MMT HYPERVELOCITY STAR SURVEY

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ABSTRACT

We describe a new survey for unbound hypervelocity stars (HVSs), stars traveling with such extreme velocities that dynamical ejection from a massive black hole (MBH) is their most likely origin. We investigate the possible contribution of unbound runaway stars, and show that the physical properties of binaries constrain low mass runaways to bound velocities. We measure radial velocities for HVS candidates with the colors of early A-type and late B-type stars. We report the discovery of 6 unbound HVSs with velocities and distances exceeding the conservative escape velocity estimate of Kenyon and collaborators. We additionally report 4 possibly unbound HVSs with velocities and distances exceeding the lower escape velocity estimate of Xue and collaborators. These discoveries increase the number of known HVSs by 60% - 100%. Other survey objects include 19 newly identified z ∼ 2.4 quasars. One of the HVSs may be a horizontal branch star, consistent with the number of evolved HVSs predicted by Galactic center ejection models. Finding more evolved HVSs will one day allow a probe of the low-mass regime of HVSs and will constrain the mass function of stars in the Galactic center.

Subject headings: Galaxy: halo — Galaxy: center — Galaxy: stellar content — Galaxy: kinematics and dynamics — stars: early-type

1. INTRODUCTION

Three-body interactions with a massive black hole (MBH) will inevitably unbind stars from the Galaxy (Hills 1988; Yu & Tremaine 2003). In 2005 we reported the discovery of the first HVS: a 3 M⊙ main sequence star traveling with a Galactic rest frame velocity of at least +709 ± 12 km s⁻¹, more than twice the Milky Way's escape velocity at the star's distance of 110 kpc (Brown et al. 2005). This star cannot be explained by normal stellar interactions: the maximum ejection velocity from binary disruption mechanisms (Blaauw 1961; Poveda et al. 1967) is limited to ~300 km s⁻¹ for 3 M⊙ stars (Leonard 1991, 1993; Tauris & Takens 1998; Portegies Zwart 2000, Davies et al. 2002; Gualandris et al. 2005). Although runaways may reach unbound velocities for very massive stars, like the hyper-runaway HD 271791 (Heber et al. 2008a), runaway ejection velocities are constrained by the properties of binaries. A massive and compact object is needed to accelerate low mass stars to unbound velocities.

There is overwhelming evidence for a ∼ 4 x 10⁶ M⊙ MBH in the dense stellar environment of the Galactic center (Schödel et al. 2003; Ghez et al. 2005). Hills (1988) coined the term HVS to describe a star ejected by the MBH. The observational signature of a HVS is its unbound velocity. Although not all unbound stars are necessarily HVSs – fast-moving pulsars, for example, are explained by supernova kicks (e.g. Arzoumanian et al. 2002) – unbound low mass main sequence stars are most plausibly explained as HVSs.

Here we introduce a new HVS survey using the MMT to target HVS candidates with masses down to ∼2 M⊙. Discovering lower-mass HVSs should provide constraints on the stellar mass function of HVSs (Brown et al. 2006a; Kollmeier & Gould 2007): the velocity distribution of low- versus high-mass HVSs may discriminate between a single MBH or binary MBH origin (Sesana et al. 2007b; Kenyon et al. 2008). Our survey strategy targets stars fainter and redder than the original HVS survey. This strategy is successful: we report the discovery of 6 unbound HVSs and 4 possibly unbound HVSs.

1.1. Recent Observations of HVSs

Observers have identified a remarkable number of HVSs in the past 3 years. Following the discovery of the first HVS (Brown et al. 2005), Hirsch et al. (2005) reported a helium-rich subluminous O star leaving the Galaxy with a rest-frame velocity of at least +717 km s⁻¹. Edelmann et al. (2005) reported an 9 M⊙ main sequence B star with a Galactic rest frame velocity of at least +548 km s⁻¹, possibly ejected from the Large Magellanic Cloud. Brown et al. (2006a, 2007a,b) reported 7 B-type HVSs discovered in a targeted HVS survey, along with evidence for an equal number of bound HVSs ejected by the same mechanism.

High-dispersion spectroscopy has shed new light on the nature of the HVSs. Przybilla et al. (2008a) have recently shown that HVS7 is a chemically peculiar B main sequence star, with an abundance pattern unusual even for the class of peculiar B stars. The star HVS3 (HE 0437-5439), the unbound HVS very near the LMC on the sky, has received the most attention. HVS3 is a 9 M⊙ B star of half-solar abundance, a good match to the abundance of the LMC (Bonanos et al. 2008; Przybilla et al. 2008b). Stellar abundance may not be conclusive evidence of origin, however. A- and B-type stars exhibit 0.5 - 1 dex scatter in elemental abundances within a single cluster, due to gravitational settling and radiative levitation in the atmospheres of the stars (Varene & Monier 1999; Monier 2005; Fossati et al. 2007; Gebran et al. 2008; Gebran & Monier 2008).

An LMC origin requires that HVS3 was ejected from the galaxy at ∼1000 km s⁻¹ (Przybilla et al. 2008b), a
velocity that can possibly come from three-body interactions with an intermediate mass black hole in a massive star cluster (Gualandris & Portegies Zwart 2007; Gvaramadze et al. 2008). Perets (2008) shows that the ejection rate of 9 M⊙ stars, however, is four orders of magnitude too small for this explanation to be plausible. The alternative explanation is that HVS3 is a blue straggler, ejected by the Milky Way’s MBH. Theorists argue that a single MBH or a binary MBH can eject a compact binary star as a HVS (Lu et al. 2007; Perets 2008); the subsequent evolution of such a compact binary can result in mass-transfer and/or a merger that can possibly explain HVS3 (Perets 2008). Proper motion measurements, underway now, will determine HVS3’s origin.

Other recent HVS work highlights the link between stellar rotation and the origin of HVSs. Main sequence B stars have fast mean \( v \sin i \sim 150 \text{ km s}^{-1} \) (e.g. Abt et al. 2002; Huang & Gies 2006). Hot blue horizontal branch (BHB) stars have slow mean \( v \sin i \sim 10 \text{ km s}^{-1} \) (because they have just evolved off the red giant branch (e.g. Behr 2003a,b). Interestingly, Hansen (2007) predicts that main sequence HVSs ejected by the Hills mechanism should be slow rotators, because stars in compact binaries have systematically lower \( v \sin i \) due to tidal synchronization. Lückmann & Baumgardt (2008), on the other hand, predict that HVSs should be fast rotators, at least for single stars spun up and ejected by a binary black hole. To date HVS1, HVS3, HVS7, and HVS8 have observed \( v \sin i \) of \( \sim 190, 55 \pm 2, 55 \pm 2, \) and \( 260 \pm 70 \text{ km s}^{-1} \), respectively [Heber et al. 2008; Przybilla et al. 2008d]. Lopez-Morales & Bonanos (2008). As discussed by Perets (2007), we clearly require a larger sample of HVSs to measure the distribution of HVS rotations and discriminate HVS ejection models.

In §2 we describe our new HVS survey strategy and summarize our observations. In §3 we discuss the Galactic escape velocity, our definition of a HVS, and the possible contribution of hyper-runaways to the population of unbound stars. In §4 we present the new unbound HVSs. In §5 we discuss a possible BHB star among the HVSs. We conclude in §6.

2. DATA

2.1. New Target Selection

HVSs are rare: our discoveries imply there are 96 ± 20 HVSs of mass 3-4 M⊙ within 100 kpc (Brown et al. 2007b). Thus to find new HVSs we must target luminous objects over a very large volume. Luminous O- and B-type HVSs, even if they lived long enough to be observed, would be lost behind a large foreground of hot white dwarfs with identical colors, \((u' - g')_0 \lesssim 0.4\). We design our new HVS survey to target early A-type stars.

Known HVSs are located at distances 50 - 100 kpc, corresponding to 19.5 < \( g_0' < 21 \) for early A-type stars. At such magnitudes, fewer than \(~100\) A-type stars have published radial velocities (Sirk et al. 2004a; Clewley et al. 2005; Xue et al. 2008). Halo BHB and blue straggler stars are a major contaminant at faint magnitudes, but fortunately the density of the stellar halo falls off very steeply. Kenyon et al. (2008) calculate the density profile of unbound HVSs is approximately \( \rho \propto r^{-2} \) (see also Kollmeier & Gould 2007); the density profile of the stellar halo is closer to \( \rho \propto r^{-3} \) (e.g. Jurić et al. 2008). Thus we maximize the contrast of HVSs with respect to indigenous halo stars by restricting ourselves to the faintest A-stars.

We select candidate HVSs in the magnitude range 19.0 < \( g_0' < 20.5 \). The faint limit is set by Sloan Digital Sky Survey (SDSS) photometric errors, which approach \( \pm 0.15 \) in \((u' - g')_0\) at \( g' = 20.5 \). The bright limit is set to provide continuity with our original HVS survey, although we impose a more stringent bright limit on the reddest stars \( g_0' > 18.6 + 10[(g' - r')_0 + 0.3] + [(u' - g')_0 - (1.2(g' - r')_0 + 1.25)] \). In other words, \( g_0' > 19.5 \) at \((r' - i')_0 = -0.2\). We use a combination of \((u' - g')_0\) and \((g' - r')_0\) colors to select stars with probable high surface gravity, and thus maximize the chance of finding main sequence HVSs.

Figure I illustrates the color selection. The original HVS survey (dashed line) was designed to avoid the locus of BHB/A-type stars; our new HVS survey (long dashed line) follows the Girardi et al. (2002,2004) main sequence tracks for solar abundance stars (solid lines) down to \( \sim 2 \text{ M}_\odot \) A-stars. Known HVSs scatter uniformly around the main sequence tracks. Known BHB stars (Xue et al. 2008), on the other hand, are systematically redder in \((u' - g')_0\).

We select stars with 0.6 < \((u' - g')_0 < 1.07\) to avoid the majority of known halo BHB stars (Figure I). We select stars with \(-0.35 < (g' - r')_0 < -0.20\) to include 3 \( \text{ M}_\odot \) stars that can viable travel 150 kpc (\(~20.5 \text{ mag}\)) in their main sequence lifetimes. Finally, we impose \(-0.5 < (r' - i')_0 < 0\) and \((g' - r')_0 < 0.2\) to exclude non-stellar objects, such as quasars. Notably, this color selection includes the first HVS, that was not formally a part of the original HVS survey.

Applying this color-magnitude selection to the SDSS DR6 photometric catalog results in 528 HVS candidates spread over 7300 deg². We have excluded the
small region of the SDSS between \( b < -l/5 + 50^\circ \) and \( b > l/5 - 50^\circ \) to avoid excessive contamination from Galactic bulge stars. Of the 528 HVS candidates, 59 were previously observed as part of our original HVS survey (Brown et al. 2007b), and 21 are in the Sirko et al. (2004a) BHB catalog. Thus we need spectra for 448 HVS candidates.

### 2.2. Spectroscopic Observations

Spectroscopic observations were obtained at the 6.5m MMT telescope with the Blue Channel spectrograph on the nights of 2008 February 6-10 and 2008 May 7-11. We operated the spectrograph with the 832 line mm\(^{-1}\) grating in second order and a 1.25\(^\circ\) slit. These settings provide wavelength coverage 3650 Å to 4500 Å and a spectral resolution of 1.2 Å. All observations were obtained at the parallactic angle.

Our goal was to obtain modest signal-to-noise (S/N) observations adequate for determining radial velocity. We typically obtained S/N = 5 in the continuum at 4000 Å in a 10 minute integration on a \( g' \) = 20 star. We obtained spectra for 233 HVS candidates, and processed the data in real-time to allow additional observations of interesting candidates. We extracted the spectra using IRAF\(^1\) in the standard way and measured radial velocities using the cross-correlation package RVSAO (Kurtz & Mink 1998). The average radial velocity uncertainty of the S/N = 5 spectra is \( \pm 20 \) km s\(^{-1}\).

### 2.3. HVS Sample

We now have spectroscopic identifications and radial velocities for 313 (59\%) of the 528 HVS candidates. 19 of the objects are newly identified \( z \approx 2.4 \) quasars, and 9 of the objects are DA white dwarfs. We present the quasars and white dwarfs in Appendix A. The remaining 285 objects have the spectra of early A- and late B-type stars. In addition, we observed the final 40 objects remaining in the original HVS survey (Brown et al. 2007b).

Because our new and original HVS surveys cover contiguous regions of color-magnitude space over the same region of sky, we consider the results of the combined surveys in this paper. We exclude stars with \( \rho_0 \) < 17 that are possibly associated with the inner halo; the inner halo has distinctly different kinematics from the outer halo (Morrison et al. 2008; Carollo et al. 2007). We also exclude all white dwarfs, quasars, and B supergiants. Our combined HVS survey contains 759 non-kinematically-selected stars 17 < \( \rho_0 \) < 20.5.

### 2.4. Radial Velocity Distribution

Figure 2 plots the distribution of line-of-sight velocities, corrected to the Galactic rest-frame (see Brown et al. 2006b), for the combined sample of 759 stars. The 731 survey stars with \( |v_r| < 275 \) km s\(^{-1}\) have a \( -1 \pm 4 \) km s\(^{-1}\) mean and a 106 \( \pm 5 \) km s\(^{-1}\) dispersion, consistent with a normal stellar halo population. Notably, there are 28 stars in the tails of the distribution with \( |v_r| > 275 \) km s\(^{-1}\).

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\(^1\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
the Galaxy around $-300$ km s$^{-1}$ (Figure 2). Bound HVSs must have main sequence lifetimes less than $\sim1$ Gyr, otherwise we would see them falling back onto the Galaxy (Brown et al. 2007b; Kollmeier & Gould 2007; Yu & Madau 2007). Given the color-selection of our survey (Figure 1), the A- and B-type HVSs must be 2-4 M$_\odot$ main sequence stars at Galactocentric distances $>40$ kpc (Figure 5).

Unfortunately, the Galactic potential is poorly constrained at distances $>40$ kpc. We consider two Galactic potential models here. Kenyon et al. (2008) discuss a spherically symmetric potential that, for the first time, fits the Milky Way mass distribution from 5 pc to 10$^5$ pc. Because the form of the potential does not yield a true escape velocity, Kenyon et al. (2008) define unbound stars as having $v_{r,f} > 200$ km s$^{-1}$ at $R = 150$ kpc. This conservative definition yields a Galactic escape velocity of 360 km s$^{-1}$ at 50 kpc and 260 km s$^{-1}$ at 100 kpc (Figure 3). Xue et al. (2008), on the other hand, fit a halo potential model to the velocity dispersion of 2466 BHB stars located 5 kpc $< R < 60$ kpc. The escape velocity resulting from the Xue et al. (2008) model is 290 km s$^{-1}$ at 50 kpc and 190 km s$^{-1}$ at 100 kpc (Figure 3).

### 3.2. Hyper-Runaways

Not all unbound stars are HVSs. The star HD 271791 is the first example of an unbound “hyper-runaway” that was ejected from the outer disk, in the direction of Galactic rotation, when its former 55 M$_\odot$ binary companion exploded as a supernova (Heber et al. 2008a; Przybilla et al. 2008a). Objects ejected in this manner are traditionally called runaways (Blaauw 1961). The term runaway also includes stars dynamically ejected from binary-binary encounters (Poveda et al. 1967).

We investigate here the possible contribution of runaways to the population of HVSs. First, we consider the properties of binaries required to produce unbound hyper-runaways. Then, we consider the production rate of stars massive enough to produce hyper-runaways.

#### 3.2.1. Binary Star Properties

Both the supernova and binary-binary ejection mechanisms share a common velocity constraint: the physical properties of binary stars. Theoretically, the maximum ejection velocity from disrupting a binary (e.g., by a supernova) is the binary orbital velocity. If the binary orbital velocity is set by the escape velocity of the primary, then the maximum ejection velocity is $v_{\infty, MS} \approx 700 (M/M_\odot)^{0.15}$ km s$^{-1}$ for stars on the upper main sequence (Leonard 1991). The maximum ejection velocity from dynamical binary-binary encounters is roughly twice the escape velocity of the most massive star (Leonard & Duncan 1988, 1994). These maximum ejection velocities are not realizable, however, because compact binaries that are too tight will merge instead of producing a runaway.

To avoid merging, a compact binary must avoid losing too much energy from Roche lobe overflow and from tidal dissipation. Stars with separations less than $2.5 R_{\text{star}}$ overfill their Roche lobes and quickly merge (e.g., Vanbeveren et al. 1998). During close binary encounters, tidal dissipation can lead to mergers of compact binaries (Lee & Ostriker 1986; McMillan et al. 1987; Leonard & Duncan 1988). These mechanisms are especially problematic for binaries involving a supernova. When a massive primary star evolves (prior to exploding), it experiences significant mass loss. Dynamical friction from the primary’s wind causes the secondary star to quickly in-spiral, thus conserving the angular momentum of the system (Vanbeveren et al. 1998). A minimum binary separation must be chosen to prevent mergers. Unfortunately, the details of tidal dissipation and stellar merging are uncertain. Thus we make only optimistic assumptions in our estimate of hyper-runaway ejection rates.

#### 3.2.2. Hyper-Runaway Ejection Rate

In the context of our HVSs, a runaway must have a velocity exceeding 400 km s$^{-1}$ to be confused with a HVS. The orbital velocity of the secondary star in a binary is

$$v_{\text{sec}} = \frac{2\pi a}{(1 + q)P},$$

where $a$ is the separation of the two stars, $q = M_2/M_1$ is the mass ratio, and $P$ is the orbital period. We insert Kepler’s third law $P^2 = 4\pi^2a^3/(GM)$ into Equation 1 set $v_{\text{sec}} \geq 400$ km s$^{-1}$, and find that the progenitor binary system must have

$$M/a \geq 0.84(1 + q)^2 (M_\odot/R_\odot)$$

(2)

to produce a $\geq 400$ km s$^{-1}$ runaway. Here, $M$ is the total mass of the binary. We will optimistically assume that the secondary fills its Roche-lobe and has a radius of $\sim 0.4a$. Because a 3 M$_\odot$ star has a 3 R$_\odot$ radius, a binary...
must have a \( \geq 8 \, R_\odot \) and a primary star with mass \( \geq 10 \, M_\odot \) to produce the requisite 3 \( M_\odot \) runaway ejected at \( \geq 400 \, \text{km s}^{-1} \) (Equation [2]).

Known HVSs have travel times spanning \( 2 \times 10^8 \) yrs (see Figure 3). The star formation rate in the solar neighborhood is 0.5 \( M_\odot \) yr\(^{-1}\) \cite{LadaLada2003}. Thus 10\(^8\) \( M_\odot \) of stars have formed in the disk in the past \( 2 \times 10^8 \) yrs.

A standard Salpeter initial mass function \cite{Salpeter1955}, normalized to \( 10^6 \, M_\odot \), predicts 3 \( \times \) \( 10^5 \) stars with masses 10-20 \( M_\odot \). All O and B stars are in binaries, and a third of the binaries are twins \cite{KobulnickyFryer2007}. Thus \( \sim10^5 \) of 10-20 \( M_\odot \) primaries are not twins. Assuming the secondaries have a Salpeter mass function \cite{KobulnickyFryer2007}, there are \( \sim800 \) secondaries with mass 3-4 \( M_\odot \). Given a log-normal distribution of binary separations, \( \sim5\% \) of binaries have 8-20 \( R_\odot \) semi-major axes enabling a 400 km s\(^{-1}\) ejection. Thus we expect \( \sim40 \) 3-4 \( M_\odot \) runaways ejected at \( \geq 400 \, \text{km s}^{-1} \) in the past \( 2 \times 10^8 \) yrs.

The Galactic disk has an exponential stellar density profile with radial scale length 2.4 kpc \cite{Siegeletal2002}. Thus the region of the outer disk \( 10 < R < 20 \) kpc, despite containing most of the disk’s area, contains no more than 10\% of the disk’s stars if we optimistically normalize the density over 5 \( < R < 20 \) kpc. Thus we predict only \( \sim4 \) possible 3-4 \( M_\odot \) hyper-runaways ejected from the outer disk in the past \( 2 \times 10^8 \) yrs.

However, potential models of the Milky Way show that a star traveling with 400 km s\(^{-1}\) in the region \( 10 < R < 20 \) kpc is bound (see Figure 3). To achieve an unbound velocity, a runaway must be ejected at 400 km s\(^{-1}\) in the direction of Galactic rotation. Assuming that runaways are ejected in random directions, no more than 10\% of ejections will be in the direction of Galactic rotation. Thus we predict \( \sim0.4 \) hyper-runaways with mass 3-4 \( M_\odot \) were ejected in the past \( 2 \times 10^8 \) yrs. In contrast, our HVS discoveries imply there were 96 \( \pm \) 20 unbound 3-4 \( M_\odot \) stars ejected over the same time period.

We conclude that 3-4 \( M_\odot \) HVSs ejected from the Galactic Center are \( \sim100 \) times more common than hyper-runaways of the same mass. Hyper-runaways are rare because of the rarity of massive stars and the requirement to avoid merging the compact binary progenitor. While it is possible for a hyper-runaway to be confused with an HVS in the absence of proper motions, the observed \( \sim3 \) \( M_\odot \) unbound stars are almost certainly HVSs ejected by the central MBH.

4. NEW HYPERVELOCITY STARS

4.1. Six Unbound HVSs

Here we describe the 6 unbound HVSs newly discovered in our survey. The first two stars are of later spectral type than the HVS discoveries in our previous targeted survey \cite{Brownetal2006b,Brownetal2007a}.

SDSS J095006.48+000853.40, hereafter HVS11, has an A1 spectral type, a \( +482 \pm 19 \) km s\(^{-1}\) heliocentric radial velocity, and a minimum velocity of \( +337 \) km s\(^{-1}\) in the Galactic rest frame. An A-type spectral classification is supported by a strong \( \lambda3933\) Ca\(\text{II}\) line in the spectrum (Figure 4). HVS11 is the reddest HVS identified to date, with a broadband color \( (g' - r')_0 = -0.256 \pm 0.028 \). A solar metallicity 2.5 \( M_\odot \) main sequence star has \( M_V = 2.5 \) \( M_\odot \) \( \simeq +0.6 \) \cite{Schalleretal1992}. This luminosity places HVS11 at an approximate Galactocentric distance \( R = 70 \) kpc.

Known HVSs are typically separated by \( 10^2 - 20^\circ \) from the nearest Local Group dwarf galaxy, however HVS11 is only \( 3^\circ9 \) from the Sextans dwarf. Any physical association with Sextans is very unlikely. Sextans is 1320 \( \pm \) 40 kpc distant \cite{Dolphinetal2003} and has a heliocentric velocity of \( 224 \pm 2 \) km s\(^{-1}\) \cite{Young2000}. Thus HVS11 is moving towards the dwarf galaxy with a relative velocity of \( +260 \) km s\(^{-1}\).

SDSS J105009.60+031550.67, hereafter HVS12, has an A0 spectral type, a \( +552 \pm 11 \) km s\(^{-1}\) heliocentric radial velocity, and a minimum velocity of \( +429 \) km s\(^{-1}\) in the Galactic rest frame. HVS12 has a strong \( \lambda3933\) Ca\(\text{II}\) line and a higher \( S/N \) than the HVS11. We measure a \( 0.8 \pm 0.1 \) equivalent width of Ca\(\text{II}\). Combining Ca\(\text{II}\) with the star’s broadband color \( (g' - r')_0 = -0.307 \pm 0.039 \), equivalent to \( (B - V)_0 = -0.05 \) \cite{Clewleyetal2005}, we estimate \( [\text{Fe/H}] = -0.5 \pm 0.7 \) \cite{Wilhelmetal1999}. HVS12 is therefore consistent with being a solar metallicity 2.5 \( M_\odot \) main sequence star, placing its at an approximate Galactocentric distance \( R = 70 \) kpc.

SDSS J105248.31−000133.94, hereafter HVS13, has a \( +575 \pm 11 \) km s\(^{-1}\) heliocentric radial velocity and a minimum velocity of \( +443 \) km s\(^{-1}\) in the Galactic rest frame. Although its \( (g' - r')_0 = -0.295 \pm 0.034 \) is nearly identical to HVS12, HVS13 is 0.23 mag bluer in \( (u' - g')_0 \) and has a B9 spectral type (Figure 4) consistent with a 3 \( M_\odot \) main sequence star (see also Figure 4), the same spectral type observed for most of the other HVSs in our survey. At \( g = 20.18 \pm 0.02 \), however, HVS13 is the faintest HVS discovered to date. A solar metallicity 3 \( M_\odot \) main sequence star has \( M_V \simeq -0.3 \) \cite{Schalleretal1992}, which places HVS13 at \( R = 125 \) kpc.

SDSS J104401.75+061139.03, hereafter HVS14, has a B9 spectral type, a \( 532 \pm 13 \) km s\(^{-1}\) heliocentric radial velocity, and a minimum velocity of 416 km s\(^{-1}\) in the Galactic rest frame. Its broadband colors are consistent with a 3 \( M_\odot \) main sequence star (Figure 4). At
$g = 19.72 \pm 0.02$, HVS14, like HVS13, has a very large Galacticocentric distance $R = 110$ kpc.

SDSS J13341.09−012114.25, hereafter HVS15, has a B9 spectral type, a 463 ± 11 km s$^{-1}$ heliocentric radial velocity, and a minimum velocity of 343 km s$^{-1}$ in the Galactic rest frame. HVS15 is the bluest of the new HVSs with $(g'-r')_0 = -0.346 \pm 0.031$, consistent with a 3 $M_\odot$ main sequence star. We previously classified HVS15 as a possibly bound HVS (Brown et al. 2007b), but in light of its probable $R = 85$ kpc distance the star is almost certainly unbound. HVS15 would be located at $R = 37$ kpc if it were a hot BHB star, yet its minimum rest frame velocity would still be in excess of the Xue et al. (2008) Galactic escape velocity estimate. We conclude that both HVS15 and HVS16 are very likely unbound.

### 4.2. Four Possible HVSs

There are four HVS candidates with minimum rest frame velocities, main sequence star distances, and BHB star distances that fall between the Kenyon et al. (2008) and Xue et al. (2008) Galactic escape velocity models. In other words, these stars are unambiguously bound in the Kenyon et al. (2008) model, and unambiguously unbound in the Xue et al. (2008) model.

The four possible HVSs are SDSS J0940.56+530901.7 and SDSS J101349.79+563111.7, SDSS J113557.47+054319.5, and SDSS J12253.40+052233.8. For all four stars, $V_{rf} > +275$ km s$^{-1}$.

### Four Possible HVSs

| ID | Type | $M_V$ | $V$ | $R_{GC}$ | $l$ | $b$ | $v_\odot$ | $v_{rf}$ | Catalog |
|----|------|------|----|---------|----|----|--------|--------|--------|
| HVS1 | B | -0.3 | 19.83 | 111 | 227.33 | +31.33 | 840 | 696 | SDSS J090744.99+024506.9 |
| HVS2 | sdO | +2.6 | 19.05 | 26 | 175.99 | +47.05 | 708 | 717 | US 708 |
| HVS3 | B | -2.7 | 16.20 | 62 | 263.04 | -40.91 | 723 | 548 | HE 0437-5439 |
| HVS4 | B | -0.9 | 18.50 | 82 | 194.76 | +42.56 | 611 | 566 | SDSS J093101.01+305119.8 |
| HVS5 | B | -0.3 | 17.70 | 45 | 146.23 | +38.70 | 553 | 649 | SDSS J091759.48+072238.3 |
| HVS6 | B | -0.3 | 19.11 | 78 | 243.12 | +59.56 | 626 | 528 | SDSS J110557.45+093439.5 |
| HVS7 | B | -1.1 | 17.80 | 60 | 263.83 | +57.95 | 529 | 416 | SDSS J113312.12+010824.9 |
| HVS8 | B | -0.3 | 18.09 | 53 | 211.70 | +46.33 | 489 | 407 | SDSS J094214.02+060323.2 |
| HVS9 | B | -0.3 | 18.76 | 68 | 244.63 | +44.38 | 628 | 485 | SDSS J102137.08+010824.9 |
| HVS10 | B | -0.3 | 19.36 | 85 | 266.51 | +55.92 | 463 | 343 | SDSS J113341.09+052233.8 |

Possible HVSs

| ID | $V$ | $R_{GC}$ | $l$ | $b$ | $v_\odot$ | $v_{rf}$ | Catalog |
|----|------|---------|----|----|--------|--------|--------|
| HVS16 | 19.49 | 90 | 285.86 | +67.38 | 443 | 367 | SDSS J12253.40+052233.8 |

### Table 1

HVS Survey Stars with $V_{rf} > +275$ km s$^{-1}$

| ID | Type | $M_V$ | $V$ | $R_{GC}$ | $l$ | $b$ | $v_\odot$ | $v_{rf}$ | Catalog |
|----|------|------|----|---------|----|----|--------|--------|--------|
| HVS1 | B | -0.3 | 19.83 | 111 | 227.33 | +31.33 | 840 | 696 | SDSS J090744.99+024506.9 |
| HVS2 | sdO | +2.6 | 19.05 | 26 | 175.99 | +47.05 | 708 | 717 | US 708 |

References. — (1) Brown et al. (2005); (2) Hirsch et al. (2005); (3) Edelmann et al. (2005); (4) Brown et al. (2006a); (5) Brown et al. (2006b); (6) Brown et al. (2007b).
timate\textsuperscript{a} the low-velocity end of HVSs. It is, however, more likely that unbound low mass A stars are ejected by a MBH. Proper motions are needed to distinguish these four stars as HVSs or runaways.

4.3. HVS Table

Table I lists the 26 stars in our HVS survey with $v_{rf} > +275$ km s$^{-1}$, plus HVS2 and HVS3 for completeness. Magnitudes and radial velocities are observed quantities, whereas luminosities and distances are inferred from spectra and colors. Columns include HVS number, stellar type, absolute magnitude $M_V$, apparent $V$ magnitude derived from SDSS photometry, Galactocentric distance $R$, Galactic coordinates $(l, b)$, heliocentric radial velocity $v_0$, minimum Galactic rest-frame velocity $v_{rf}$ (not a full space velocity), and catalog identification. We report the weighted average velocity measurements for each object. Thus the velocities in Table I may vary slightly from earlier work.

We do not report errors in Table I because formal uncertainties are misleadingly small compared to the (unknown) systematic errors. For example, our radial velocities have 11-17 km s$^{-1}$ uncertainties, but we have no constraint on the proper motion component of the rest frame velocity $v_{rf}$. The luminosity estimates are precise at the 10\% level for main sequence stars. However, the luminosity estimates could be over-estimated by an order of magnitude for post-main sequence stars.

5. THE NATURE OF HYPERVELOCITY STARS

We argued previously that HVSs must be short-lived main sequence stars (Brown et al. 2007b). Follow-up observations have, remarkably, confirmed that four B-type HVSs are main sequence stars: HVS1 is a slowly pulsating B variable (Fuentes et al. 2006), HVS3 is a 9 M$_\odot$ B star (Bonanos et al. 2008, Przybilla et al. 2008), HVS7 is a 3.7 M$_\odot$ Bp star (Przybilla et al. 2008c), and HVS8 is a rapidly rotating B star (Lopez-Morales & Bonanos 2008).

The identification of HVSs as main sequence stars is in stark contrast to the halo stars in our survey, which are, presumably, evolved 0.6-1 M$_\odot$ stars on the BHB. BHB stars among the HVSs would be exciting, however, because unbound BHB stars would allow us to probe the low-mass regime of HVSs.

Kenyon et al. (2008) calculate the observable spatial and velocity distribution of HVSs as a function of mass, and predict that BHB stars are a factor of $\sim$10 times less abundant than main sequence HVSs. Roughly speaking, solar mass HVSs are 10 times more abundant than 3-4 M$_\odot$ HVSs, but spend 1\% of their lifetime in the BHB phase with luminosity comparable to an 2.5 M$_\odot$ main sequence star. Not all of our HVSs have the colors of a 2.5 M$_\odot$ main sequence star (see Figure 1). Yet, given the 16 - 20 HVSs identified to date, the predictions of Kenyon et al. (2008) imply there should be 1$\pm$1 BHB stars among our HVSs.

5.1. A Possible BHB HVS

BHB stars and main sequence stars are distinguished by surface gravity: low surface gravity BHB stars have narrower Balmer lines (at a given effective temperature) than high surface gravity main sequence stars. Spectroscopic measures of surface gravity work for temperatures cooler (redder) than $(B-V)_0 = 0$ (e.g. Kinman et al. 1994, Wilhelm et al. 1999, Clewley et al. 2002), colors that we probe now with our new HVS survey.

Applying the Clewley et al. (2002, 2004) surface gravity measures to the new HVSs, HVS12 is a possible BHB star. The line width-shape technique indicates HVS12 has low surface gravity, although the $D_{0.15}$-color technique is ambiguous because of HVS12’s blue $(B-V)_0 = −0.05 \pm 0.04$ color. If HVS12 is a BHB star with $[Fe/H] = −1.5$, then it has $M_V$(BHB)$\approx +1.2$ (Brown et al. 2008), and is located at $R \approx 50$ kpc. HVS12 is clearly unbound at this distance (see Figure 3).

Interestingly, HVS12 was previously classified as a BHB star by Sirko et al. (2004a), Sirko et al. (2004a) published a sample of 1170 BHB stars observed as misidentified quasars and filler objects in the SDSS spectroscopic survey. For HVS12 they report a 532 ± 35 km s$^{-1}$ heliocentric velocity and a 0.847 Ca $\equiv$ equivalent width, consistent at the 1-σ level with our own measurements. Xue et al. (2008) have recently re-analyzed the SDSS BHB sample and combined it with additional targeted observations from the SEGUE survey. Xue et al. (2008) classify HVS12 as a possible BHB star, but exclude it from their rigorously selected BHB sample. High $S/N$ spectroscopy and photometry is required to confirm the nature of HVS12.

Although HVS12 is a clear outlier in the velocity distribution of BHB stars (see Figure 4 of Sirko et al. 2004b), HVS12 was not previously recognized as an unbound star. The median depth of the Sirko et al. (2004a) sample is $q_0 = 17.35$, corresponding to a distance of $\sim$15 kpc for a BHB star (see Figure 5). A star with $v_{rf} \approx 400$ km s$^{-1}$ at the median depth of the Sirko et al. (2004a) sample is thus bound. What appears to have escaped notice,
however, is that HVS12 is fainter, and bluer, than 96% of the Sirko et al. (2004a) BHB sample.

Figure 5 compares the distribution of stars in our HVS surveys and the Sirko et al. (2004a) BHB sample in a color-magnitude diagram. For reference, we draw lines of constant distance for main sequence stars with solar abundance (solid lines, Girardi et al. 2002, 2004) and for halo BHB stars with [Fe/H] = −1.7 (dashed lines, Brown et al. 2008). Note that the color-magnitude selection of the new HVS survey is such that every star has $R > 40$ kpc, whether a main sequence star or a BHB star (Figure 4).

The presence of only one HVS among the 1170 Sirko et al. (2004a) BHB stars and the 10224 Xue et al. (2008) BHB candidates shows the immense dilution due to stars in the Galactic halo. It is important to minimize contamination from foreground stellar populations when looking for HVSs. Our surveys find HVSs because we target stars that are bluer and/or fainter than the bulk of halo BHB stars.

6. CONCLUSIONS

We describe a new targeted HVS survey, a spectroscopic survey of faint stars $19 < g′ < 20.5$ with early A-type and late B-type colors. Recent observations confirm that 3 of our B-type HVSs are 3-4 $M_\odot$ main sequence stars.

The observational signature of a HVS is its unbound velocity, which we determine by comparing observed radial velocities and distances to Galactic potential models. We argue that the known properties of binaries and the rarity of massive stars make a hyper-runaway like HD 271791 a rare object. A MBH ejection remains the most plausible origin of unbound low-mass stars.

Our HVS survey is 59% complete and, combined with our original HVS survey, shows a remarkable velocity distribution: 26 stars with $v_{rf} > +275$ km s$^{-1}$ and only 2 stars with $v_{rf} < -275$ km s$^{-1}$. Here we report the discovery of 6 new unbound HVSs in excess of the conservative escape velocity model of Kenyon et al. (2008), and 4 additional unbound HVSs in excess of the escape velocity model of Xue et al. (2008).

One of the new HVSs may be an evolved BHB star. The Kenyon et al. (2008) ejection models predict BHB HVSs are $\sim 10$ times less abundant than the main sequence HVSs in our survey, consistent with the existence of 1 ± 1 BHB stars in our HVS sample. Of course, the exact number of BHB HVSs depends on the mass function of stars near the central MBH. BHB HVSs therefore have the potential to probe the low-mass regime of HVSs and constrain the mass function of stars in the Galactic center.

HVSs are fascinating because their properties are tied to the nature and environment of the MBH that ejects them (Levin 2006; Baumgardt et al. 2006; Merritt 2006; Ginsburg & Loeb 2006, 2007; Demarque & Virani 2007; Gualandris & Portegies Zwart 2007; Sesana et al. 2006, 2007a, b, c; Lu et al. 2007; Kollmeier & Gould 2007; Hansen 2007; Perets et al. 2007; Perets 2008; Sherwin et al. 2008; Svensson et al. 2008; O’Leary & Loeb 2008; Lockmann & Baumgardt 2008), and their trajectories probe the dark matter halo through which they move (Gnedin et al. 2005; Yu & Madau 2007; Wu et al. 2008; Kenyon et al. 2008).

Our ultimate goal is to find a statistical sample of $\sim 100$ HVSs to measure the distribution of HVS properties and discriminate HVS ejection models.

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Facilities: MMT (Blue Channel Spectrograph)

APPENDIX

DATA TABLE

Table A2 presents the 19 $z \sim 2.4$ quasars and 9 DA white dwarfs in our survey. Table columns include RA and Dec coordinates (J2000), $g′$ apparent magnitude, $(u′ − g′)_0$ and $(g′ − r′)_0$ color, and spectroscopic identification.
### Table A2
QUASARS AND WHITE DWARFS

| RA   | Dec  | g'   | (u' - g')_0 | (g' - r')_0 | Type |
|------|------|------|-------------|-------------|------|
| 4:06:24.10 | -4:19:34.0 | 20.594 | 0.763 | -0.268 | QSO |
| 8:05:30.10 | 2:18:45.9 | 20.448 | 0.804 | -0.225 | QSO |
| 8:06:21.32 | 33:38:32.8 | 19.993 | 0.649 | -0.244 | WD |
| 8:23:36.89 | 1:52:55.9 | 20.445 | 0.873 | -0.220 | QSO |
| 9:03:21.90 | 49:51:49.0 | 20.315 | 0.639 | -0.276 | WD |
| 9:19:14.83 | 12:52:06.0 | 20.014 | 0.725 | -0.250 | WD |
| 9:22:11.31 | 45:57:19.4 | 20.244 | 0.900 | -0.270 | QSO |
| 9:52:18.52 | 33:24:46.4 | 20.110 | 0.638 | -0.250 | WD |
| 10:00:52.77 | 40:51:23.3 | 20.078 | 1.021 | -0.216 | QSO |
| 10:18:11.91 | 50:16:00.9 | 20.422 | 0.611 | -0.292 | QSO |
| 10:42:58.03 | 28:30:33.4 | 20.361 | 1.000 | -0.344 | QSO |
| 10:45:01.96 | -1:19:46.7 | 20.284 | 0.673 | -0.263 | QSO |
| 11:02:16.15 | 7:54:20.7 | 19.773 | 0.853 | -0.211 | QSO |
| 11:10:19.82 | 59:14:59.3 | 19.753 | 0.887 | -0.291 | QSO |
| 11:18:54.44 | 30:27:09.9 | 20.366 | 0.757 | -0.239 | QSO |
| 11:41:02.74 | 42:20:34.0 | 20.561 | 0.847 | -0.337 | QSO |
| 11:56:56.37 | 22:41:55.3 | 20.141 | 0.794 | -0.271 | QSO |
| 11:57:26.83 | -1:29:14.9 | 19.872 | 0.610 | -0.271 | WD |
| 12:15:53.64 | 34:23:18.2 | 20.058 | 0.831 | -0.223 | QSO |
| 12:29:08.32 | 49:58:27.2 | 20.416 | 0.961 | -0.213 | QSO |
| 13:07:54.94 | 48:35:25.9 | 20.168 | 0.661 | -0.238 | QSO |
| 14:13:42.51 | 44:25:50.0 | 20.457 | 0.807 | -0.224 | QSO |
| 14:22:00.74 | 43:52:53.2 | 19.821 | 0.715 | -0.271 | WD |
| 15:33:00.04 | 49:29:48.3 | 19.278 | 0.611 | -0.248 | WD |
| 15:43:24.56 | 36:26:49.5 | 19.599 | 0.926 | -0.275 | QSO |
| 15:58:51.85 | 22:21:59.9 | 19.671 | 0.817 | -0.292 | QSO |
| 16:11:27.35 | 26:56:10.9 | 19.977 | 0.647 | -0.205 | WD |
| 17:40:43.32 | 67:24:41.5 | 19.680 | 0.663 | -0.268 | WD |
