HYPERVELOCITY BINARY STARS: SMOKING GUN OF MASSIVE BINARY BLACK HOLES

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ABSTRACT

The hypervelocity stars recently found in the Galactic halo are expelled from the Galactic center through interactions between binary stars and the central massive black hole or between single stars and a hypothetical massive binary black hole. In this Letter, we demonstrate that binary stars can be ejected out of the Galactic center with velocities up to \(10^8 \text{ km s}^{-1}\), while preserving their integrity, through interactions with a massive binary black hole. Binary stars are unlikely to attain such high velocities via scattering by a single massive black hole or through any other mechanisms. On the basis of the above theoretical prediction, we propose a search for binary systems among the hypervelocity stars. Discovery of hypervelocity binary stars, even one, is definitive evidence of the existence of a massive binary black hole in the Galactic center.

Subject headings: black hole physics — Galaxy: center — stellar dynamics

1. INTRODUCTION

Evidence of a massive black hole (MBH) is securely established in the Galactic center (GC; Schödel et al. 2002; Ghez et al. 2003, 2005; Eisenhauer et al. 2005). Recent discoveries of young stars in the subparsec region around the GC (Sanders 1992; Ghez et al. 2003) and hypervelocity stars (HVs; first recognized by Hills 1988) in the Galactic halo (Brown et al. 2005, 2006a, 2006b; Edelmann et al. 2005; Hirsch et al. 2005) have stimulated the hypothesis of a second MBH or an intermediate-mass BH (IMBH), which may be common in galactic nuclei if they are assembled through mergers of smaller galaxies and/or star clusters with central MBHs or IMBHs (Begelman et al. 1980; Yu 2002; Volonteri et al. 2003). IMBHs can transport young stars to their current locations (Hansen & Milosavljevic 2003) where in situ star formation is suppressed by the strong tidal force of the MBH. Through close encounters, a massive binary black hole (BBH) may also eject nearby stars to become HVs (Yu & Tremaine 2003; Baumgardt et al. 2006; Levin 2006; Sesana et al. 2006). Direct observational evidence for a secondary MBH is difficult to establish because the semimajor axis of the BBH could be well within the orbit of the most central S stars, which have orbital periods longer than a decade (Schödel et al. 2002; Ghez et al. 2003).

With a simple scaling argument in § 2 and a series of numerical calculations in §§ 3 and 4, we demonstrate that hypervelocity binary stars (HVBSs) with velocities up to \(10^8 \text{ km s}^{-1}\) can be ejected out only by their dynamical interactions with a massive BBH. We propose a search for HVBSs among HVs. Discovery of hypervelocity binary stars, even one, is definitive evidence for the existence of a massive BBH in the GC.

2. DOMAINS OF RELEVANT DYNAMICAL PROCESSES

We characterize the dynamics of stars around an MBH in galactic centers with the following critical radii: (1) the Schwarzschild radius is \(r_{\text{sch}} = 2GM_{\text{MBH}}c^2 / 3.4 	imes 10^{-5} M_\odot \text{ pc}\), where \(M_{\text{MBH}}\) is the MBH’s mass \(M_\odot\) normalized by that of the MBH in the GC (in units of \(3.6 \times 10^6 M_\odot\); Ghez et al. 2005; Eisenhauer et al. 2005); \(G\) is the gravitational constant, and \(c\) is the speed of light; (2) the tidal radius for a single star with mass \(m_\star\) and radius \(r_\star\) is \(r_{\text{tid}} = r_\star \left( \eta M_{\text{MBH}} m_\star \right)^{1/3} = 3.5 \times 10^{-6} \left( \eta M_{\text{MBH}} m_\star \right)^{1/3} (M_\odot/m_\star)^{1/3} (r_{\text{sch}}/r_\star)\) pc, where a constant \(\eta = 2.21\) and 0.844 for a homogeneous, incompressible body and \(n = 3\) polytrope, respectively (Sridhar & Tremaine 1996; Quinlan 1996). BBHs, if extant in nearby normal galaxies, would be the primary and secondary MBHs, respectively (Quinlan 1996). BBHs, if present in nearby normal galaxies, would be the primary and secondary MBHs, respectively (Quinlan 1996). BBHs, if present in nearby normal galaxies, would be the primary and secondary MBHs, respectively (Quinlan 1996). BBHs, if present in nearby normal galaxies, would be the primary and secondary MBHs, respectively (Quinlan 1996). BBHs, if present in nearby normal galaxies, would be the primary and secondary MBHs, respectively (Quinlan 1996).
velocity. Consequently, one component of the binary star would be ejected out of the system with hypervelocity up to 10^7 km s^{-1}, and the other would become more tightly bound to the BH (Hills 1988). Around a hard BBH with \( a_{\text{BH}} \leq a_1 \), most low-angular-momentum single stars that enter into the region \( r_0 < r \leq a_{\text{BH}} \) can also be ejected by the BBH. The rms of the velocities of the ejected stars at infinity is given by

\[
v_{\text{ej}} = \sqrt{2 \frac{K G M_{\text{BH1}}}{r_{\text{ej}}}} \frac{M_{\text{BH2}}}{M_{\text{BH1}} a_{\text{BH1}}} \approx 900 \text{ km s}^{-1} \frac{m_{\text{BH1}}^{0.25}(1 - v^{3/2})}{0.1 a_1 a_{\text{BH1}}}^{1/2}
\]

(see Yu 2002, eq. [17]), where \( K = 1.6 \) is a constant and the \( M_{\text{BH1}} \sigma \) relation obtained by Tremaine et al. (2002) is adopted. The main portion of \( \delta v \) is due to the impulse induced by the secondary MBH \( F_{\text{d}} \), where \( F = G M_{\text{BH1}}/a_{\text{BH1}}^{3/2} \) is the force per unit mass from the secondary BH and \( \delta t \sim (G M_{\text{BH1}} a_{\text{BH1}}^{3/2})^{1/2} \) is the interaction time. Provided that \( a_{\text{BH1}} \) is substantially larger than \( r_0 \), there is a large probability for a binary star’s periapse not to enter into the region \( r \leq r_0 \) (with respect to either component of the BBHs) before it is ejected. Consequently, binary stars that enter into the region \( r_0 < r \leq a_{\text{BH1}} \) may be ejected with large velocities while preserving their systems’ integrity, as HVBSs.

### 3. Numerical Method

In order to determine the probability of HVBS formation, we simulate the interaction of binary stars with BBHs. Instead of carrying out a comprehensive series of prohibitive complex four-body problems, we note that the motion of a binary star with masses \( m_1 \) and \( m_2 \) in the potential of a BBH may be greatly simplified in the limit of \( m_1, m_2 \ll M_{\text{BH1}}, M_{\text{BH2}} \), because the motion of the BHs is not affected by the binary star and can be described in terms of a two-body problem. We set the center of mass of the BBH to be at rest at the origin of the coordinate system. Each component of the binary star moves in the potential of the rotating BBH and that of its stellar companion (i.e., \( G m_i/r - r \sim G m_i r \cdot r_i \), \( i \neq j, i, j = 1, 2 \)).

We present numerical results of the interaction of a binary star with a massive BBH in Figures 2 and 3. We assume various values for the semimajor axes of binary stars (with \( a_1 = 0.1 \)

![Fig. 2.—Probability for ejecting HVBSs. (a) Fraction of undisrupted binary stars that are expelled after their interactions with a hypothetical BBH. The BBH mass ratio is set to \( r = 0.01 \). The thick lines are for the BH mass in the Milky Way with different model parameters for the BBH and binary star’s semimajor axes. The thin long-dashed line represents the BBH mass in M31, and the thin dotted line represents M32. The circles/triangles/squares mark the radii \( r_0 \), in this case. (b) Fraction of binary stars that are expelled away as a whole with hypervelocity \( v_\text{ej} > 900 \text{ km s}^{-1} \) after their interactions with the assumed BBH in galactic centers. The line types and the solid points are the same as those in (a). As a reference, the thin solid line represents the fraction of single stars that are expelled with \( v > 900 \text{ km s}^{-1} \) after their three-body interactions with an identical BBH, as represented by the thick solid line.

### 4. Numerical Results and Discussions

We present numerical results of the interaction of a binary star with a massive BBH in Figures 2 and 3. We assume various values for the semimajor axes of binary stars (with \( a_1 = 0.1 \)

![Image 45x537 to 287x727]
and 0.3 AU; note that here 0.3 AU is taken as an upper limit because binaries with larger $a_b$ are likely to be disrupted by encounters with single stars in the GC within a Hubble time; Yu & Tremaine (2003) and for the BBH semimajor axes: $a_{BBH} = 0.1a_b = 0.37, 5.88, 0.48$ mpc [$= (4.9, 23, 7.2)$ $r_{BBH}^o$ for the Milky Way, M31, and M32, respectively] and $a_{BBH} = 2r_{BBH}^o = 0.15$ mpc (for the Milky Way). The component masses of the binary star are set to be $m_1 = m_2 = 1 M_{\odot}$, and our results are not modified by other values of binary masses. The BBH mass ratio is set to be $\nu = 0.01$ unless otherwise stated. For simplicity, the BBH is set to be on a circular orbit, and the initial intrinsic orbits of binary stars are also circular. Figure 2a shows that the probability of the binary star being ejected away as a whole from the BBH is generally larger than 50% if $r_p > r_{MBH}^o$ and that binary stars are more likely to be dissociated with decreasing pericenter distances $r_p$. Given the same BBH mass and semimajor axis, binary stars with larger $a_b$ values are more likely to be dissociated (see Fig. 2, thick solid line and dot-dashed line). If we keep $a_{BBH} = 0.1a_b$ but set $\nu = 0.001$ for the assumed BBH in the GC, the probability of ejecting HVBSs is smaller (down to 20% at $r_p = a_{BBH}$) since $a_{BBH}$ is smaller than the tidal radius of the primary MBH $r_{MBH}^o$ and most of the binary stars are tidally broken up.

Figure 3 shows the dependence of the ejection velocities of HVBSs on the pericenter distance $r_p$, which is generally consistent with the dependence of the ejection velocities of single stars through three-body interactions with the BBH (thin solid line). The $v_{ej}$ can attain values up to $10^3$ km s$^{-1}$ at $r_p \sim a_{BBH} = 0.1a_b$, and it remains roughly constant with decreasing $r_p$ but decreases with increasing $r_p$. The ejection velocities of HVBSs depend on the BBH mass and semimajor axis (see eq. [1]). With all else being equal, the ejection velocities increase with increasing BH mass (see Fig. 3, thin lines) and decrease with increasing BBH semimajor axis (thick short-dashed line and thick solid line).

Figure 2b shows that the probability of the binary star being ejected away as a whole with hypervelocity $v_{ej} > 900$ km s$^{-1}$ from the BBH has a peak value of 10%–50% at $r_p \sim (0.1–1.5)a_{BBH}$ and it decreases for both larger and smaller values of $r_p$. (Due to the deceleration in the Galactic potential, an ejected binary star, HVBS, with $v_{ej}^o = 900$ km s$^{-1}$ would attain an asymptotic velocity 700 km s$^{-1}$ at the galactocentric distance 50 kpc, which corresponds to the observed radial velocities of HVSSs in the Galactic halo.) The decline of ejection probability of binary stars with high velocities at large $r_p$ is consistent with that for single stars (thin solid line). But the rarity of ejecting HVBSs at small $r_p$ is mainly due to the dissociation of binary stars by the Hills mechanism, as indicated in Figure 2a. (Note that the encounters with a BBH at small $r_p$ require low-angular-momentum orbits. After the depletion of such an initial population, the likelihood to eject HVBSs at small $r_p$ declines because, through two-body relaxation, the remaining binary stars would slowly lose their angular momenta to other stars and reach the vicinity of the BBH preferentially with large $r_p$.)

Our calculations show that for a larger BBH semimajor axis $a_{BBH} = 0.3a_b$ in the GC, the peak probability is about 5%–10%, which is still nonnegligible. The ratio of number densities between the HVBSs and the single HVSs contains information on the fraction of binary stars in the GC, the BBH mass ratio, and semimajor axis. If a BBH with $\nu \sim 0.01$ and $a_{BBH} \sim 0.1a_b$ exists in the GC, according to Figure 2b, the probability of binary stars being ejected with $v_{ej}^o > 900$ km s$^{-1}$ would be at least about $\frac{1}{4} - \frac{1}{4}$ of the probability of single stars being ejected with such hypervelocities provided that $r_p \approx r_{MBH}^o$. If the density of binary stars with $a_b \sim 0.1–0.3$ AU is about 10% of that of the single stars in the GC, the fraction of HVBSs among the HVSs would then be at least about 3%–5%.

The ejection rate of HVSs by an assumed BBH (with $\nu = 0.01$ and $a_{BBH} = 0.5$ mpc) in the GC would be $\sim 10^{-7}$ yr$^{-1}$ if the low-angular-momentum stars initially in the loss cone are depleted and the loss cone is refilled by two-body relaxation processes (Yu & Tremaine 2003). If the fraction of binary stars with $a_b \leq 0.3$ AU in the GC is about 10% of the total stars, the ejection rate of HVBSs would be $\geq 5 \times 10^{-6}$ yr$^{-1}$. By applying the same method that is adopted by Yu & Tremaine (2003) we obtain ejection rates for M32 (with $\nu = 0.01$) and $a_{BBH} = 0.48$ mpc), which is similar to that for the Milky Way. But for M31 (with $\nu = 0.01$ and $a_{BBH} = 5.9$ mpc), we obtain lower ejection rates ($\sim 10^{-6}$ yr$^{-1}$ for HVSs and $\sim 10^{-6}$ to $10^{-7}$ yr$^{-1}$ for HVBSs). For M31, we adopt the surface density distribution estimated by Kormendy & Bender (1999, eq. [1]), and we neglect the departure of stellar distribution from spherical symmetry (Bender et al. 2005) as for the other cases. Asphericity, if significant, would enhance the ejection rates of HVSs and HVBSs.

Several HVSs have recently been discovered through spectroscopic observations (Brown et al. 2005, 2006a, 2006b; Edelmann et al. 2005; Hirsch et al. 2005). The presence of any HVBSs among this sample is difficult to be spatially resolved. But the spectrum of the more conspicuous primary would exhibit measurable ($\sim 100$ km s$^{-1}$ sin $i$) periodic variations on the timescale of a few to several times 10 days. Transits may also introduce observable periodic light-curve modulations. Nondetection of HVBSs does not rule out the existence of a BBH in the GC since their absence can be attributed to (1) a low rate of binary stars injection into the region $r_{MBH}^o < r \leq a_{BBH}$, (2) a relative com-
pact BBH with $a_{BBH} < r_{tid}^*$, or (3) a relatively soft BBH that is unable to eject stars with sufficiently high velocities.

In contrast, the detection of any HVBSs unequivocally proves the existence of BBH because the production of HVBSs by any other mechanism appears to be challenging and unlikely:

1. The Hills mechanism cannot lead to the production of HVBSs because it requires the breakup of a binary star by a single MBH.

2. In principle, tidal disruption of a hierarchical triple star (a close binary plus a less tightly bound tertiary companion) by the central MBH may lead to the capture of the tertiary by the MBH and the ejection of the close binary as an HVBS. However, the rate of ejection of HVBSs by this mechanism is negligible if the following factors are taken into account.

   a) The fraction of the binaries with additional companions (triple, quadruple, or quintuple) is about 60% of the binaries observed locally by Tokovinin et al. (2006).

   b) All known tertiary companions around the binaries have periods longer than 2 yr (with semimajor axis $\approx 2$ AU) and $\approx 90\%$ of the tertiary companion have orbital periods ranging from 5 to $10^4$ yr.

   c) The typical ejection speed of the close binary due to the breakup of a hierarchical triple with semimajor axis 2 AU is only $\sim 400$ km s$^{-1}$. If the ejection speed follows a Gaussian distribution with a dispersion that is about 20% of the average speed (the dispersion is mainly due to the different orbital phases and orientations of the binary orbit relative to the MBH; see, e.g., Bromley et al. 2006, Fig. 1), stars with velocity $v_{ej}$ higher than 700 or 900 km s$^{-1}$ would be beyond 3 or 5 $\sigma$ from the mean, which corresponds to small probabilities of $1.3 \times 10^{-5}$ or $3 \times 10^{-7}$. Thus, the ejection rate of HVBSs due to the tidal breakup of hierarchical triple stars is only a factor of $0.6 \times 0.1 \times 1.3 \times 10^{-3} \sim 8 \times 10^{-5}$ or $2 \times 10^{-8}$ of the number of HVBSs due to the Hills mechanism. We note that the argument above has some uncertainties because the estimate derived for the solar neighborhood is uncertain, and it is not clear whether the triple distribution at the GC is the same as that in the solar neighborhood.

3. HVBSs may also be ejected as stars are scattered off a cluster of stellar-mass black holes (SBHs) orbiting a central MBH. In principle, the ejected stars can be binaries. But the perturbation on the velocity of ejection star(s), $\delta v$, is primarily due to close encounters with slightly more massive SBHs at a distance about the solar radius (O’Leary & Loeb 2006). Such close encounters can lead to either the disruption of the binary system or an exchange in which the SBH captures one component of the initial binary while the other is ejected as a single star. The newly formed star-SBH binary cannot be ejected out of the GC as an HVBS since the SBHs are closely bound to the central MBH with a substantially negative specific energy ($|E| > |v| \delta v$ because usually $\delta v \ll v$). Whereas the detection of an HVS provides support for the existence of an MBH in the GC (Hills 1988; Brown et al. 2005), the detection of an HVBS will be the smoking gun for the existence of a massive BBH in the GC (or M31, M32).

Our numerical calculations show that both $a_\phi$ and the eccentricities of the binary may be strongly modified during their interactions with the BBH. The eccentricity of the binary-stars’ orbits can be excited up to 0.9–1, which may lead to the merger of the two components of the binary star with small relative velocity. Therefore, the interactions between binary stars on bound orbits and a BBH may provide a channel for the formation of S stars discovered in the GC. It is plausible that both the formation of S stars and the ejection of HVBSs are by-products during the process of a BBH spiraling inward toward the primary MBH.

The velocity of some binary stars ejected by interactions with a BBH can be smaller than the escape velocity of the Galactic halo, and these stars are bound to the Galaxy. Such a binary may already be contained in existing observational data. For example, Scorpius X-1, an X-ray binary, is found to have a velocity of $\sim 480$ km s$^{-1}$ with its past perigalactic distance of $\sim 500$ pc to the GC (Mirabel & Rodrigues 2003). This object could be explained as a binary formed in the GC and ejected out by a BBH from there, although other explanations, such as a natal kick of supernovae explosion, are possible.

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