

A SUCCESSFUL TARGETED SEARCH FOR HYPERVELOCITY STARS

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ABSTRACT

Hypervelocity stars (HVSs) travel with velocities so extreme that dynamical ejection from a massive black hole is their only suggested origin. Following the discovery of the first HVS by Brown and collaborators, we have undertaken a dedicated survey for more HVSs in the Galactic halo and present here the resulting discovery of two new HVSs: SDSS J091301.0+305120 and SDSS J091759.5+672238, traveling with Galactic rest-frame velocities of at least $+558 \pm 12$ and $+638 \pm 12$ km s⁻¹, respectively. Assuming the HVSs are B8 main-sequence stars, they are at distances of ~ 75 and ~ 55 kpc, respectively, and have travel times from the Galactic center consistent with their lifetimes. The existence of two B8 HVSs in our 1900 deg² survey, combined with the Yu & Tremaine HVS rate estimates, is consistent with HVSs drawn from a standard initial mass function but inconsistent with HVS drawn from a truncated mass function like the one in the top-heavy Arches cluster. The travel times of the five currently known HVSs provide no evidence for a burst of HVSs from a major infall event at the Galactic center in the last ~ 160 Myr.

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

1. INTRODUCTION

All galaxies with bulges probably host massive black holes (MBHs) in their centers. Hills (1988) first showed that a three-body interaction involving a MBH and a stellar binary can eject one member of the binary with >1000 km s⁻¹ velocity. Hills called stars ejected with >1000 km s⁻¹ velocities “hypervelocity stars.” Hypervelocity stars (HVSs) are thus a natural consequence of the presence of a massive black hole in a dense stellar environment.

Brown et al. (2005) reported the first discovery of an HVS: a $g' = 19.8$ late B-type star, ~ 110 kpc distant in the Galactic halo, traveling with a Galactic rest-frame velocity of at least $+709 \pm 12$ km s⁻¹ (heliocentric radial velocity $+853$ km s⁻¹). Photometric follow-up revealed that the object is a slowly pulsating B main-sequence star (Fuentes et al. 2006). Only interaction with an MBH can plausibly accelerate a $3 M_{\odot}$ main-sequence B star to such an extreme velocity.

Our HVS discovery inspired a wealth of work from both observers and theorists. Edelmann et al. (2005) report a $8 M_{\odot}$ main-sequence B star, ~ 60 kpc distant, traveling with a Galactic rest-frame velocity of at least $+548$ km s⁻¹ that may be an HVS ejected from the LMC. Hirsch et al. (2005) report a helium-rich subluminescent O star, ~ 20 kpc distant, traveling with a Galactic rest-frame velocity of at least $+717$ km s⁻¹ that is probably an HVS ejected from the Galactic center. Holley-Bockelmann et al. (2006) suggest that outliers in the velocity distribution of intra-cluster planetary nebulae around M87 may be HVSs. In this Letter, we report the discovery of two more HVSs from our ongoing HVS survey.

With HVSs now an observed class of objects, it is important to define true HVSs. Runaway B stars located many kiloparsecs above the Galactic plane have long been known, but their velocities are typically $\lesssim 200$ km s⁻¹, and they are very probably bound to the Galaxy. HVSs, on the other hand, are unbound. More importantly, the classical supernova ejection (Blaauw 1961) and dynamical ejection (Poveda et al. 1967) mechanisms

that explain runaway B stars cannot produce ejection velocities that exceed ~ 300 km s⁻¹ (Leonard 1993; Gualandris et al. 2005). Thus, we relax Hill’s 1000 km s⁻¹ velocity requirement and define an HVS as an unbound star with an extreme velocity that can be explained so far only by dynamical ejection associated with an MBH.

HVSs are important tools for understanding the nature and environs of MBHs: Holley-Bockelmann et al. (2006) predict that a thin torus of ejected HVSs is the signature of two MBHs forming a tight binary. Ginsburg & Loeb (2006) suggest that the stars on highly eccentric orbits around Sgr A* may be the former companion stars to HVSs ejected by the MBH. Levin (2005) shows that an intermediate-mass black hole (IMBH) on a circular inspiral into the Galactic center produces an isotropic burst of HVSs; an IMBH on an eccentric inspiral produces broad jets of HVSs. Gualandris et al. (2005) find that HVSs produced from stellar binary encounters with single MBHs have higher ejection velocities than HVSs from binary MBHs. Gnedin et al. (2005) show that the distance and full space motion of HVSs can provide significant constraints on the shape and orientation of the Galactic dark matter halo. Yu & Tremaine (2003) expand Hill’s original analysis and show that single-star encounters with binary MBHs produce ~ 10 times more HVSs than stellar binary encounters with single MBHs.

Our Letter is organized as follows. In § 2 we describe our survey target selection and observations. In § 3 we present the new HVSs. We conclude in § 4 by discussing what the observed set of HVSs implies about their origin and the nature of the Galactic center.

2. DATA

2.1. Target Selection

HVSs ought to be rare: Yu & Tremaine (2003) predict there should be $\sim 10^3$ HVSs in the entire Galaxy. Thus, in any search for HVSs, survey volume is important. Solar neighborhood surveys have not discovered HVSs because, even if they were perfectly complete to a depth of $d = 1$ kpc, there is an $\sim 0.1\%$

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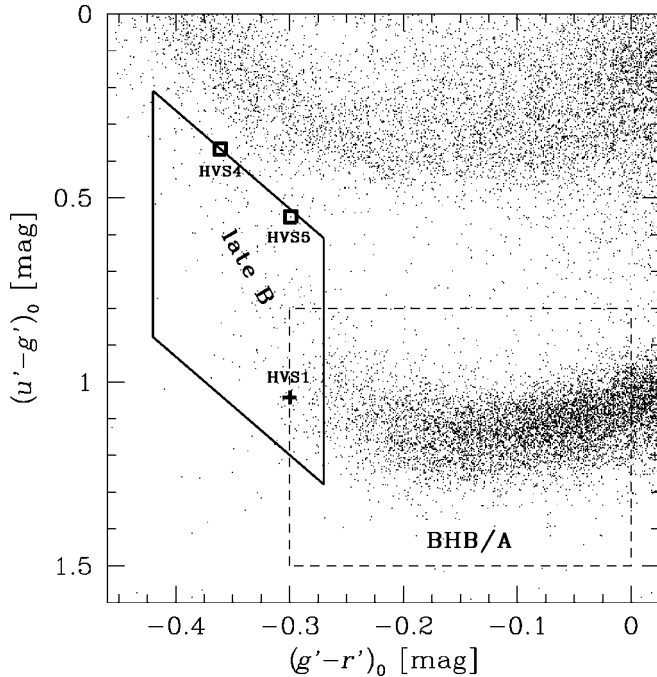


FIG. 1.—Color-color diagram showing our color selection, illustrated with every star in the SDSS DR4 $17.5 < g'_0 < 18.5$. For reference, BHB/A stars are located in the dashed box (Yanny et al. 2000). Candidate late B-type stars are seen extending up the stellar sequence toward the ensemble of white dwarfs and are selected by the solid parallelogram. The original HVS1 (Brown et al. 2005) is marked by plus sign, and the new HVSs are marked by open squares.

chance of finding an HVS in such a small volume. Finding a new HVS among the Galaxy's $\sim 10^{11}$ stars also requires a selection of targets with a high probability of being HVSs. Our observational strategy is twofold. Because the density of stars in the Galactic halo drops off as approximately r^{-3} , and the density of HVSs drops off as r^{-2} (if they are produced at a constant rate), we target distant stars where the contrast between the density of HVSs and that of indigenous stars is as large as possible. Second, the stellar halo contains mostly old, late-type stars. Thus, we target faint B-type stars, stars with lifetimes consistent with travel times from the Galactic center but that are not a normally expected stellar halo population. This strategy makes sense because 90% of the $K < 16$ stars in the central 0.5° of the Galactic center are in fact normal main-sequence B stars (Eisenhauer et al. 2005).

We use SDSS photometry to select candidate B stars by color. To illustrate the color selection, Figure 1 shows a color-color diagram of stars with B- and A-type colors in the Sloan Digital Sky Survey Fourth Data Release (SDSS DR4; Adelman-McCarthy et al. 2006). We use dereddened colors computed from $E(B - V)$ values obtained from Schlegel et al. (1998). The dashed box indicates the selection region used by Yanny et al. (2000) to identify blue horizontal-branch (BHB) candidates. Interestingly, there is a faint group of stars with late B-type colors extending up the stellar sequence toward the ensemble of white dwarfs with $(u' - g')_0 \lesssim 0.5$. We select candidate B stars inside the solid parallelogram defined by $-0.42 < (g' - r')_0 < -0.27$ and $2.67(g' - r')_0 + 1.33 < (u' - g')_0 < 2.67(g' - r')_0 + 2.0$.

Our sample of candidate B stars is 100% complete in the magnitude range $17.0 < g'_0 < 19.5$. We observed a complete sample of 79 candidate B stars in the 1900 deg^2 region of the SDSS DR4 bounded by $7^{\text{h}}40^{\text{m}} < \text{R.A.} < 10^{\text{h}}50^{\text{m}}$ and $\text{decl.} > 15^\circ$. Figure 2 displays the locations of the objects on the sky.

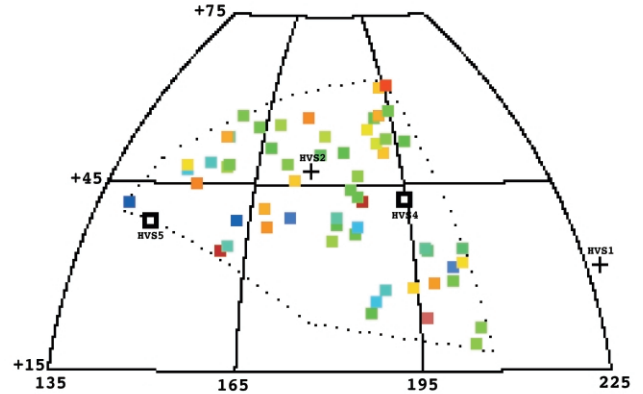


FIG. 2.—Aitoff sky map, in Galactic coordinates, showing the complete sample of 61 late B-type stars. Dotted lines indicate the 1900 deg^2 region of the SDSS DR4 we observed. Radial velocities, in the Galactic rest frame, are indicated by the color of the solid squares: purple is -300 , green is 0 , and red is $+300 \text{ km s}^{-1}$. The new HVSs are completely off this color scale and are marked by open squares; HVS1 (Brown et al. 2005) and HVS2 (Hirsch et al. 2005) are marked by plus signs.

The Hirsch et al. (2005) HVS is located in this region on the sky, but it is not a part of our survey because its photometric colors lie far outside of our selection box.

2.2. Spectroscopic Observations

Observations were obtained on the nights of 2005 December 3–5 with the Blue Channel Spectrograph on the 6.5 m MMT telescope. The spectrograph was operated with the 832 line mm^{-1} grating in second order, providing 1.2 \AA spectral resolution and $3660\text{--}4500 \text{ \AA}$ wavelength coverage. Exposure times ranged from 5 to 30 minutes and were chosen to yield a signal-to-noise ratio of 15 in the continuum at 4000 \AA . Comparison lamp exposures were obtained after every exposure.

Radial velocities were measured using the cross-correlation package RVSAO (Kurtz & Mink 1998). The average uncertainty is $\pm 12 \text{ km s}^{-1}$. We correct the heliocentric velocities to the local standard of rest (Hogg et al. 2005) and remove the 220 km s^{-1} solar reflex motion. Thus, all velocities reported here are in the Galactic rest frame, indicated v_{RF} . The velocities of the candidate B stars are indicated by color in Figure 2.

2.3. Selection Efficiency and Unusual Objects

Our sample of 79 targets is composed of 61 late B-type stars, 17 faint (mostly DA) white dwarfs, and one low- z galaxy. We derive spectral types of the late B-type stars based on line indices described in Brown et al. (2003); the types range from B6 to A1. Thus, our target selection is 77% efficient for selecting stars of late B spectral type. Changing the color selection edge from $(g' - r')_0 = -0.42$ to -0.38 would eliminate more than half of the white dwarfs and the galaxy, and would increase the target selection efficiency for late B-type stars to 90%. We plan to publish the faint white dwarfs and other unusual objects in a future paper describing the HVS survey as a whole.

3. HYPERVELOCITY STARS

Our targeted search for HVSs uncovered two new HVSs, SDSS J091301.0+305120 (hereafter HVS4) and SDSS J091759.5+672238 (hereafter HVS5). Figure 3 plots a histogram of Galactic rest-frame radial velocity for the 61 late B-type stars in our sample.

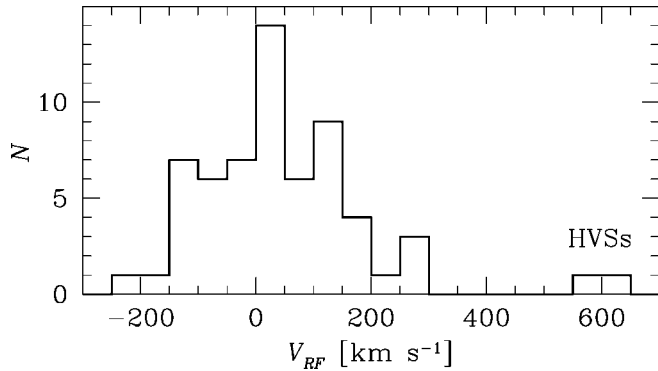


FIG. 3.—Velocity histogram of the late B-type stars. Two new HVSs are identified moving away with Galactic rest-frame velocities of at least $+558$ and $+638$ km s^{-1} .

Ignoring the HVSs, our sample has a velocity dispersion of ± 114 km s^{-1} consistent with a Galactic halo population. HVS4 and HVS5 are traveling with $v_{\text{RF}} = +558 \pm 12$ and $+638 \pm 12$ km s^{-1} (heliocentric radial velocities $+603$ and $+543$ km s^{-1}), respectively, and are 5σ outliers from this distribution. The escape velocity of the Galaxy is approximately 300 km s^{-1} at 50 kpc (Wilkinson & Evans 1999); thus, HVS4 and HVS5 are clearly unbound to the Galaxy.

The new HVSs are not physically associated with any other Local Group galaxy. HVS4 and HVS5 are located at $(l, b) = (194.8, 42.6)$ and $(146.3, 38.7)$, respectively (see Fig. 2). HVS4 is separated from Leo A by 10° on the sky, but the galaxy is in the distant background 800 kpc away (Dolphin et al. 2002). Even if HVS4 were a $M_V = -6$ supergiant at the distance of Leo A, the star's radial velocity differs from Leo A by 575 km s^{-1} . The closest galaxy to HVS5 is the Ursa Minor dwarf 31° away, yet the velocity difference is even more extreme at 730 km s^{-1} .

Both HVS4 and HVS5 have spectral types consistent with B8; however, our low-resolution spectra do not allow us to determine exact stellar parameters. Stars of this spectral type are likely BHB stars or main-sequence B stars/blue stragglers. Two of the three previously reported HVSs are main-sequence B stars (Fuentes et al. 2006; Edelmann et al. 2005). We note that the Balmer line widths of HVS4 and HVS5 are too broad to be consistent with those of luminosity class I B supergiants. If we assume the HVSs are BHB stars rather than B stars, their blue colors mean they are hot, extreme BHB stars, and thus they are intrinsically very faint. The $M_V(\text{BHB})$ relation of Clewley et al. (2002) yields $M_V(\text{BHB}) \approx +2.0$ and $+1.5$ and heliocentric distance estimates $d_{\text{BHB}} \approx 20$ and 18 kpc for HVS4 and HVS5, respectively. In the BHB interpretation, the volume we effectively survey is much smaller than in the B star interpretation. Thus, the BHB interpretation requires more than

an order of magnitude larger production rate for HVSs. Because two of the previous HVSs are B stars and because the B star interpretation implies a lower production rate probably consistent with Yu & Tremaine (2003), we assume that HVS4 and HVS5 are B stars for the purpose of discussion. The ultimate discriminant will come from higher resolution, higher signal-to-noise ratio spectroscopy.

We estimate the luminosity of a B8 star from the Schaller et al. (1992) stellar evolution tracks for a $4 M_\odot$ star with $Z = 0.02$. Such a star spends 160 Myr on the main sequence and produces $400 L_\odot$ at $T_{\text{eff}} \sim 13,000$. This luminosity corresponds to $M_V(\text{B8}) \approx -0.9$ (using a bolometric correction of -0.80 ; Kenyon & Hartmann 1995) and heliocentric distances $d_{\text{B8}} \approx 75$ and 55 kpc for HVS4 and HVS5, respectively. Assuming the Sun is 8 kpc distant from the Galactic center, the galactocentric distances of HVS4 and HVS5 are thus $r \approx 80$ and 60 kpc, respectively.

If HVS4 and HVS5 originate from the Galactic center, the travel times to their present locations are approximately 130 and 90 Myr, respectively, consistent with the 160 Myr main-sequence lifetime of a $4 M_\odot$ star. If the HVSs are BHBs or blue stragglers, their lifetimes are considerably longer, and the travel time constraint is relaxed.

Our radial velocities provide only a *lower* limit to the HVSs' true space velocities. HVS4 and HVS5 have bright apparent magnitudes ($g' = 18.40$ and 17.93 , respectively) and are present in the USNOB1 (Monet et al. 2003) and GSC2.3 (B. McLean, 2006 private communication) catalogs. However, the HVSs are listed with no measurable proper motions, consistent with the estimated distances.

Table 1 summarizes the properties of all five known HVSs. The columns include, from left to right, the HVS identification number, Galactic coordinates (l, b) , apparent magnitude g' , minimum Galactic rest-frame velocity v_{RF} (not a full space velocity), heliocentric distance estimate d , travel time estimate from the Galactic center t_{GC} , and catalog identification. We note that the B9 M_V estimate was incorrect in Brown et al. (2005) and should be $M_V(\text{B9}) = -0.3$. Thus, the correct distance and travel time estimates to HVS1 are $d \sim 110$ kpc and $t_{\text{GC}} \sim 160$ Myr, as indicated.

4. DISCUSSION

The very existence of the HVSs places interesting limits on the stellar mass function of HVSs, the origin of massive stars in the Galactic center, and the history of stellar interactions with the MBH. Interestingly, all five known HVSs are moving with positive radial velocity, consistent with the picture of a Galactic center origin.

In principle, we can constrain the stellar population from which the HVSs originate by combining predictions of HVS

TABLE 1
HYPERVELOCITY STARS

ID	l (deg)	b (deg)	g' (mag)	v_{RF} (km s^{-1})	d (kpc)	t_{GC} (Myr)	Catalog ID
HVS1	227.3	31.3	19.8	+709	110	160	SDSS J090745.0+024507 ^a
HVS2	176.0	47.1	18.8	+717	19	32	US 708 ^b
HVS3	263.0	-40.9	16.2	+548	61	100	HE 0437-5439 ^c
HVS4	194.8	42.6	18.4	+558	75	130	SDSS J091301.0+305120
HVS5	146.3	38.7	17.9	+638	55	90	SDSS J091759.5+672238

^a Brown et al. (2005).

^b Hirsch et al. (2005).

^c Edelmann et al. (2005).

rates with the results of our survey. Yu & Tremaine (2003) predict an HVS rate of $\sim 10^{-5} \text{ yr}^{-1}$ ejected by a single MBH at the Galactic center. An HVS moving 600 km s^{-1} travels 120 kpc in 200 Myr; thus, the Yu & Tremaine (2003) rate implies ~ 2000 HVSs of all types to a depth of 120 kpc. Our $g'_0 < 19.5$ magnitude-limited survey reaches the same depth $d = 120 \text{ kpc}$ for B8 stars, and we find two B8 HVSs over our 1900 deg^2 region, implying 43 ± 31 B8 HVSs over the entire sky. We ask whether this number of B stars is consistent with the number expected from a standard initial mass function (IMF). We make the simple assumption that HVSs sample the full range of stellar mass uniformly; we do not account for variations in the binary fraction as a function of stellar mass. A Salpeter IMF (Salpeter 1955), integrated over the mass range $0.2\text{--}100 M_\odot$ and normalized to 2000 stars, contains 26 stars between 3 and $5 M_\odot$. A Scalo IMF (Scalo 1986), similarly calculated, contains 13 stars between 3 and $5 M_\odot$. The IMF predictions are systematically lower than the observed frequency implied by the two B stars in our survey, but because of small number statistics there is no significant inconsistency.

In the Galactic center, there is some indication that the IMF is top-heavy. For example, Stolte et al. (2005) study the mass-segregated Arches cluster and argue for truncation at masses less than $6 M_\odot$. Integrating the Stolte et al. (2005) mass function $\Gamma = -0.86$ over the mass range $3\text{--}100 M_\odot$ and normalizing it to 2000 stars result in $750\text{--}5 M_\odot$ stars, an order of magnitude more late B HVSs than implied by our observations. Thus, our observations already indicate that the HVS parent population is not composed entirely of clusters like Arches or that the Yu & Tremaine (2003) HVS rate is an underestimate.

HVS travel times from the Galactic center constrain the history of stellar interactions with the MBH. Assuming the new HVSs are B stars, travel time estimates for the known HVSs are spread rather uniformly between 30 and 160 Myr. Thus, there is as yet no evidence for a burst of HVSs from a major

infall event at the Galactic center in the last ~ 160 Myr. The current constraints are less clear if HVS4 or HVS5 are not B stars. If new discoveries of HVSs continue to show no evidence for coherent bursts of HVSs, theories of infalling massive star clusters (Gerhard 2001; Kim & Morris 2003) possibly containing an IMBH (Hansen & Milosavljević 2003) to transport B stars near the MBH may not be applicable to the Galaxy.

It is interesting that the northern HVSs all have similar $b \sim 40^\circ$ (see Fig. 2). An inspiraling binary black hole produces a unique distribution of HVSs on the sky (Levin 2005; Holley-Bockelmann et al. 2006). Detailed theoretical predictions of the distribution of HVSs on the sky ejected by a single MBH at the Galactic center would be an important test bed for future HVS observations.

HVSs are becoming important tools for understanding MBHs. Discovering additional HVSs in a well-defined volume will provide better constraints on the origin of HVSs and the nature of the Galactic center. Proper-motion measurements of HVSs, measured with the *Hubble Space Telescope*, *Gaia*, or the *Space Interferometry Mission*, may provide significant constraints on the shape of the Galaxy's dark matter potential (Gnedin et al. 2005). The distribution of HVSs in velocity and space may constrain the history of stellar interactions with the MBH. Identifying HVSs around other galaxies (Holley-Bockelmann et al. 2006) is also an exciting prospect. We are continuing our radial velocity survey of every late B-type star in the SDSS.

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Facilities: MMT(Blue Channel Spectrograph)

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