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DISCOVERY OF AN UNBOUND HYPERVELOCITY STAR IN THE MILKY WAY HALO

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ABSTRACT

We have discovered a star, SDSS J090745.0+024507, leaving the Galaxy with a heliocentric radial velocity of 853 ± 12 km s^{-1}, the largest velocity ever observed in the Milky Way halo. The star is either a hot blue horizontal-branch star or a B9 main-sequence star with a heliocentric distance of 39 or 71 kpc, respectively. Corrected for the solar reflex motion and to the local standard of rest, the Galactic rest-frame velocity is 709 km s^{-1}. We suggest that this star is the first example of a hypervelocity star ejected from the Galactic center, as predicted by Hills and later discussed by Yu & Tremaine. The star's radial velocity vector points 174° from the Galactic center. The star has [Fe/H] $\sim$ 0, consistent with a Galactic center origin, and a travel time of $\lesssim$80 Myr from the Galactic center, consistent with its stellar lifetime. If the star is indeed traveling from the Galactic center, it should have a proper motion of ~0.3 mas yr^{-1} observable with the *Space Interferometry Mission* or the *Global Astrometric Interferometer for Astrophysics*. Identifying additional hypervelocity stars throughout the halo will constrain the production rate history of hypervelocity stars at the Galactic center.

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

1. INTRODUCTION

In a prescient paper, Hills (1988) suggests that a stellar binary interaction with the Milky Way's central black hole could eject one member of the binary with a velocity >1000 km s^{-1}. Yu & Tremaine (2003) further develop Hill's analysis and suggest two additional mechanisms to eject "hypervelocity" stars (HVSs) from the Galactic center: close encounters of two single stars and three-body interactions between a single star and a binary black hole. Yu & Tremaine (2003) predict production rates for all three mechanisms. Even the discovery of a single HVS can place important constraints on the formation mechanism and the nature of the Galactic center.

In our survey of faint blue horizontal-branch (BHB) candidates in the Galactic halo, we have discovered a star, SDSS J090745.0+024507, traveling with a heliocentric radial velocity of 853 ± 12 km s^{-1}. Corrected to the local standard of rest and for the solar reflex motion, the Galactic rest-frame velocity of this star is $v_{\rm RF} = 709$ km s^{-1}. The observed radial velocity is only a *lower* limit to the star's true space velocity, but the radial velocity alone substantially exceeds the escape velocity from the Galaxy.

The distance to the HVS is 55 ± 16 kpc (see below). At a galactocentric distance of 50 kpc, the mass of the Milky Way is $5.4 \times 10^{11}\ M_\odot$ (Wilkinson & Evans 1999) and the escape velocity is 305 km s^{-1}. Thus, the HVS is moving well over *twice* the escape velocity and in a direction 174° from the Galactic center.

By comparison, traditional "high-velocity" and "runaway" stars are stars with peculiar velocities greater than 30 km s^{-1}. High-velocity stars are typically early-type stars in the Galactic disk moving away from star formation regions (e.g., Hoogerwerf et al. 2001). Runaway B-type stars have been observed up to ~15 kpc above the Galactic plane and moving with radial velocities up to 200 km s^{-1} (Lynn et al. 2004; Magee et al. 2001; Ramspeck et al. 2001; Rolleston et al. 1999; Mitchell et al. 1998; Holmgren et al. 1992; Conlon et al. 1990). The highest velocity halo star was observed by Carney et al. (1988) moving through the solar neighborhood with a total Galactic rest-frame velocity of 490 km s^{-1}. In all cases, these high-velocity and runaway stars are very probably bound to the Galaxy.

In § 2, we describe the target selection and the spectroscopic observations of our BHB candidate sample. The HVS is a 6 σ outlier from the distribution of radial velocities of this sample. In § 3, we demonstrate the robustness of the radial velocity and discuss the HVS's stellar properties. In § 4, we discuss the significance of the star's hypervelocity.

2. TARGET SELECTION AND OBSERVATIONS

We have been using BHB stars to trace velocity structure in the Milky Way halo (Brown et al. 2003, 2004). In 2003, as part of an effort to measure the dynamical mass of the Milky Way more accurately, we used Sloan Digital Sky Survey (SDSS) Early Data Release and Data Release 1 photometry to select faint $19.75 < g'_0 < 20.25$ BHB candidates for spectroscopic observations. We identified BHB candidates by their A-type colors following Yanny et al. (2000): $0.8 < (u' - g') < 1.5$, $-0.3 < (g' - r') < 0.0$. Figure 1 shows this color selection box and colors of the 36 observed BHB candidates. The density of BHB candidates in this color/magnitude range is 0.3 objects deg^{-2}. Our observational strategy was to observe objects well placed in the sky at the time of observation. Thus, our sample of 36 stars is "randomly" selected from the area covered by the SDSS Early Data Release and Data Release 1.

We obtained spectra of the 36 BHB candidates with the 6.5 m MMT telescope during 2003 April, July, and December. We used the MMT Blue Channel spectrograph with an 832 line mm^{-1} grating in second order. This setup provides 1.0 Å spectral resolution using a 1″ slit. With a dispersion of 0.36 Å pixel^{-1} on the 2688 × 512 CCD, our spectral coverage is 950 Å. All observations were made at the parallactic angle. On nights of good seeing <1″, we obtained S/N $\sim$ 20 at 4000 Å in 1 hr of integration.

The 36 BHB/A stars are all located in the Galactic halo with heliocentric distances in the range 30 kpc $< d <$ 80 kpc. We measure heliocentric radial velocities using the cross-correlation package RVSAO (Kurtz & Mink 1998). We correct the velocities to the local standard of rest (Dehnen & Binney 1998).

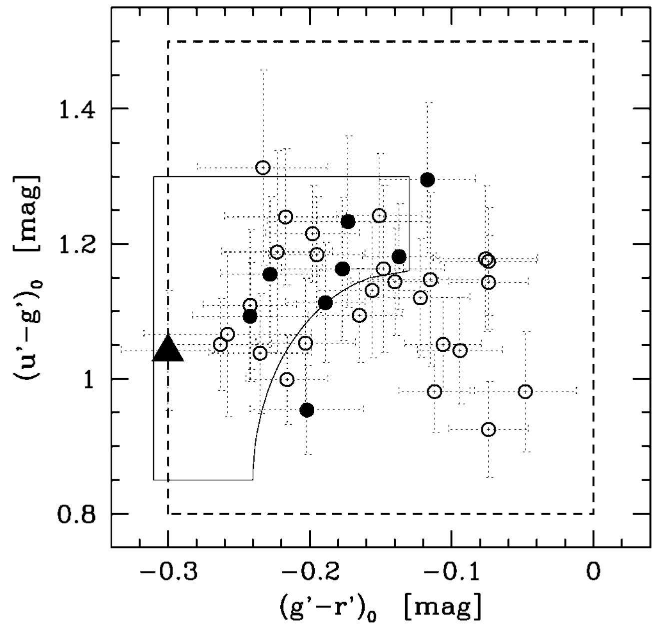

FIG. 1.—Color-color plot of our sample. The dashed box indicates the selection box for A-type stars. Symbols mark the colors of observed targets, with filled circles marking the BHB stars. Most of the filled circles fall in the Sirko et al. (2004) BHB selection box indicated by the solid line. The filled triangle marks the HVS.

We assume the stellar halo has no mean rotation and correct the velocities for the reflex motion of the local 220 km s^{-1} orbital motion.

Figure 2 plots a histogram of the radial velocities in the Galactic rest frame for all 36 BHB/A stars. Ignoring the HVS, the sample has a velocity dispersion of ±120 km s^{-1}, consistent with a halo population. The mean velocity of the sample (when we ignore the HVS) is −7 km s^{-1}. The 709 ± 12 km s^{-1} HVS, SDSS 090745.0+024507, is a 6 σ outlier from the observed distribution of radial velocities.

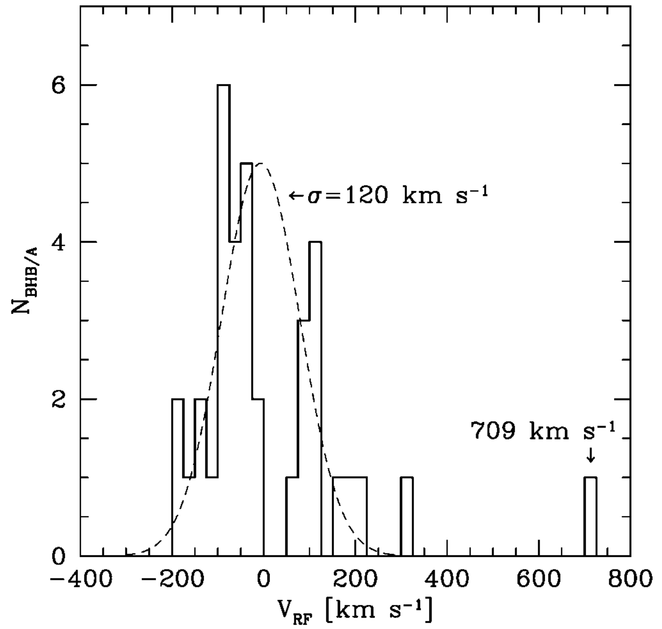

FIG. 2.—Galactic rest-frame radial velocity distribution for our 36 BHB/A star sample. The HVS is a 6 σ outlier from the observed distribution.

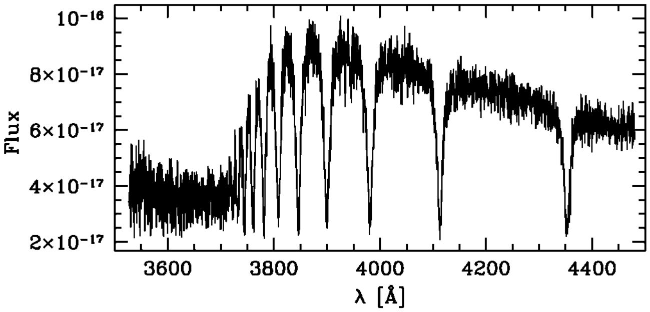

FIG. 3.—MMT spectrum of the HVS.

3. THE HYPERVELOCITY STAR

The HVS is located at $9^{\mathrm{h}}07^{\mathrm{m}}45\overset{\mathrm{s}}{.}0$, $+2°45'07''$ (J2000.0). In Galactic coordinates, the star is located at (l, b) = (227°20′07″, +31°19′55″).

Figure 3 shows the MMT Blue Channel spectrum of the HVS. The spectrum represents 60 minutes of integration time and has S/N = 20 at 4000 Å. The spectrum shows a raw heliocentric radial velocity of 853 ± 12 km s^{-1}. Corrected to the local standard of rest, the Galactic velocity components are $U = -491$ km s^{-1} (radially outward), $V = -532$ km s^{-1} (opposite the Galactic rotation direction), and $W = 441$ km s^{-1} (vertically upward).

3.1. *Verifying the Radial Velocity*

The substantial radial velocity is evident even from inspection of the two-dimensional spectra. Figure 4 shows the Hγ line of the HVS shifted nearly on top of the night-sky line at 4358.34 Å.

Moreover, the spectrum in Figure 3 is not based on a single observation but on a series of three 20 minute observations obtained over 1 hr. The wavelength solution for the three observations is nearly identical to the wavelength solutions obtained throughout the rest of that night. We verify the wavelength solution by measuring the velocity of the night-sky lines. The Hg line at 4358.34 Å (see Fig. 4) has the best signal-to-noise ratio and a −0.7 ± 2.5 km s^{-1} velocity consistent with zero. We conclude that the wavelength solution is robust.

We measure radial velocities for the three individual obser-

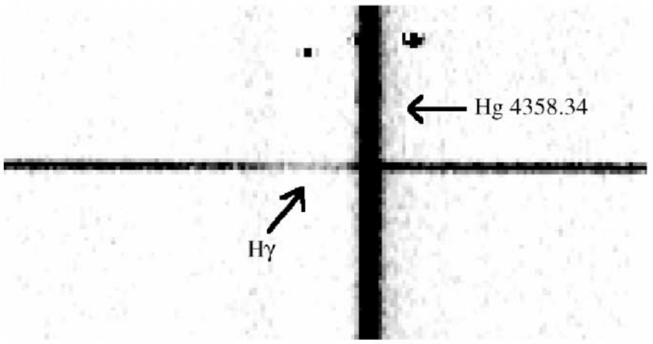

FIG. 4.—Portion of the two-dimensional spectrum. The large radial velocity is evident from Hγ being shifted nearly on top of the night-sky Hg line at 4358.34 Å.

vations and find that the velocities agree to ± 5 km s^{-1}. Moreover, we measure radial velocities using three different stellar templates (for B7, B9, and A1 spectral types) and find that the velocities agree to ± 3 km s^{-1}. We conclude the radial velocity is accurate. If the HVS were a close binary, any systematic velocity offset is likely to be small fraction of the observed velocity.

3.2. *Stellar Properties*

The HVS has dereddened colors $(u' - g')_0 = 1.04 \pm 0.09$ and $(g' - r')_0 = -0.30 \pm 0.03$, marked by the filled triangle in Figure 1. These colors indicate it is probably a hot BHB star or a late B-type main-sequence star. Its apparent magnitude is $g' = 19.81 \pm 0.02$.

We classify the HVS's spectral type as B9.2, with an uncertainty of 1.2 spectral subtypes. This classification is based on line indices described in Brown et al. (2003). The spectral type is in perfect agreement with the star's estimated effective temperature, $T_{\rm eff} \sim 10{,}500$ K (R. Wilhelm 2004, private communication).

We measure the HVS's metallicity based on the equivalent width of the Ca II K line and the star's photometric colors. However, the Ca II K line provides little leverage on [Fe/H] at high $T_{\rm eff}$. Thus, there is considerable uncertainty in [Fe/H]. Interpolated tables (Wilhelm et al. 1999) show that [Fe/H] can range from -0.4 to well over 0.0; we conclude that the star's metallicity is roughly solar, [Fe/H] ~ 0.0. Solar metallicity suggests the HVS is probably a B9 main-sequence star, but it is not a compelling argument.

We estimate the HVS's surface gravity by measuring the size and steepness of its Balmer jump (Kinman et al. 1994) and the widths and the shapes of its Balmer lines (Clewley et al. 2002). These independent techniques indicate that the star is a low surface gravity BHB star. However, classification by surface gravity is ambiguous at this $T_{\rm eff}$. The $T_{\rm eff}$ and log g of the horizontal branch crosses the main sequence around ~10,000 K. Thus, we cannot reliably distinguish between a hot BHB or a B9 main-sequence star based on its surface gravity. This uncertainty is problematic for estimating the star's distance: a hot BHB star and a B9 main-sequence star with the same $T_{\rm eff}$ and log g differ in luminosity by a factor of ~4.

We estimate the HVS's distance, first assuming it is a hot BHB star. We calculate luminosity using the M_V(BHB) relation of Clewley et al. (2002), which combines the Gould & Popowski (1998) *Hipparcos*-derived M_V zero point, the Clementini et al. (2003) LMC-derived M_V-metallicity slope, and the Preston et al. (1991) M_V-temperature correction. If it is a hot BHB star, the HVS has $M_V({\rm BHB}) = 1.9$ and a heliocentric distance $d_{\rm BHB} = 39$ kpc. Hot BHB stars are intrinsically less luminous stars that hook down off the classical horizontal branch. We thus consider 39 kpc as a lower limit for the HVS's distance.

We next estimate the HVS's distance assuming it is a B9 main-sequence star. To estimate the luminosity of a B9 star, we look at the Schaller et al. (1992) stellar evolution tracks for a 3 $M_\odot$ star with $Z = 0.02$. Such a star spends 3.5×10^8 yr on the main sequence and produces 160 $L_\odot$ when it has $T_{\rm eff} \sim 10{,}500$ K. We convert this luminosity to absolute magnitude using the bolometric corrections of Kenyon & Hartmann (1995). If it is a B9 main-sequence star, the HVS has $M_V({\rm B9}) = 0.6$ and a heliocentric distance of $d_{\rm B9} = 71$ kpc.

For purposes of discussion, we assume the HVS has the average distance of these two estimates: $d = 55$ kpc. This estimate places the star at $z = 29(d/55)$ kpc above the Galactic disk and at $r = 60(d/55)$ kpc from the Galactic center.

4. DISCUSSION

Remarkably, Hills (1988) predicted the existence of HVSs as a consequence of the presence of a massive black hole at the Galactic center. Other mechanisms fail to produce velocities as large as the one we observe for the HVS. For example, the star is not associated with the Sgr stream, nor is its radial velocity consistent with any other member of the Local Group. Association with high-velocity clouds is unlikely given their low velocity dispersion of ± 120 km s^{-1} (Putman et al. 2002). The HVS is also unlikely to be in the tail of the Galactic halo velocity distribution: our target selection yields 10^4 stars over the entire sky, and we should have to observe 10^9 objects to find one 6 σ outlier. Supernova ejection (Blaauw 1961) and dynamical ejection (Poveda et al. 1967) are mechanisms thought to produce runaway B stars, but both mechanisms predict maximum ejection velocities of ~300 km s^{-1} (Leonard 1993).

Hills (1988) predicts that tightly bound stellar binaries encountering the central black hole can eject one star with velocity $\gtrsim$1000 km s^{-1} from the Galactic center. The HVS likely had an ~45 AU pericenter passage (Yu & Tremaine 2003) and left its companion in a tightly bound orbit around the Galactic center. Yu & Tremaine (2003) also predict that the close encounter of two single stars or the three-body interaction between a single star and a binary black hole can result in similar ejection velocities from the Galactic center. Yu & Tremaine (2003) show that the production rates for these mechanisms are: (1) 10^{-11} yr^{-1} for single-star encounters, (2) 10^{-5} yr^{-1} for binary star encounters with the central black hole, and (3) 10^{-4} yr^{-1} for single-star encounters with a binary black hole. Thus, the very existence of the HVS rules out the single-star encounter mechanism.

Recent measurements of stellar orbits around the Galactic center provide overwhelming evidence of a 4×10^6 $M_\odot$ black hole at the Galactic center (Ghez et al. 2003, 2005; Schödel et al. 2003). Although it is difficult to imagine a B star forming near the central black hole, many young, massive stars *are* observed within 1 pc of the Galactic center (e.g., Genzel et al. 2003). Moreover, one of the stars used to measure the mass of the black hole has a 45 ± 16 AU periapse and an orbital eccentricity $e = 0.974 \pm 0.016$, giving it a periapse velocity $12{,}000 \pm 2000$ km s^{-1} (Ghez et al. 2005).

The radial velocity vector of the HVS points 174° from the Galactic center, suggestive of a Galactic center origin. Even when we assume that the observed radial velocity is the full space motion of the HVS, the travel time from the Galactic center is $\lesssim$80 Myr. The lifetime of a B9 main-sequence star, by comparison, is approximately 350 Myr; the age of a star on the horizontal branch is much longer. Thus, the star's solar metallicity, its direction of travel, and its travel time are all consistent with a Galactic center origin.

If the HVS is traveling on a radial path from the Galactic center, we predict its proper motion is ~$0.3(d/55)$ mas yr^{-1}. The USNO-B1 catalog (Monet et al. 2003) and the Guide Star Catalog, version 2.3.1 (B. McLean 2005, private communication) list the star with a proper motion of 14 ± 12 and 20 ± 11 mas yr^{-1}, respectively, but in nearly opposite directions. The average of these proper motions is 3 ± 8 mas yr^{-1}, consistent with zero. We searched for the star on 50–100 yr old plates in the Harvard Plate Archive to increase the observed time baseline, but the HVS was too faint. The *Space Interferometry Mission* and the *Global Astrometric Interferometer for Astrophysics* mission should be able to observe 20 mag stars with accuracies of 0.004 mas yr^{-1} (A. Gould 2005, private communication) and 0.16 mas yr^{-1} (Perryman 2002), respectively, and thus may determine the full space motion of the HVS.

We can use our sample to place an upper limit on the production rate of HVSs. Our sample of 36 BHB/A stars fills an effective volume of $\sim 10^3$ kpc^3, indicating an upper limit on the density of hypervelocity BHB/A stars, $\sim 10^{-2}$ kpc^{-3}. If it takes 10^8 yr for an HVS to leave the Galaxy, the Yu & Tremaine (2003) production rates imply a total of 10^3–10^4 HVSs within the halo, a density of 10^{-3} to 10^{-2} kpc^{-3}. At first glance, there appears to be rough agreement between the observed and predicted density of HVSs. However, BHB/A stars represent only a small fraction of the total population of halo stars, and there are essentially no constraints on the fraction of the binary population they might represent near the Galactic center.

The discovery of an HVS, as predicted by Hills (1988) and Yu & Tremaine (2003), provides an interesting piece of new evidence for a massive black hole at the Galactic center. Ironically, this evidence comes from the radial velocity of a star ∼60 kpc from the Galactic center. We are now using the MMT Hectospec spectrograph, a 300 fiber spectrograph with a 1° diameter field of view (Fabricant et al. 1998), to observe additional $g'_0 \sim 20$ BHB candidates over wide areas of sky. The identification of more HVSs as a function of distance and position on the sky will place better constraints on the production mechanism and production rate of these unusual stars. Observing HVSs over a wide range of distances will allow us to measure the production history at the Galactic center and could probe the history of the central black hole over the past 10^8 yr.

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