

THE ANISOTROPIC SPATIAL DISTRIBUTION OF HYPERVELOCITY STARS

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ABSTRACT

We study the distribution of angular positions and angular separations of unbound hypervelocity stars (HVSs). HVSs are spatially anisotropic at the 3σ level. The spatial anisotropy is significant in Galactic longitude, not in latitude, and the inclusion of lower velocity, possibly bound HVSs reduces the significance of the anisotropy. We discuss how the observed distribution of HVSs may be linked to their origin. In the future, measuring the distribution of HVSs in the southern sky will provide additional constraints on the spatial anisotropy and the origin of HVSs.

Key words: Galaxy: center – Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: stellar content

1. INTRODUCTION

Unbound hypervelocity stars (HVSs) were predicted by Hills (1988) as the natural consequence of the massive black hole (MBH) in the Galactic center. Following the discovery of the first HVS (Brown et al. 2005), observers have reported the discovery of at least 16 unbound HVSs and evidence for a similar number of bound HVSs ejected by the same mechanism (Hirsch et al. 2005; Edelmann et al. 2005; Brown et al. 2006a, 2006b, 2007a, 2007b, 2008). Follow-up observations of four HVSs establish they are main-sequence B stars (Fuentes et al. 2006; Bonanos et al. 2008; Przybilla et al. 2008b, 2008c; López-Morales & Bonanos 2008) such as the S-stars orbiting Sgr A* today (Ghez et al. 2003; Eisenhauer et al. 2005; Martins et al. 2008). Although not all unbound stars are necessarily HVSs—the massive B star HD 271791 is the first example of an unbound “hyper-runaway” ejected from the outer disk (Heber et al. 2008; Przybilla et al. 2008a)—runaway ejection velocities are limited to $\sim 300 \text{ km s}^{-1}$ for $3 M_{\odot}$ stars (Leonard & Duncan 1988, 1990; Leonard 1991, 1993; Portegies Zwart 2000; Davies et al. 2002; Gualandris et al. 2005). Thus the 14 unbound $2.5\text{--}4 M_{\odot}$ stars found in the Brown et al. (2007b, 2008) targeted surveys are almost certainly HVSs ejected from the Galactic center.

Remarkably, eight of the 14 HVSs in the Brown et al. (2007b, 2008) targeted surveys are located in just two constellations, Leo and Sextans, even though the surveys cover $1/5^{\text{th}}$ of the sky. This spatial anisotropy is almost certainly linked to the origin of the HVSs.

In Section 2 we show that the observed distribution of HVSs on the sky is anisotropic at the 3σ level. In Section 3 we discuss plausible explanations for the observed anisotropy of HVSs.

2. OBSERVED ANISOTROPY

2.1. Sample

We consider the 14 HVSs from the combined surveys of Brown et al. (2007b, 2008). Our surveys use the MMT telescope to measure radial velocities for stars with the colors of $2.5\text{--}4 M_{\odot}$ stars. Heliocentric velocities are converted to Galactocentric velocities assuming that the local rotation speed is 220 km s^{-1} and that the Sun moves at $(U, V, W) = (10, 5.2, 7.2) \text{ km s}^{-1}$ relative to the local standard of rest (Dehnen & Binney 1998). The original HVS survey (Brown et al. 2007b) is 100% complete for stars with $17 < g_0' < 19.5$ over 7300 deg^2 covered by the Sloan Digital Sky Survey Data Release 6. The

new HVS survey (Brown et al. 2008) is 59% complete for stars with $19.5 < g_0' < 20.5$ over the same region of sky.

Figure 1 plots the spatial distribution of stars with observed velocities. The combined HVS survey contains 693 stars and 14 HVSs in the 7300 deg^2 Sloan region covering the north Galactic cap. HVS2 (Hirsch et al. 2005) is also located in this region (see Figure 1); however it falls outside our color/magnitude criteria. Thus we exclude HVS2 from this analysis.

2.2. Significant Anisotropy

Figure 2 plots the cumulative Galactic longitude and latitude distributions of the HVSs and the other survey stars. Kolmogorov–Smirnov (K-S) tests find 0.007 and 0.11 likelihoods that the HVSs are drawn from the same longitude and latitude distributions, respectively, as the survey stars. Thus the distribution of HVS longitudes appears anisotropic at the 3σ level.

As a second test, we explore the anisotropy in terms of the distribution of angular separations, θ , of the HVSs compared to the survey stars. Because the new HVS survey is not yet complete, we calculate θ 's for all unique pairs of stars in the new and original surveys separately. The original survey includes HVS4–HVS10; a K-S test finds a 0.031 likelihood that those HVSs are drawn from the same distribution of θ as the original survey stars. The new survey includes HVS1 and HVS11–HVS16; a K-S test finds a 7×10^{-9} likelihood that those HVSs are drawn from the same distribution of θ as the new survey stars. Figure 3 plots the θ 's of both surveys concatenated together. The likelihood of the combined set of HVSs is 7×10^{-8} ; thus the distribution of HVS angular separations differs from the distribution of survey star angular separations at the 5σ level.

As a third test, we measure the clustering of HVSs using the two-point angular correlation function $w(\theta)$. We use a Monte Carlo estimator (Landy & Szalay 1993) and compare the observed HVSs against 10^5 sets randomly drawn from the survey region. The lower panel of Figure 3 plots the resulting $w(\theta)$ in 15° bins. Error bars are determined by Poisson statistics. HVSs are clustered at small angular separations $\theta < 45^\circ$ and missing at large angular separations $\theta > 60^\circ$ with $\sim 3.5\sigma$ significance.

2.3. Velocity Dependence

We now consider the spatial anisotropy of lower velocity stars that may also be HVSs. Brown et al. (2008) identify four

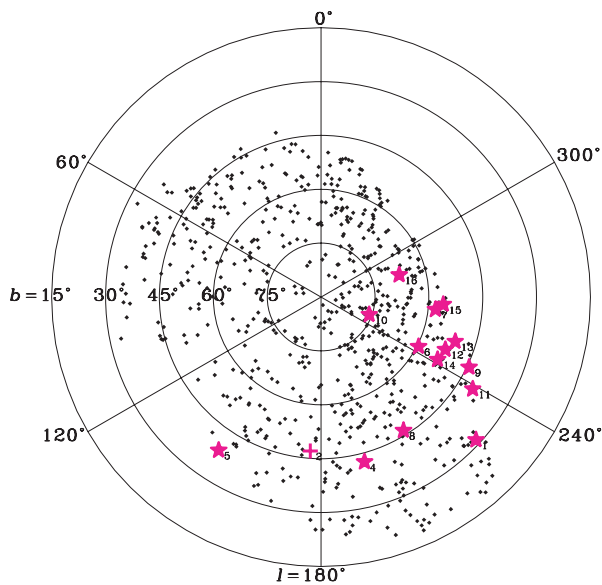


Figure 1. Polar projection, in Galactic coordinates, showing the 14 unbound HVSs (stars) and the 693 other stars (diamonds) in our HVS survey (Brown et al. 2008) covering the north Galactic cap. HVS2, while not part of the survey, is also marked (plus sign).

“possible HVSs,” stars that are bound in the Kenyon et al. (2008) potential model but unbound in the Xue et al. (2008) potential model. Adding the four possible HVSs to the above analysis reduces the significance of the anisotropy to the 2σ level. There are also eight possibly “bound HVSs,” stars with $v_{rf} > +275 \text{ km s}^{-1}$ that are significant outliers from the overall velocity distribution (Brown et al. 2008). Adding the bound HVSs to the above analysis yields an insignificant anisotropy. Thus lower velocity stars have a more isotropic distribution, a trend noted previously in Brown et al. (2007a).

2.4. HVS Pairs

There are three pairs of unbound HVSs with angular separations less than $3^\circ 5'$ (see Figure 1): HVS7 & HVS15 near $(l, b) = (265^\circ, 55^\circ)$, HVS12 & HVS13 and HVS12 & HVS14 near $(l, b) = (245^\circ, 52^\circ)$. Any physical association between the individual HVSs, however, appears unlikely. HVS7 & HVS15 are separated by $2^\circ 5'$ but have velocities and distances that imply a $\sim 70 \text{ Myr}$ difference in travel time from the Galactic Center (see Figure 3 of Brown et al. 2008). HVS12 has a 429 km s^{-1} minimum rest-frame velocity very similar to that of HVS13 and HVS14, but it has half the distance of the

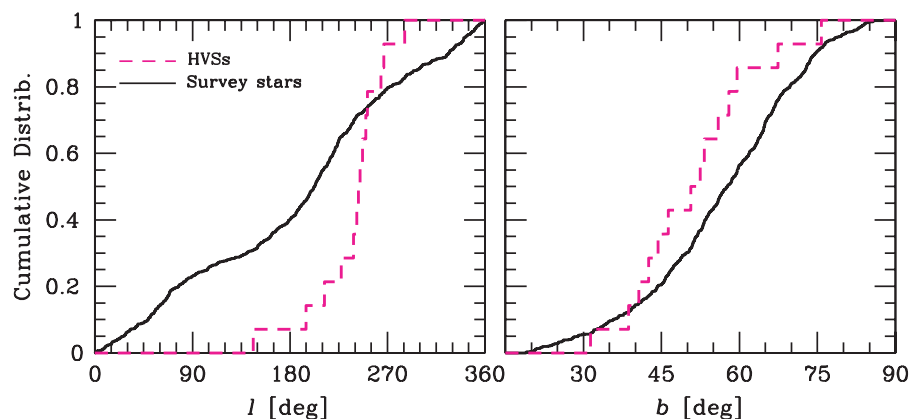


Figure 2. Cumulative distributions of Galactic l and b of the 14 HVSs (dashed lines) and the 693 other stars (solid lines) in our HVS survey (Brown et al. 2008).

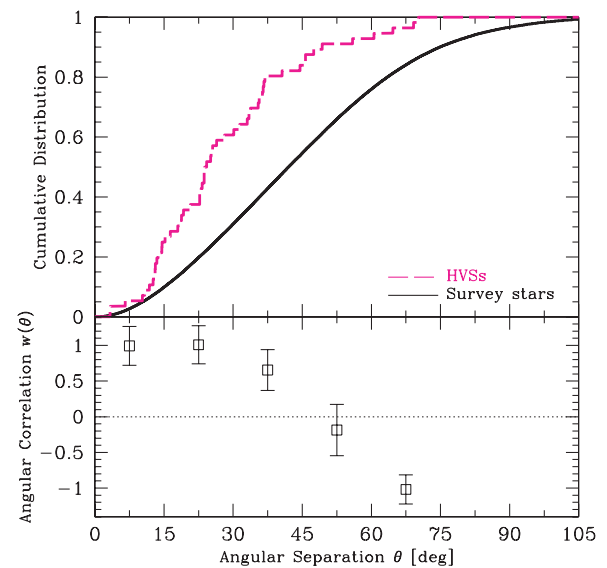


Figure 3. Upper panel: cumulative distribution of angular separations, θ . Lower panel: two-point angular correlation function $w(\theta)$ of the HVSs with respect to sets randomly drawn from the survey region.

other two HVSs. Thus none of the HVS pairs shares a common ejection event.

3. ORIGIN OF THE SPATIAL ANISOTROPY

We observe that the spatial anisotropy of unbound HVSs is statistically robust, that lower velocity HVSs are systematically more isotropic, and that apparent close pairs of HVSs are physically unrelated. Possible explanations for the observations include:

Selection Effect. Previously, we argued that the HVS anisotropy may be a selection effect of our magnitude-limited survey and the Sun’s off-center location in the Galaxy (Brown et al. 2007a). However, this selection effect can account only for an extra $\sim 10\%$ HVSs in the anti-center hemisphere, not all of the HVSs in the anti-center hemisphere. Moreover, the observed HVSs cluster around $l = 240^\circ$, not $l = 180^\circ$.

Runaways. Runaway stars like HD 271791 may contaminate the population of HVSs. However, we expect runaways ejected from the disk to have an isotropic distribution in Galactic longitude, as demonstrated by the Martin (2006) *Hipparcos*-selected sample of runaway B stars. Moreover, because runaways are systematically ejected at low velocities (e.g., Portegies Zwart 2000), the fastest runaways are those ejected in the direction of

Galactic rotation and thus preferentially found at low Galactic latitudes. Thus the expected distribution of runaway longitudes and latitudes are contrary to the observed distribution of HVSSs.

Large-Scale Structure. The distribution of Local Group dwarf galaxies is anisotropic, possibly due to a tidal origin (e.g., Metz et al. 2008). A tidal debris origin appears supported by the clumping of HVS travel times around 100–200 Myr; however the travel times are simply a product of the HVS's $\sim 500 \text{ km s}^{-1}$ velocities and our magnitude-limited survey depth of 50–100 kpc. HVS travel times are in fact problematic for a tidal debris origin because the times are a significant fraction of the stars' main-sequence lifetimes, and multiple (gas-rich) tidal disruption events would be required to explain the full 2×10^8 yr span of HVS travel times. No dwarf galaxy in the Local Group travels with radial velocities comparable to the unbound HVSSs; known dwarf galaxy remnants such as the Sgr stream (Ibata et al. 1994) are bound. We thus consider tidal debris an unlikely explanation for the observed set of HVSSs (however, see Abadi et al. 2008).

Binary Black Hole. While an equal-mass binary MBH is ruled out in the Galactic Center (Reid & Brunthaler 2004), theorists speculate that the massive star clusters in the Galactic Center form intermediate mass black holes (IMBHs) in their cores. If such IMBHs exist, dynamical friction causes them to in-spiral into the central MBH, preferentially ejecting HVSSs from their orbital planes. Thus the expected signature of an IMBH in-spiral is a ring of HVSSs around the sky (Gualandris et al. 2005; Levin 2006; Sesana et al. 2006). Baumgardt et al. (2006) argue, however, that stellar interactions perturb the orbital plane of an in-spiraling IMBH; the resulting HVS distribution in this scenario may in fact be isotropic. Moreover, a single IMBH in-spiral event happens on timescales 10–100 times shorter than the observed span of HVS travel times; multiple IMBH in-spiral events are required to explain the observed HVSSs.

Galactic Center Structure. The Galactic center contains many well defined structures. As illustrated in Paumard et al. (2006), the molecular gas circumnuclear disk and the ionized northern arm are roughly aligned with the plane of the Milky Way. The gaseous minispiral is perpendicular to the plane of the Milky Way. Notably, the stellar disk 0.1 pc from the MBH is roughly perpendicular to the gaseous components (Lu et al. 2008). The stellar disk contains massive stars (Tanner et al. 2006; Paumard et al. 2006), possibly formed in situ from a gas accretion disk (Genzel et al. 2003; Levin & Beloborodov 2003). Dynamical interactions between a pair of stellar disks may scatter stars toward the MBH, explaining both the S-stars and the HVSSs (Löckmann et al. 2008; Perets et al. 2008). Clearly, the Galactic center contains nonisotropic distributions of stars and gas which may provide a natural source for the observed anisotropy of HVSSs ejected from the Galactic center. However, it is unclear if the observed structures can persist long enough to explain the anisotropic distribution of HVSSs.

4. CONCLUSION

Unbound HVSSs are spatially anisotropic at the 3σ level. The anisotropy is most significant in Galactic longitude, and not in latitude. Lower velocity HVSSs are systematically more isotropic, and apparent close pairs of HVSSs are physically unrelated.

The observed distribution of HVSSs is linked to the origin of the HVSSs. Abadi et al. (2008) propose a tidal debris explanation, although this appears difficult to reconcile with all the observations. We investigate other physical models for

the anisotropy in a separate paper. In the future, measuring the distribution of bound and unbound HVSSs over the southern sky will allow us to better constrain the anisotropy and the origin of HVSSs.

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Facilities: MMT (Blue Channel Spectrograph)

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