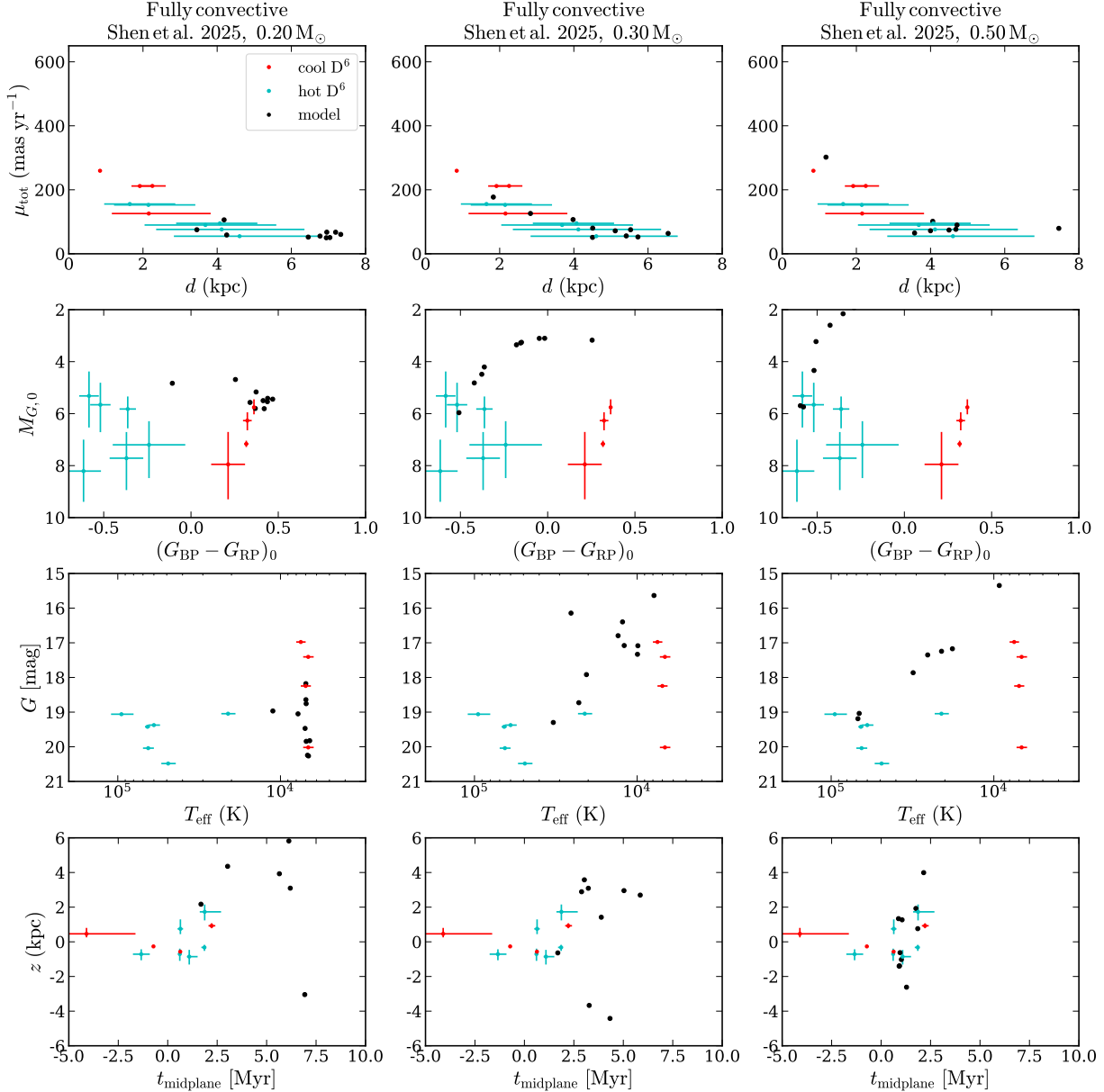


FIG. 8.— Same as Figure 6, but comparing to the fully convective C/O-star models from Shen (2025). Each column shows a different remnant mass. The $0.2 M_{\odot}$ and $0.3 M_{\odot}$ models produce some sources with colors and magnitudes similar to observed cool and hot D⁶ stars, respectively, but predict larger t_{midplane} than most observed systems. The $0.5 M_{\odot}$ model evolves more quickly and predicts some hot D⁶-like sources, while also producing detectable sources more luminous than any observed object.

distant hypervelocity candidates from the much larger population of nearby WDs. *Gaia* will not provide parallaxes for stars much fainter than those considered here, so our search has likely recovered most of the low-hanging fruit accessible to a simple tangential-velocity selection in the near future. Blind spectroscopic surveys can still expand the sample by detecting objects below the *Gaia* limit, or objects above the *Gaia* limit whose velocities are primarily radial and therefore missed by our proper-motion selection.

7. SUMMARY AND CONCLUSIONS

We have presented a systematic search for hypervelocity WD-like runaways from thermonuclear SNe using *Gaia* DR3 astrometry and photometry. Our selection is

intentionally simple: we search for blue sources whose *Gaia* astrometry implies high tangential velocities. The resulting sample contains 92 candidates. We classify all of them using a combination of new spectroscopy and archival data, giving the search a well-defined selection function suitable for population modeling.

Since the first results of our search were presented by E23, there have been several theoretical developments which shape our interpretation of the observed sources. Following Bauer et al. (2021), E23 interpreted the high velocities of observed D⁶ stars as evidence that they are massive ($M \gtrsim 0.8 M_{\odot}$), and for this reason, E23 concluded that the Zhang et al. (2019) models could not adequately explain the observed population: those models could predict plausible temperatures, luminosities, and

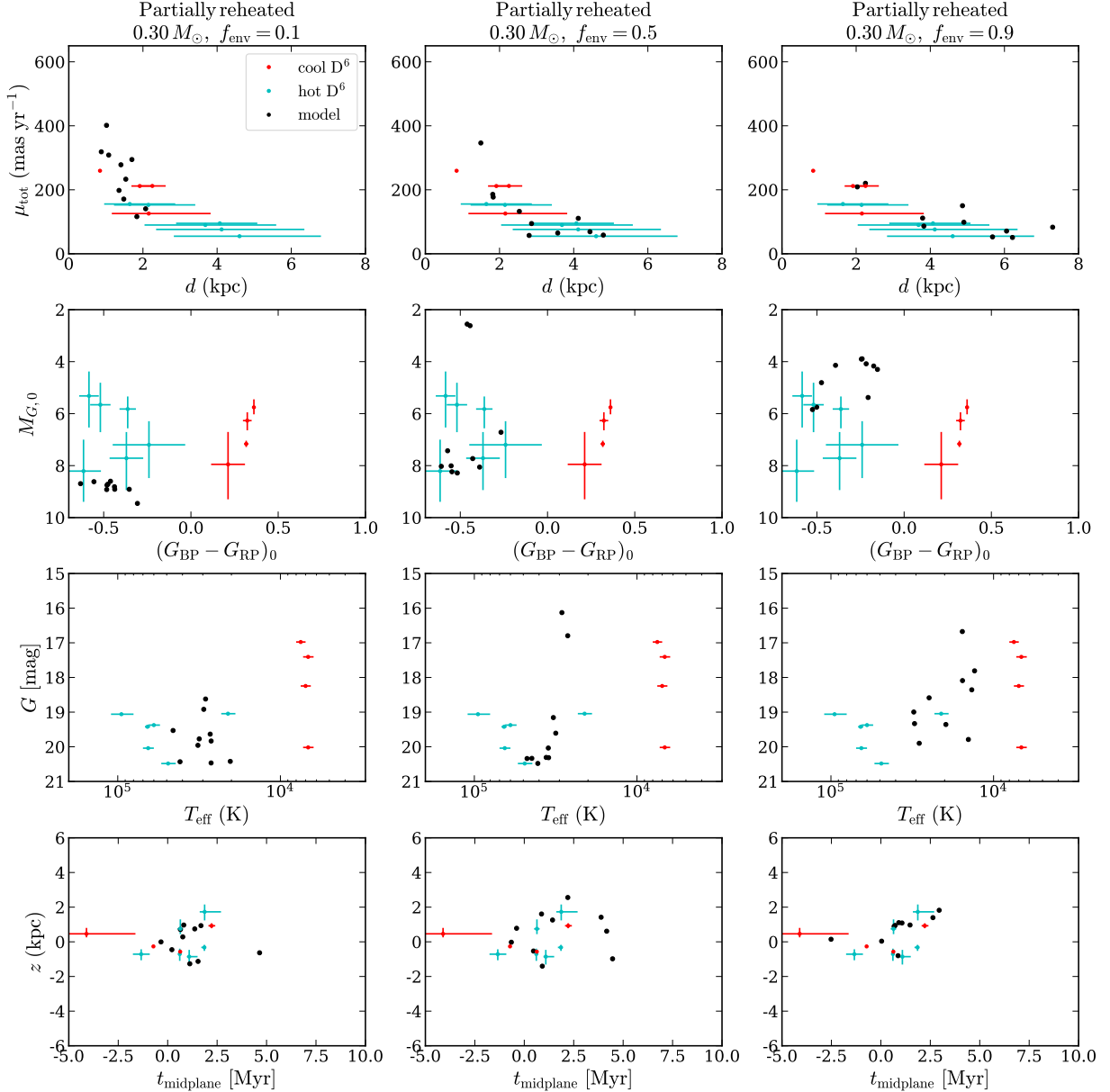


FIG. 9.— Same as Figure 6, but comparing to partially reheated WD models from Zhang et al. (2019). All three columns show the $0.30 M_{\odot}$ model, with $f_{\text{env}} = 0.1, 0.5$, and 0.9 from left to right. Increasing f_{env} heats a larger fraction of the envelope, producing brighter, longer-lived detectable sources and therefore lowering the birth rate required to recover 10 objects.

ages, but only for lower runaway star masses than implied by the observed ejection velocities.

However, several works have since proposed that observed D⁶ stars are the remnants of donors that were partially disrupted during a WD merger or the resulting explosion (e.g. Shen 2025; Pakmor et al. 2025; Bhat et al. 2026b; Glanz et al. 2025). In this case, the surviving remnant can achieve higher velocities than the pre-SN orbital velocity, and there is no simple mapping between ejection velocity and donor mass. In this case, the observed temperatures, luminosities, and ages become easier to explain.

Our main results are summarized below.

1. The search recovers 10 suspected D⁶ stars and three LP 40-365 stars (Table 1). The confirmed runaways are preferentially brighter, closer to the Galactic

plane, and have larger RV amplitudes than the false positives, but they cannot be cleanly selected without spectroscopic follow-up (Figure 1). The false positives separate into a bright population of mostly A/F-type main-sequence stars near the tangential-velocity threshold and a faint population dominated by WDs and other sources with poorly constrained parallaxes.

2. Three of the suspected D⁶ stars are new discoveries. J1251-5059 is a cool object resembling the original D⁶ sample from Shen et al. (2018b) (Figure 2), while J0812-5943 and J1949+0745 are hot, hydrogen-deficient, C/O rich stars whose spectra resemble the previously known hot D⁶ population (Figures 3 and 4). Orbit integrations imply ejection

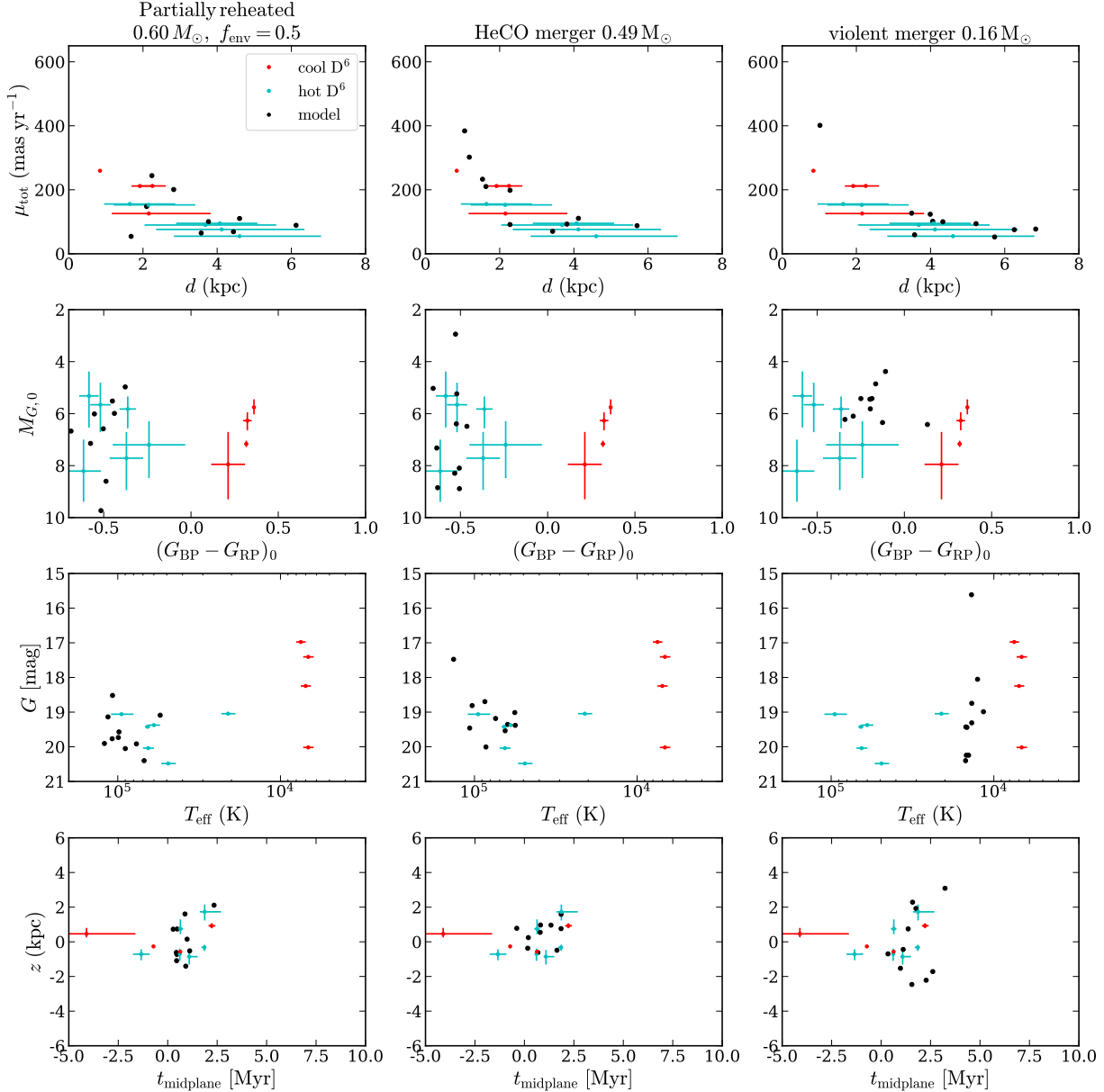


FIG. 10.— Same as Figure 6, but comparing a partially reheated $0.60 M_{\odot}$ WD model with $f_{\text{env}} = 0.5$ from Zhang et al. (2019) (left), a $0.49 M_{\odot}$ WD ejected from a merger of two hybrid WDs (center; Glanz et al. 2025), and a $0.16 M_{\odot}$ remnant ejected from a violent merger (right; Bhat et al. 2026b). The partially reheated model predicts hot, blue detections, but is shorter-lived than the more deeply heated violent-merger remnants. The HeCO model from Glanz et al. (2025) broadly reproduces the observed properties of hot D^6 stars. The violent-merger model from Bhat et al. (2026b) matches some intermediate-temperature systems, with somewhat larger t_{midplane} than the bulk of the observed population.

velocities above 1000 km s^{-1} for all three new objects (Figure 5) and slightly fainter absolute magnitudes than the sample of previously known D^6 stars. Poorly constrained distances limit precise measurements of ejection velocities or luminosities for the three new discoveries.

3. The known population of hypervelocity runaways is heterogeneous, spanning at least an order of magnitude in effective temperature and three orders of magnitude in luminosity (Figure 5). The D^6 stars show tentative evidence for a bimodal temperature distribution (Figure 5), though two objects have intermediate temperatures. For all the evolution-

ary models we considered, the effective temperature at late times is primarily a function of mass, with more massive models predicting higher temperatures. The four cool D^6 stars are best reproduced by low-mass models with $M \lesssim 0.2 M_{\odot}$, while the temperature of the hot D^6 stars appear to imply $M \gtrsim 0.4 M_{\odot}$. It is thus natural to ascribe the apparent temperature bimodality to a bimodality in the mass of the surviving remnant. The inferred birth rate of D^6 stars varies by more than an order of magnitude across models (Table 3), with longer-lived models implying lower birth rates.

4. No single evolutionary model reproduces the full

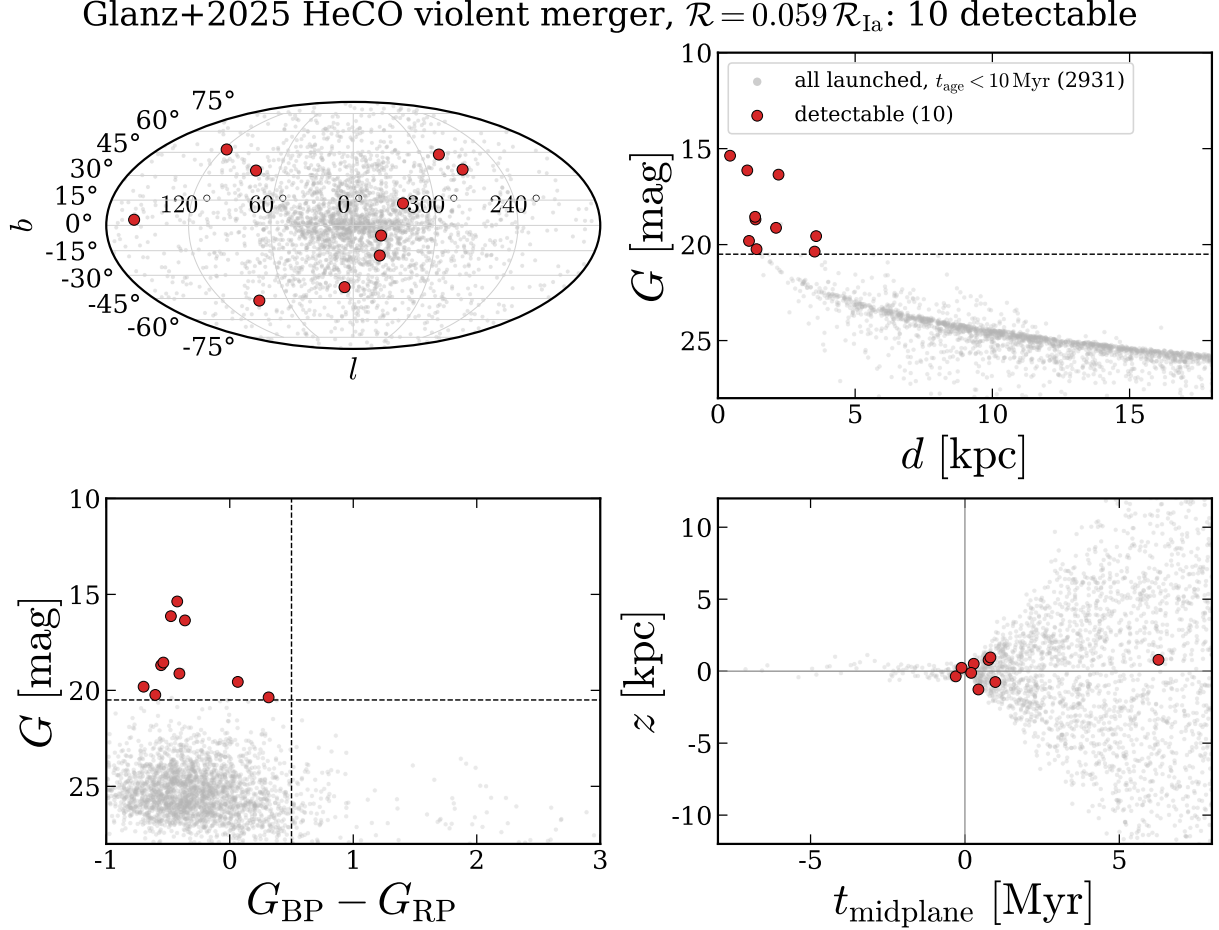


FIG. 11.— Comparison of the observed and underlying D^6 star population. Gray points show all simulated runaways launched in the last 10 Myr under the Glanz et al. (2025) evolutionary model, while red points show the subset detectable to our search. The panels show sky position, apparent magnitude as a function of distance and observed color, and height above the Galactic plane as a function of midplane-crossing time. Dashed lines mark the magnitude and color cuts of our search. The model predicts that extending the search to fainter magnitudes would uncover a larger population of D^6 stars, but such objects could be efficiently selected only with precise astrometry beyond the *Gaia* faint limit.

range of observed D^6 star properties. Most superficially shocked donor models from Wong & Bildsten (2025) and Bhat et al. (2025) are on average too faint and short-lived to explain the full sample (Figures 6 and 7), but the lowest-mass models from Wong & Bildsten (2025) are a reasonably good match to the cool D^6 stars, especially D6-2. Fully convective models from Shen (2025) can produce long-lived, more luminous remnants, but these models generally predict older ages at the time of detection than inferred for the observed population (Figure 8). This tension could be alleviated by modest increases in the temperature of these models. Partially reheated models from Zhang et al. (2019) span a useful range of behavior, with hotter and longer-lived detectable populations as a larger fraction of the envelope is reheated (Figure 9). The observed population is difficult to reconcile with a single-parameter family of models. The data instead favor a heterogeneous population in which both remnant mass and heating depth vary substantially across systems.

5. Of the evolutionary models we considered, violent-

merger remnants and other partially reheated models match the ages, colors, and magnitudes of the largest number of observed D^6 stars (Figure 10). These models predict runaway stars that are heated more deeply than superficially shock-heated models but that still fade more rapidly than fully convective models. None of the models fully explain the cool D^6 star population, as the range of ejection velocities across the four observed objects likely requires multiple formation pathways. The low-mass models from Shen (2025) and Bhat et al. (2026b) – which are most simply understood as being products of violent mergers – may produce objects similar to D6-1, D6-3, and J1251-5059. The low-mass shocked donor models from Wong & Bildsten (2025) seem most promising to explain the physical parameters and low velocity of D6-2.

The “hybrid” HeCO merger model from Glanz et al. (2025) predicts a detected population similar to the observed hot D^6 stars. This does not necessarily imply that this specific model is the most correct. Rather, it suggests that the degree and depth of heating in that calculation is closer to

the effective thermal evolution of the observed remnants – particularly the hot remnants – than either superficially shocked or fully reheated models.

6. For the models that best resemble the observed sample, the required birth rates are a few percent of the Galactic SNe Ia rate (Table 3). This suggests that most SNe Ia do not produce an observable D⁶-like remnant in the region of parameter space probed by our search. This conclusion applies only to detectable remnants; we cannot rule out a scenario in which many SNe Ia produce surviving remnants that are fainter than the currently-known classes of runaways. The simplest explanation for the low inferred birth rate of SN runaways is that most Type Ia SNe cause both WDs to explode, as has been predicted by several recent calculations (e.g. Pakmor et al. 2022; Boos et al. 2024; Shen et al. 2024; Pollin et al. 2024).

Another possible explanation is that most SNe Ia arise from a single-degenerate channel, which would produce lower-velocity runaways not detectable with our search (e.g. Marietta et al. 2000; Pan et al. 2012; Rau & Pan 2022). However, this scenario struggles to explain the lack of detected runaways in remnants of historical supernovae (Kerzendorf et al. 2012, 2013, 2014, 2018; Shields et al. 2023), as well as the delay time distribution and several other population properties of SNe Ia (e.g. Maoz et al. 2014). Other channels in which no companion star survives (e.g. Soker 2026) are also consistent with the results of our search.

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APPENDIX

AN UPDATED RADIAL VELOCITY FOR US 708

US 708 is the only confirmed hypervelocity hot subdwarf. Geier et al. (2015) reported an RV of $917 \pm 7 \text{ km s}^{-1}$ for US 708 based on Keck/ESI spectra. That RV led E23 to infer an ejection velocity of $833^{+17}_{-16} \text{ km s}^{-1}$, which is uncomfortably high for the supernova runaway scenario with a helium-star donor (Justham et al. 2009; Wang & Han 2009; Neunteufel 2020; Neunteufel et al. 2022), though it could be explained if the progenitor binary was on a halo orbit (e.g. Brown et al. 2015).

We observed US 708 with Keck/ESI on MJD 60343 and measured an RV of $818 \pm 15 \text{ km s}^{-1}$. This value is $\approx 100 \text{ km s}^{-1}$ slower than that measured by Geier et al. (2015), but still $\approx 100 \text{ km s}^{-1}$ faster than the RV of $708 \pm 15 \text{ km s}^{-1}$ originally reported by Hirsch et al. (2005). To understand the origin of this tension, we retrieved the 10 ESI spectra of US 708 presented by Geier et al. (2015) from the Keck archive and re-reduced them using MAKEE. From the coadded spectrum, we measure an RV of $835 \pm 10 \text{ km s}^{-1}$, which is consistent with the measurement from our data and inconsistent with the RV reported by Geier et al. (2015). Additional unpublished spectra confirm this lower RV (S. Geier, private communication).

We conclude that the true RV of US 708 is $835 \pm 10 \text{ km s}^{-1}$, about 80 km s^{-1} lower than assumed in most analyses in the last decade. We suspect that the different RV reported by Geier et al. (2015) is due to an error in air-to-vacuum wavelength conversion. Integrating US 708's trajectory with this new RV yields an ejection velocity of $802^{+14}_{-13} \text{ km s}^{-1}$. This is only $\sim 30 \text{ km s}^{-1}$ slower than reported by E23; our lower RV is partially offset by the fact that we integrate orbits in a realistic Galactic potential rather than assuming straight-line trajectories. Our inferred ejection velocity is in plausible agreement with predictions of simulations for sdB + WD binaries in which the WD undergoes a double detonation after accreting helium from an sdB star, though still on the high side for sdB stars massive enough to continue burning helium (Bauer et al. 2019; Rajamuthukumar et al. 2025).

SUMMARY OF FOLLOW-UP

TABLE 4: All *Gaia* sources returned by the ADQL query from Section 2.4, together with results from our follow-up spectroscopy and archival classifications. Sources are sorted by $v_{\perp, \text{lower}} = 4.74\mu/(\varpi + \sigma_{\varpi})$, the 1σ lower limit on their tangential velocity. $v_{\perp}$ is a point-estimate of the sources' tangential velocity (Equation 1). Both $v_{\perp}$ and $v_{\perp, \text{lower}}$ can be negative for sources with negative parallaxes; this implies a large but poorly constrained tangential velocity. Objects with common names are detections recovered by the search, while unnamed sources are false positives. References: S18: Shen et al. (2018b); R19: Raddi et al. (2019).

Source ID	Name	G	ϖ	μ	$v_{\perp}$	$v_{\perp, \text{lower}}$	RV	verdict	follow-up
		[mag]	[mas]	[mas yr $^{-1}$]	[km s $^{-1}$]	[km s $^{-1}$]	[km s $^{-1}$]		
2448037457850504832		20.40	-0.85 ± 0.91	122.8	-687	9167		DA WD	SOAR
2402028733088281984		20.28	-0.77 ± 0.80	59.0	-362	9145	-10 ± 50	MS	SOAR
5290552672404889984	J0812-5943	20.48	-0.51 ± 0.57	89.9	-833	6841	-1200 ± 10	hot D ⁶	SOAR/GMOS
1357638170128486400		20.48	-0.62 ± 0.71	63.5	-481	3517		blended	
6156470924553703552	J1235-3752	19.05	-0.10 ± 0.24	95.2	-4685	3183	-1694 ± 10	hot D ⁶	MagE
2156908318076164224	D6-3	18.25	0.42 ± 0.10	212.0	2374	1922	-20 ± 80	cool D ⁶	S18
6736291479453047552		20.17	-0.71 ± 0.86	52.5	-349	1704	-120 ± 100	DA WD	SOAR/GMOS
5805243926609660032	D6-1	17.41	0.53 ± 0.07	211.7	1890	1669	1200 ± 40	cool D ⁶	S18
4080377230814011136		20.34	-1.04 ± 1.22	55.6	-253	1485		blended	
3917003370724484352		20.44	-0.91 ± 1.28	100.7	-523	1285		DC WD	SOAR/LRIS
6003972342578025344		20.10	-0.60 ± 0.83	52.4	-411	1101		blended	
1356636716899212800		20.33	-0.23 ± 0.53	66.9	-1388	1056	-160 ± 50	DA WD	LRIS
4184081105961170816		20.43	-0.42 ± 0.76	74.7	-843	1030	-60 ± 50	MS	LRIS
3992451210082879488		20.16	-0.45 ± 0.87	86.7	-907	994	180 ± 50	DA WD	LRIS
1798008584396457088	D6-2	16.98	1.19 ± 0.07	259.5	1030	977	80 ± 10	cool D ⁶	S18
3335306915849417984	J0546+0836	19.06	0.07 ± 0.31	76.1	5289	942	1200 ± 20	hot D ⁶	LRIS/ESI/X-shooter
4298029440184716160	J1949+0745	20.04	0.20 ± 0.59	152.8	3599	911	100 ± 40	hot D ⁶	LRIS
468855092650116480		20.42	0.01 ± 0.76	128.1	43058	783		blended	
1259197996445745792		20.23	-0.10 ± 0.56	75.2	-3559	774	-40 ± 50	DA WD	LRIS

TABLE 4 – continued

Source ID	Name	G [mag]	ϖ [mas]	μ [mas yr ⁻¹]	$v_{\perp}$ [km s ⁻¹]	$v_{\perp, \text{lower}}$ [km s ⁻¹]	RV [km s ⁻¹]	verdict	follow-up
5250394728194220800	J0927-6335	19.37	0.13 ± 0.21	54.9	2062	764	-2285 ± 20	hot D ⁶	MagE/X-shooter
6712254192464970368		12.64	0.32 ± 0.02	53.9	794	744		MS	GaiaXP
4396371856111979776		20.34	-0.64 ± 0.97	51.6	-380	741	-450 ± 100	DA WD	SOAR
1153320661688203136		20.10	0.01 ± 0.64	101.1	34551	728	180 ± 50	DA WD	SOAR
2289780724881070592		20.48	-0.09 ± 0.53	65.4	-3413	702	-100 ± 50	DA WD	LRIS
6621783871766231296		20.13	-0.38 ± 0.73	51.0	-632	698		blended	
1044958121413909888		20.45	-0.12 ± 0.72	87.5	-3386	693	260 ± 50	DA	LRIS
1160986392332702720		15.14	0.41 ± 0.03	62.8	730	677	-117 ± 20	MS	SDSS
3946876384391994496		14.28	0.40 ± 0.02	59.2	700	662	76 ± 12	MS	Brown et al. (2008)
6727110900983876096	J1825-3757	13.26	1.05 ± 0.03	147.8	666	649	-47 ± 5	LP 40-365	R19
6563500886388740864		20.15	0.19 ± 0.48	90.8	2320	644	-50 ± 50	DA WD	SOAR
1473381658945235584		20.30	0.51 ± 0.53	136.5	1266	621	30 ± 50	DA WD	LRIS
3688712561723372672		18.77	1.42 ± 0.20	211.6	706	620	140 ± 14	DA WD	SDSS
3983606360591141504		14.02	0.87 ± 0.02	116.2	634	620	122 ± 10	MS	LAMOST
6078434976557457536	J1251-5059	20.02	0.43 ± 0.53	125.7	1380	619	-870 ± 5	cool D ⁶	SOAR/GMOS/X-shooter
6775068295327939456		20.45	-0.11 ± 0.65	69.8	-2932	616	-120 ± 50	DA WD	SOAR
6164642052589392512	J1332-3541	19.42	0.66 ± 0.54	155.5	1112	613	1090 ± 50	hot D ⁶	MagE/LRIS
4201939094650159488		20.12	-0.52 ± 1.02	64.8	-590	613		blended	
724149735422162816		10.77	1.04 ± 0.02	136.0	619	606	92 ± 10	MS	LAMOST
3542263595793124480		19.18	0.67 ± 0.46	144.3	1016	604		blended	
6194859965015895808		14.56	0.41 ± 0.03	55.7	650	602		MS	GaiaXP
4709163672760735488		11.57	0.56 ± 0.02	73.5	617	600	-100 ± 3	MS	GaiaRVS
2316981409896303232		15.23	0.56 ± 0.03	75.8	636	599	50 ± 50	MS	SOAR
3637020190774216064		20.46	0.07 ± 1.03	138.4	9234	594	40 ± 50	DA WD	SOAR
3804182280735442560	J1109+0001	19.09	0.40 ± 0.31	87.6	1051	592	100 ± 10	LP 40-365	LRIS/X-shooter
5814962273679342208		14.79	0.40 ± 0.02	52.7	621	588		MS	GaiaXP
300228113890870528		14.95	0.40 ± 0.03	53.4	636	588		MS	GaiaXP
5703888058542880896		19.60	1.36 ± 0.32	207.9	723	586	270 ± 50	DA WD	LRIS
5517276097516408576		19.33	0.10 ± 0.35	55.3	2735	582		blended	
6610315175214347264		14.43	0.41 ± 0.02	52.4	610	578		MS	GaiaXP
3792840680855962240		15.07	0.46 ± 0.03	60.1	619	576	290 ± 10	MS	LAMOST
4771417432717575680		19.93	0.13 ± 0.32	54.2	1998	571	120 ± 50	DA WD	SOAR
660204643116592768		20.38	0.72 ± 0.66	165.3	1082	564	-100 ± 50	DA WD	LRIS
4998384365291044096		15.00	0.45 ± 0.04	58.0	606	560		MS	GaiaXP
5474401427567487616		20.40	-0.28 ± 0.73	52.8	-881	559	350 ± 50	DA WD	SOAR
6021110567768770816		20.26	-0.21 ± 0.78	67.4	-1512	557	140 ± 50	blended	SOAR
3739128262233092352		20.21	-0.04 ± 0.58	62.6	-7973	550	60 ± 50	DB WD	DBSP,ESI
6777304839418469248		20.44	-0.22 ± 0.77	61.7	-1308	534	-180 ± 100	DA WD	SOAR
4546525523392712064		19.39	0.52 ± 0.32	93.6	860	534	-240 ± 50	DA WD	DBSP
6853349473073333632		19.56	0.50 ± 0.46	107.7	1027	532	90 ± 50	DA WD	SOAR/GMOS
3002601569231013504		20.12	0.53 ± 0.65	130.8	1180	526	180 ± 50	DA WD	SOAR
2393804867149529856		19.78	0.13 ± 0.41	58.8	2167	513	-40 ± 50	DA WD	SOAR
3507697866498687232	J1311-1846	18.26	0.60 ± 0.19	83.1	653	496	55 ± 10	LP 40-365	LRIS/X-shooter
5361430834062743424		20.13	0.36 ± 0.52	90.6	1186	484	-230 ± 50	DA WD	SOAR
6508240879378242560		20.11	0.37 ± 0.59	96.0	1218	473		blended	

TABLE 4 – continued

Source ID	Name	G	ϖ	μ	$v_{\perp}$	$v_{\perp, \text{lower}}$	RV	verdict	follow-up
		[mag]	[mas]	[mas yr ⁻¹]	[km s ⁻¹]	[km s ⁻¹]	[km s ⁻¹]		
5998866829060560768		19.49	0.73 ± 0.44	115.6	754	468	-65 ± 10	MS	MagE
5183592902806605824		19.81	0.73 ± 0.58	128.2	836	463	-20 ± 50	sdO/B	SOAR
4781587644689625600		20.28	0.14 ± 0.57	69.4	2347	462	160 ± 50	DA WD	SOAR
4129413800145771776		19.30	0.65 ± 0.35	96.2	697	452	-290 ± 80	DA WD	LRIS
1512757030058082304		19.94	0.35 ± 0.33	64.3	879	450	-70 ± 50	DA WD	LRIS
1271663056690275712		19.20	0.46 ± 0.22	65.0	669	450	-118 ± 38	DA WD	SDSS
1533746771456004480		20.04	0.71 ± 0.58	121.4	813	447	-194 ± 43	DA WD	SDSS
6536783647184624640		19.94	0.07 ± 0.53	55.9	3844	444	70 ± 50	DA WD	SOAR/GMOS
4096984529352659584		19.60	0.40 ± 0.49	83.0	983	440	60 ± 50	MS	LRIS
6592388973858801920		18.45	0.39 ± 0.19	52.3	638	425	170 ± 40	DA WD	SOAR
5772035376916929408		20.17	0.17 ± 0.43	51.8	1478	415	190 ± 50	DA WD	SOAR
6729448153444659712		20.45	0.87 ± 1.00	161.6	885	410	-60 ± 100	DA WD	SOAR
3880049472115990400		20.34	-0.23 ± 1.24	87.0	-1801	408		WB	
5160882249616496768		20.25	0.79 ± 0.64	121.7	730	404	-60 ± 50	DA WD	LRIS
6688913592127235584		19.19	0.41 ± 0.29	59.8	686	404	220 ± 50	DA WD	SOAR/GMOS
3460197452350766464		20.48	-0.10 ± 0.73	52.2	-2579	389	-20 ± 40	DA WD	SOAR
744576492507398272		20.30	-0.01 ± 0.86	65.9	-56608	365	-180 ± 50	DA WD	LRIS
3792579576908228608		20.45	-0.28 ± 1.08	55.3	-923	329	10 ± 50	DA WD	SOAR
3366889189061553664		20.47	-0.29 ± 1.17	56.3	-906	303	-20 ± 50	MS	LRIS
4059697822386864512		20.49	-1.33 ± 2.72	85.7	-306	290	0 ± 50	MS	SOAR
4104739694138461184		20.23	-0.21 ± 1.27	56.5	-1248	252		blended	
6217835085113310208		20.28	-0.14 ± 1.19	50.0	-1739	225	-40 ± 50	DA WD	SOAR
5181766613992671104		20.49	-1.13 ± 2.67	56.6	-236	174	80 ± 50	DA WD	LRIS
2552009991792563840		20.06	-2.01 ± 0.96	59.1	-139	-267		WB	
4096331041464263296		19.99	-1.42 ± 0.82	58.6	-195	-463	-120 ± 50	MS	LRIS
5104365427803800832		20.18	-1.11 ± 0.74	56.9	-243	-742	-90 ± 50	DA WD	LRIS
6278906633842892160		20.43	-1.00 ± 0.85	84.6	-402	-2676	70 ± 50	DA WD	LRIS
6703717691563155968		19.24	-0.53 ± 0.53	52.7	-471	-79269	0 ± 50	DA WD	SOAR

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