ON THE SPATIAL DISTRIBUTION AND THE ORIGIN OF HYPERVELOCITY STARS

YOUJUN LU,1 FUPENG ZHANG,1 AND QINGJUAN YU2

1 National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China; luyj,fpzhang@bao.ac.cn
2 Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China; yuqj@kiaa.pku.edu.cn

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ABSTRACT

Hypervelocity stars (HVSs) escaping away from the Galactic halo are dynamical products of interactions of stars with the massive black hole(s) (MBH) in the Galactic Center (GC). They are mainly B-type stars with their progenitors unknown. OB stars are also populated in the GC, with many being hosted in a clockwise-rotating young stellar (CWS) disk within half a parsec from the MBH and their formation remaining puzzles. In this paper, we demonstrate that HVSs can well memorize the injecting directions of their progenitors using both analytical arguments and numerical simulations, i.e., the ejecting direction of an HVS is almost anti-parallel to the injecting direction of its progenitor. Therefore, the spatial distribution of HVSs maps the spatial distribution of the parent population of their progenitors directly. We also find that almost all the discovered HVSs are spatially consistent with being located on two thin disk planes. The orientation of one plane is consistent with that of the (inner) CWS disk, which suggests that most of the HVSs originate from the CWS disk or a previously existed disk-like stellar structure with an orientation similar to it. The rest of HVSs may be correlated with the plane of the northern arm of the mini-spiral in the GC or the plane defined by the outer warped part of the CWS disk. Our results not only support the GC origin of HVSs but also imply that the central disk (or the disk structure with a similar orientation) should persist or be frequently rejuvenated over the past 200 Myr, which adds a new challenge to the stellar disk formation and provides insights to the longstanding problem of gas fueling into MBHs.

Key words: black hole physics – Galaxy: center – Galaxy: halo – Galaxy: kinematics and dynamics – Galaxy: structure

1. INTRODUCTION

In the past several years, surveys of hypervelocity stars (HVSs) have found 16 HVSs with velocities substantially higher than the Galactic escape velocity (Brown et al. 2005; Hirsch et al. 2005; Edelmann et al. 2005; Brown et al. 2007, 2009a). Most HVSs are B-type stars probably with masses \( \sim 3–4 M_\odot \), ages \( \gtrsim (1–2) \times 10^8 \) yr, and lifetime \( \sim (1.6–3.5) \times 10^5 \) yr (Brown et al. 2007, 2009a). Their heliocentric distances range from several tens to a hundred kpc and their spatial distribution on the sky is probably anisotropic (Brown et al. 2009a, 2009b; Abadi et al. 2009). The young nature and the spatial anisotropic distribution of these stars, as well as their hypervelocities, should be related to their origin.

A few dynamical mechanisms, involving interactions with the massive black hole (MBH) in the Galactic Center (GC), were proposed to eject stars with such hyper velocities (Hills 1988; Yu & Tremaine 2003; Bromley et al. 2006; Gualandris et al. 2005; Levin 2006; Baumgardt et al. 2006; Sesana et al. 2006; Perets et al. 2007; O’Leary & Loeb 2008; Löckman & Baumgardt 2008), including tidal breakup of binary star systems by the central MBH and three-body interactions of single stars with a hypothetical binary black hole (BBH) in the GC. The sources of (binary) stars injected into the vicinity of the MBH are often (implicitly) assumed to be isotropically distributed in previous studies, as the majority of the GC stars are isotropically distributed; and different ejection mechanisms may result in different spatial distributions of HVSs, depending on whether the central MBH is a single or a binary and relevant binary parameter (Yu & Tremaine 2003; Bromley et al. 2006; Sesana et al. 2006). Hence, the spatial distribution of HVSs was proposed to be useful in identifying the ejection mechanism responsible for the observed HVSs.3

The progenitors of the discovered B-type young HVSs and their sources, however, should be distinct populations from the majority of the GC stars (which are typically old). Observations have indeed shown various young stellar structures in the GC, which may be possible parent populations of the HVS progenitors, including a clockwise young stellar disk (CWS) and the other possible counterclockwise one within 0.5 pc from the central MBH (Levin & Beloborodov 2003; Paumard et al. 2006; Lu et al. 2009; Bartko et al. 2009), young stellar clusters like the Arches and the Quintuplet systems at several tens pc away from the center, and the tidal remnants of those clusters (Portegies Zwart et al. 2002). There also exist other organized structures in the GC, such as the circumnuclear molecular disk, the northern arm (Narm), and the bar components of the minispiral at a few pc from the center, with which young stars may be associated (Yusef-Zadeh et al. 2000; Paumard et al. 2006). These structures may also be related to the sources of HVSs. All the structures above are not isotropically distributed, but either planar or orbiting on some specific planes around the central MBH. The HVSs, if ejected by interactions of stars originating from these sources with the central MBH(s), are very likely to be spatially correlated. And their spatial distribution should be mapping the distribution of the parent populations of their progenitors, if the

3 Some other observational properties of HVSs, such as the binarity, rotational velocity, and metallicity, were also proposed to be useful in identifying the ejection mechanisms of the HVSs (e.g., Lu et al. 2007; Hansen 2007; Przybilla et al. 2008b; López-Morales & Bonanos 2008; Perets 2009a, 2009b).
ejected HVSs can well memorize the injecting direction of their progenitors.

This paper is organized as follows. In Section 2, we study how the spatial distribution of HVSs is related with the geometrical structure of the parent population of their progenitors. In Section 3, we find that most HVSs discovered so far are probably originated from the CWS or a disk-like stellar structure with an orientation similar to that of the CWS disk in the GC. Discussion and conclusions are given in Sections 4 and 5.

2. THE DEFLECTION ANGLE: THE DIRECTION CHANGE OF HVSs FROM ITS PROGENITOR

In this section, we use both analytical analysis and numerical calculations to demonstrate that HVSs can well memorize the injecting direction of their progenitors. We do this for different possible dynamical mechanisms of ejecting HVSs introduced in Section 1.

2.1. Tidal Breakup of a Binary Star by the Central MBH

If a binary star initially unbound or weakly bound to the central MBH approaches the vicinity of the MBH within a tidal distance $R_{\text{tid}} \simeq a_0(\sqrt{m_{\text{MBH}}/m_1})^{1/3}$, the binary is probably tidally broken up, and one component of the binary may be ejected as a HVS, where $M_*$ is the mass of the central MBH ($\sim 4 \times 10^6 M_\odot$, Ghez et al. (2008); Gillessen et al. (2009)), $m_{\text{HVS}}$ and $m_*$ are the mass of the ejected HVS and the other binary component, respectively, and $a_0$ is the semimajor axis of the binary (Hills 1988; Yu & Tremaine 2003). The initial injecting velocity of the binary is $\Psi_0 \approx \sqrt{G M_*/a_0} \propto 1$, where $G$ is the gravitational constant, and then the velocity of the ejected HVS can be approximated by Yu & Tremaine (2003) and Bromley et al. (2006)

$$v_{\text{HVS}}^{\infty} \sim 960 \text{ km s}^{-1} \left(\frac{0.6 \text{ AU}}{a_0}\right)^{1/2} \left(\frac{m_{\text{HVS}} + m_*}{8 M_\odot}\right)^{1/3} \times \left(\frac{2 m_*/(m_{\text{HVS}} + m_*)}{4 \times 10^6 M_\odot}\right)^{1/6}. \quad (1)$$

The orbit of the ejected HVS and the initial orbit of the injecting binary both have eccentricities $e$ close to 1 and can be approximated as rectilinear at distances faraway from the MBH. Below we aim to find out the range of the deflection angle of these two rectilinear directions.

For convenience, we first consider a purely two-body problem that a star with mass $m_* \ll M_*$ starts at a velocity $v_{\text{ini}} = (G M_*/a)^{1/2}$ from infinity and is moving toward the MBH on a hyperbolic orbit with periapsis distance $R_{\text{min}} \ll a$. The velocity of the star at periapsis is $v_p = v_{\text{ini}}(2a/R_{\text{min}} + 1)^{1/2}$, and then the deflection angle of its direction from its initial injecting velocity is $\pi/2 - \Psi_1$, where $\tan \Psi_1 = \sqrt{1 - e^2} \simeq \sqrt{2 R_{\text{min}}/a \simeq v_{\text{ini}}^{\infty}(2R_{\text{min}}/GM_*)^{1/2}}$. If the star moves toward the MBH on a parabolic or elliptical orbit with eccentricity close to 1, the deflection angle of the stellar velocity moving from almost the infinity (excluding locations near the apoaoposity) to the periapsis $R_{\text{min}}$ is about $\pi/2$. Similarly as above, for a star that can escape the BH with velocity $v_{\text{ini}}^{\infty}$, the deflection angle of the escaping star from its velocity at $R_{\text{min}}$ is $\pi/2 - \Psi_2$ with $\tan \Psi_2 \simeq v_{\text{ini}}^{\infty}(2R_{\text{tid}}/GM_*)^{1/2}$. For the HVSs discovered so far, we have $v_{\text{ini}}^{\infty} \sim 750$–$1000 \text{ km s}^{-1}$ obtained by removing the velocity deceleration due to the Galactic potential measured by Xue et al. (2008). Note that the relative change of the eccentricity vector (pointing toward the periapsis from the MBH) is $\sim \delta v_p/v_p \sim \Psi_2^2$ and it is negligible compared to $\Psi_2$ for sufficiently small $\Psi_2$, where $\delta v_p \sim (m_{\text{HVS}}/m_*)v_{\text{ini}}^{\infty}(m_{\text{HVS}} + m_*)/a_0$ is the change of the velocity of the binary component ejected as the HVS after the binary breakup. For the process of tidal breakup of a binary star at a distance of $R_{\text{tid}}$ from the MBH, we approximately have $R_{\text{min}} \simeq R_{\text{tid}}$, and the total deflection angle $\Theta$ of the ejected HVS from the original injecting binary is about $\pi - \sqrt{\Psi_0^2 + \Psi_2^2}$. The $\Theta$ is $\sim \pi - (\Psi_0 + \Psi_2)$ if the HVSs and the injecting binary are on the same orbital plane and $\sim \pi - \Psi_0$ for $v_{\text{ini}}^{\infty} \gg v_{\text{ini}}^{\infty}$. For $a_0 \sim 0.6 \text{ AU}$, $v_{\text{HVS}}^{\infty} \sim 1000 \text{ km s}^{-1}$, and $v_{\text{ini}}^{\infty} \sim 250 \text{ km s}^{-1}$, we have $\sqrt{\Psi_0^2 + \Psi_2^2} \sim 0.2 \sim 10^2$, that is, the HVSs are almost reversing the injecting direction of their progenitors.

To confirm the above analysis, we numerically realize the process of ejecting an HVS as a binary interacts with a MBH. We use an explicit fifth(fourth)-order Runge–Kutta scheme to integrate the full three-body problem (Dormand & Prince 1980; Haier et al. 1993). In the three-body simulations, we first assume that all binary stars initially move on hyperbolic orbits with $v_{\text{ini}}^{\infty} \sim 250 \text{ km s}^{-1}$ from infinity. In the calculations we set other relevant parameters as follows. (1) The distribution of the semimajor axes $a_0$ of binary stars is assumed to follow $P(a_0) \propto 1/a_0$ as suggested by observations of binaries with O-type or B-type primary stars (Kobulnicky & Fryer 2007). The lower limit of $a_0$ is roughly set to 0.03 AU, i.e., about twice the physical radius of a 4 $M_\odot$ star, and the upper limit of $a_0$ is set to 2 AU to ensure that the ejected star can escape to large Galactic radii. (2) The mass distribution of primary stars $m_1$ follows the Miller–Scalo initial mass function, i.e., $f(m_1) \propto m_1^{-\alpha}$ and $\alpha \sim 2.7$ (Kroupa 2002). For massive binary stars, the distribution of the secondary star or the mass ratio $q = m_2/m_1(< 1)$ can be described by two populations: (a) a twin population, i.e., about 40% binary stars have $q \sim 1$ or $m_2 \sim m_1$, and (b) the rest binaries follow a $q(f(q) \sim constant distribution (Kobulnicky & Fryer 2007; Kiminki et al. 2008, 2009). (3) The eccentricity of the binary star is assumed to be 0. (4) The orientation of the binary orbital plane is randomly chosen. (5) The probability distribution of the closest approach distances to the MBH is $P(R_{\text{min}}) \propto R_{\text{min}}^{-\alpha}$, which corresponds to the impact parameter distribution $P(b) \propto b^{-\alpha}$. We only select those cases that the masses of ejected stars are in the mass range (3 $M_\odot$, 4 $M_\odot$) of the observed HVSs and calculate the probability distribution of their deflection angles $\Theta$. As seen from panel (a) of Figure 1, the values of $\Theta$ range from $165^5$ to $180^5$, consistent with our analysis above. The distribution of $\Theta$ does not show dependence on $v_{\text{ini}}^{\infty}$. The reason for this independence is as follows. If the mass of the central MBH (here, the MBH in the GC) and the mass of an HVS are fixed, $v_{\text{ini}}^{\infty}$ is primarily determined by the semimajor axis of the binary, and given $R_{\text{tid}} \propto a_0$, $\tan \Psi_2 \propto v_{\text{ini}}^{\infty}(2R_{\text{tid}}/GM_*)^{1/2}$ is independent of $a_0$ and hence $v_{\text{ini}}^{\infty}$.

We also calculate the deflection angle distribution for the case that the injected binary stars are initially on weakly bound and highly eccentric orbits, instead of unbound orbits. In this case, the only difference in the initial conditions from that for initially unbound binaries is as follows: the apoapsis distribution of the orbit of the binary barycenter follows $P(r_{\text{apo}})dr_{\text{apo}} \propto r_{\text{apo}}^{-1}dr_{\text{apo}}$, $r_{\text{apo}}$ is in the range (0.04 pc, 0.5 pc), and the distribution of the closest approach $R_{\text{min}}$, i.e., the periapsis distance of the orbit of the binary barycenter, is the same as above. The above distribution of the apoapsis is adopted so that the energy distribution of the binaries injected from a disk structure is
consistent with the density distribution of young stellar disk recently discovered in the GC (Levin & Beloborodov 2003; Paumard et al. 2006; Lu et al. 2009; Bartko et al. 2009). The radial distribution of stars within the young stellar disk plane is \( \propto r^{-2.3 \pm 0.7} \) in Lu et al. (2009) and \( \propto r^{-2.1 \pm 0.8} \) in Paumard et al. (2006). The resulted distribution of \( \Theta \) is shown in panel (b) of Figure 1. And \( \Theta \) is also in the range from 165\(^\circ\) to 180\(^\circ\), which again confirms our analysis above that HVSs memorize the direction of their original binaries well.

2.2. Dynamical Ejection by a Binary Black Hole

HVSs can also be produced by three-body interactions of a single star with a hard BBH. A BBH is hard if its semimajor axis \( a_{\text{BBH}} \) is less than \( a_0 = GM_{*2}/4\sigma^2 \), where \( \sigma \) is the stellar velocity dispersion of the host galaxy and \( M_{*2} \) is the mass of the secondary black hole. For a hard BBH, most low-angular-momentum stars that can enter into the region \( r \lesssim a_{\text{BBH}} \) will be ejected after one or several encounters with the BBH and the rms of the velocities of the ejected stars at infinity is

\[
v_{\text{HVS}}^\infty \approx \sqrt{2KGM_{*1}M_{*2}/(M_{\text{BBH}})} \approx 930 \text{ km s}^{-1}m_{*1}^{0.25}(1 - v)^{1/2}(0.1a_0/a_{\text{BBH}})^{1/2},
\]

(see Equation (1) in Lu et al. 2007), where \( M_{*1} = M_{*1}' + M_{*2}' \), \( v \equiv M_{*2}'/M_{*1}' \), \( m_{*} = M_{*}/(4 \times 10^6 M_\odot) \), \( K \approx 1.6 \). Unless the eccentricity of the BBH is excited to an extremely high value shown in some numerical simulations (Baumgardt et al. 2006; Matsubayashi et al. 2007; L"ockman & Baumgardt 2008), the BBH can stay at its hard stage for a long time (e.g., up to 10\(^7\) yr in Yu & Tremaine 2003) and ejection of HVSs from the GC would last that long. A BBH with an extremely high eccentricity has a much shorter lifetime due to gravitational radiation, which is substantially smaller than the travel time span (\( \sim 2 \times 10^3 \) yr) of the observed HVSs.

In this mechanism, HVSs are ejected out from distances \( R_{\min} \lesssim a_{\text{BBH}} \), and we have \( \tan \Psi_2 = v_{\text{HVS}}^\infty \sqrt{R_{\min}/\alpha_{\text{BBH}}} \lesssim 2.5 \sqrt{M_{*2}/M_{*1}} \). If \( M_{*2} \sim M_{*1} \), we have \( \Psi_2 \sim 50^\circ \), and thus HVSs have lost their memory of the direction of their progenitors and the information of the BBH orbital plane may be imprinted on the spatial distribution of HVSs. Current observational constraints on the mass of the secondary BBH in the GC give \( M_{*2} \lesssim 0.01M_{*1} \) (Hansen & Milosavljevic 2003; Yu & Tremaine 2003; Gillessen et al. 2009), for which we have \( \Psi_2 \lesssim 14^\circ \). If the progenitor of the HVS is unbound to the BBH with small initial velocities, it is ejected out generally after one or a few close encounters with the BBH, and we have \( \tan \Psi_1 \lesssim v_{\text{inj}}^\infty(a_{\text{BBH}}/GM_{*1})^{1/2} \). For \( v_{\text{inj}}^\infty \ll v_{\text{HVS}}^\infty \), we have \( \Psi_1 \ll \Psi_2 \). If the injecting star is initially on a bound (and highly eccentric) orbit, it may be ejected out as a HVS after many times of encounters with the BBH, and the accumulated relative change of the eccentricity vector is \( \sim \Psi_2^2 \) and negligible for sufficiently small \( \Psi_2 \). In this case, the total deflection angle \( \Theta \) of the ejected HVS from the injecting direction of its progenitor is thus \( \pi - \sqrt{\Psi_1^2 + \Psi_2^2} \sim \pi - \Psi_2 \), and thus HVSs may have a good memory of the direction of their progenitors. We do numerical experiments on three-body interactions between single stars and a BBH with \( M_{*} = 4 \times 10^6 M_\odot, v = 0.003 \), and \( a_{\text{BBH}} = 0.1a_0 \), where the two BHs are set to be sufficiently close so that they are able to eject stars with the observed hypervelocities. As shown in Figure 2, the deflection angles \( \Theta \) obtained from the calculations range from 165\(^\circ\) to 180\(^\circ\), no matter whether the injecting stars are initially unbound (panel (a) in Figure 2) or weakly bound (i.e., highly eccentric) orbits (panel (b) in Figure 2). The result is not sensitive to the BBH eccentricity, \( a_{\text{BBH}} \), and the orientation of the BBH orbital plane.

HVSs may also be produced by interactions of single stars with a cluster of stellar-mass black holes in the vicinity of the central MBH. In this case, the velocity kick \( \delta v \) received by the star when it passes by the stellar-mass black hole is typically larger and comparable to the orbital velocity of the stellar-mass black hole \( v_{\text{orb}} \), and thus the deviation of the deflection angle from \( \pi \) may be substantially larger than those discussed above. Therefore, it may be difficult for the HVSs produced by this mechanism to memorize the direction of their progenitors and hence difficult to explain the consistence of the HVS plane and the CWS plane shown in Section 3 below.

Additional deflection of the moving direction of HVSs may be introduced if the Galactic potential is substantially flattened or triaxial; but this deflection, typically \( \lesssim 2^\circ \) for...
the deviation angles of ejected HVSs from the direction of the warped part of the CWS disk are less likely to be consistent with the fitted plane of the warped part of the CWS disk. The normal of the fitted plane is close to the Narm plane (see Figure 4). After including them (SDSS J1403+1450 and SDSS J1546+2437) are within their error range. For the second group of five HVSs, we obtain \((l, b) = (188^\circ, -52^\circ)\) with \(P_{\chi^2} = 0.87\), and \((l, b) = (22^\circ, 5^\circ)\) corresponds to the fit being better by chance and it is high enough so that the fit is acceptable. We take the error of the fitted normal \(\sim 1000 \text{ km s}^{-1}\), is negligible (Yu & Madau 2007; Gnedin 2005).

In summary, it is plausible to use the spatial distribution of HVSs unbound to the Galactic potential to map the parent population of their progenitors and reveal their origin if the HVSs are produced by the tidal breakup of binary stars or the BBH mechanism.

3. COMPARISON WITH OBSERVATIONS

Figure 3 shows the spatial distribution of all (16) HVSs detected so far (filled circles) in the Galactic coordinates by a Hammer–Aitoff projection. The spatial distribution of these HVSs is anisotropic at a 3.5\(\sigma\) level (Brown et al. 2009a, 2009b) and the majority of the HVSs are located at Galactic longitudes \(l \sim 240^\circ–270^\circ\) (Abadi et al. 2009). The projection of other various planar structures in the GC is also plotted in the figure. As shown in Figure 3, most HVSs (11 among 16) situate close to the plane of the clockwise young stellar disk; and a second group, including four other HVSs and possibly a specific one among the above 11, situate close to the Narm plane. Only one HVS, i.e., HE 0437-5439, is neither on the CWS plane nor on the Narm plane, which was suggested to be ejected from the LMC (Edelmann et al. 2005; Bonanos et al. 2008; Przybilla et al. 2008a). Almost all HVSs are quite far away from the planes of other structures plotted in the figure.

We use the \(\chi^2\) statistic to fit the possible planar structures of the HVSs. The normal \(\hat{n}\) to the best-fit plane of the HVSs is obtained by minimizing \(\chi^2 = \sum (\frac{\hat{n} \cdot \vec{d} \vec{c}_{ri}}{\sigma_{d ri}})^2 (i = 1, 2, \ldots)\), where \(\vec{c}_{ri}\) is the unit position vector of the \(i\)th HVS seen from the GC and \(\vec{d} \vec{c}_{ri}\) is its possible deviation from an original plane for which we take equivalently as the error of \(\vec{c}_{ri}\) in standard statistics. As the thickness (half-opening angle) of the CWS plane is \(\sim 7^\circ–10^\circ\) (Lu et al. 2009; Bartko et al. 2009) and the deviation angles of ejected HVSs from the direction of their parent population should be about \(\sim 0^\circ–15^\circ\), we set the amount of \(\vec{d} \vec{c}_{ri}\) correspondingly to a deviation of \(7^\circ\). Thus, we obtain the normal of the best-fit plane of the 11 HVSs \((l, b) = (309^\circ, -15^\circ)\) with \(P_{\chi^2} = 0.82\), where \(P_{\chi^2}\) gives the probability of \(\chi^2\) being higher by chance and it is high enough so that the fit is acceptable. We take the error of the fitted normal direction as \(\delta l \simeq \pm 6^\circ\) and \(\delta b \simeq \pm 8^\circ\), which roughly correspond to the 68% confidence level. The normal of the CWS disk plane, or at least the normal of the CWS disk in the inner region of \((0^\circ–3^\circ5)\), \((l, b) = (310^\circ, -18^\circ)\), (Paumard et al. 2006; Lu et al. 2009; Bartko et al. 2009) is within the error range. For the secondary group of five HVSs, we obtain \((l, b) = (188^\circ, -52^\circ)\) with \(P_{\chi^2} = 0.87\), and \((l, b) = (\pm 22^\circ, 5^\circ)\) corresponds to the 68% confidence level. The normal to the observed Narm plane \((l, b) = (162^\circ, -47^\circ)\) (Paumard et al. 2006) is at the 80% confidence level of the best-fit value.

Bartko et al. (2009) recently reported that the outer part of the CWS disk may be significantly warped and the normal of the warped part is \((l, b) = (136^\circ, -44^\circ)\). This normal is close to the normal of the Narm plane as shown in Figure 4, which suggests some physical connection between the Narm and the outer warped part of the CWS disk. The normal of the outer warped part of the CWS disk is at the 99.9% confidence level of the best fit. Compared with the plane of the Narm, statistically the plane defined by the normal of the warped part of the CWS disk is less likely to be consistent with the fitted plane of the second population of HVSs.

It is worthy to note that there are four other HVS candidates listed in Brown et al. (2009a). As shown in Figure 4, two of them (SDSS J1403+1450 and SDSS J1546+2437) are within \(\sim 16^\circ\) to the CWS plane and the other two (SDSS J0940+5309 and SDSS J1014+5631) are within \(3^\circ\) to the Narm plane. If they are confirmed to be HVSs and included in the fit, the normals to the two best-fit planes are \((l, b) = (318^\circ, -9^\circ)\) with \(P_{\chi^2} = 0.81\) and \((l, b) = (180^\circ, -50^\circ)\) with \(P_{\chi^2} = 0.79\), consistent with the planar structures fitted above. Even for the eight bound “hypervelocity” stars listed in Brown et al. (2009a), four of them are close to the CWS disk within \(15^\circ\), so are three of them to the Narm plane (see Figure 4). After including them, the normals to the two best-fit planes are \((l, b) = (311^\circ, -14^\circ)\) with \(P_{\chi^2} = 0.44\) and \((l, b) = (176^\circ, -53^\circ)\) with \(P_{\chi^2} = 0.30\), respectively. As seen from Figure 5, after including the HVS candidates and the bound ones, the planar structure close to the CWS disk appears more obvious as their locations extend to a
widener area in the sky. Only one object among the bound sample, SDSS J1404+3522, with the smallest Galactocentric distance, is significantly separate from the above two planes. We note here that the bound population of “hypervelocity” stars are more likely to be contaminated by the high-velocity stars produced by other mechanisms as they have substantially smaller velocities than the unbound stars.

We have also tested that the fits cannot be passed statistically if choosing other observed structures, such as the bar, the circumnuclear molecular disk, or the counter clockwise-rotating disk. The fit cannot be passed, either, if the two groups of HVSs above are combined together and fit to only one best orientation. If they are fit together to two randomly oriented planes (with normals \( \mathbf{n}^1, \mathbf{n}^2 \)), the best-fit normals obtained by minimizing \( \chi^2 = \sum \min(\| ( \mathbf{n}^1 \cdot \mathbf{d}_c)^2, ( \mathbf{n}^2 \cdot \mathbf{d}_c)^2 \|) \) are almost the same as those obtained above by fitting the two groups separately, where “min” is used in the formula of \( \chi^2 \) so that each star is fit to the plane closer to it.

Assuming that the parent population of the observed HVSs are on the two fitted disks with a thickness of 7° and normal of \( (l, b) = (311°, -14°) \) and \( (176°, -53°) \), we simulate the process of tidal breakup of binary stars around the central MBH using similar initial conditions as that in Section 2. As shown in Figure 5, the spatial distribution of the simulated HVSs can well match the distribution of observed HVSs. Similar spatial distribution can also be reproduced if the BBH ejection mechanism is alternatively adopted. For simplicity, we do not present that in details.

4. DISCUSSION

As we have demonstrated above, the spatial distribution of the discovered HVSs is consistent with being located on two thin disk planes, and these two planes are consistent with that of the (inner) CWS disk, and the Narm or the outer warped part of the CWS disk, respectively. We discuss two possible explanations to these results below.

One explanation could be that the HVSs are originated from some unknown and previously existed disk-like stellar structures with orientation similar to that of the CWS disk, and the Narm or the outer warped part of the CWS disk. If this is true, one needs to answer what and where the unknown structures are, why their structures are consistent with the CWS and Narm (or the warped outer part of the CWS disk), and whether the consistency is coincident or some natural outcome.

The other explanation is that most HVSs are originated from the CWS disk and a second population of HVSs may be originated from the Narm or the outer warped part of the CWS disk. For this explanation, the young CWS disk should persist or be frequently rejuvenated over the past \( \sim 2 \times 10^8 \) yr as constrained by the travel time of these HVSs \( \sim (1-2) \times 10^3 \) yr, which is extremely puzzling. The ages of the OB stars in the disk are only \( \sim 6 \pm 2 \) Myr. As the in situ formation of the CWS stellar disk is already difficult due to the suppression of star formation by the MBH tidal field (Levin & Beloborodov 2003; Lu et al. 2009; Bartko et al. 2009; Sanders 1992; Nayakshin & Cuadra 2005; Bonnell & Rice 2008), how have young stars been continuously forming in the disk and in the meantime how can the disk plane maintain its direction? One key to solve this puzzle would be continuous sinking of cold gas onto the CWS disk. However, the observed gaseous structures located just outside the CWS disk generally do not have the same direction as the disk. Solutions to this puzzle will provide profound insights to the gas fueling into the vicinity of the central MBH in the GC and MBHs in other galactic nuclei in general. Detailed studies of physical properties of HVSs (e.g., metallicity) and their relations with those in the CWS stellar disk may also help to unveil the secret of their star formation.

It appears that the counterclockwise disk is not correlated with the currently discovered HVSs. The current observed B-types in the CWS disk region are also more isotropic than the O/WR stars (Bartko et al. 2010), which appears not to be the same as the planar distribution of HVSs. The correlation between the observed HVSs and the CWS disk plane may suggest that (1) only the B-type stars on the disk plane can be perturbed to inject into the immediate vicinity of the central MBH as the progenitors of HVSs (e.g., by secular evolution of the disk, see Madigan et al. 2009); and (2) B-type stars initially formed on the disk may be heated up by relaxation processes later. Detailed study of this relation may provide some constraints/hints on the mechanism to deliver stars to the vicinity of the central MBH.

It is worthy to further explore how the orbits of (binary) stars in the CWS and the young stellar structure associated with the Narm plane or the outer warped part of the CWS disk are perturbed so that they can move to the immediate vicinity of the central MBH(s). This perturbation may be due to some massive perturbers (Perets et al. 2007) or secular evolution of the structures themselves (Madigan et al. 2009). Perturbations on other young stellar structures, such as the tidal streams of young stellar clusters like the Arches and the Quintuplet systems, may also inject (binary) stars to the immediate vicinity of the central MBH(s) and lead to ejection of HVSs. Therefore, there may be other planar-like spatial distribution of young HVSs. If these could be found in future HVS surveys, together with those found so far, the spatial distribution of HVSs will be mapping young stellar structures ever existed in the GC over the past \( 2 \times 10^8 \) yr. With more and more HVSs to be discovered in the all-sky survey in the future, the statistical methods on how to extract the stellar structures would need to be improved and the detailed improvement method should depend on how complicated or simple the structures would be.
In Section 2.2, we dealt with interactions of a BBH with unbound or weakly bound stars. One concern would be that tightly bound stars in the vicinity of the MBH may also be ejected away with hypervelocities by interacting with an intermediate-mass BH (IMBH), and their ejection may have some preferred direction if the IMBH orbit is highly eccentric. In this case, the ejecting direction is perpendicular to the Runge–Lenz vector of the IMBH orbit over a period of a few Myr (e.g., as discussed in Levin 2006; Sesana et al. 2006). Baumgardt et al. (2006) argue that the orbital orientation of the highly eccentric IMBH orbit may experience rapid changes and hence randomize the HVS ejection directions, which is inconsistent with the anisotropic spatial distribution of the observed HVSs. Hence, it is very likely that the HVSs discovered so far are irrelevant to the interactions of tightly bound stars with a highly eccentric BBH.

One natural prediction of the HVS origination proposed above is that some B-type HVSs exist close to the CWS disk plane and the Narm plane or the outer warped part of the CWS disk in the southern hemisphere, which should be a crucial check by future HVS surveys.

If old-population HVSs can be detected, their spatial distribution may be different from those shown in Figure 3, as the parent population of their progenitors may be significantly isotropic than that of the discovered B-type HVSs. Studying the spatial distribution of different types of HVSs may help to reveal information on the star formation and the dynamical environment in the GC.

5. CONCLUSIONS

Using both analytical arguments and numerical simulations, we have demonstrated that HVSs can well memorize the injecting directions of their progenitors. In another words, the ejecting direction of an HVS is almost anti-parallel to the injecting direction of its progenitor. Therefore, the spatial distribution of HVSs should map the spatial distribution of the parent population of their progenitors directly. We also find that most of the discovered HVSs are spatially consistent with being located on two thin disk planes. The orientation of one plane is consistent with that of the (inner) CWS disk, which suggests that most of the HVSs originate from it or a disk-like stellar structure with a similar orientation to it. The rest of HVSs may be correlated with the plane of the northern arm of the mini-spiral in the GC or the plane defined by the outer warped part of the CWS disk. Our results not only support the GC origin of HVSs but also imply that the central disk (or the disk structure with a similar orientation) should persist or be frequently rejuvenated over the past 200 Myr, which adds a new challenge to the stellar disk formation and provides insights to the longstanding problem of gas fueling into MBHs.

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