Maximum speed of hypervelocity stars ejected from binaries

Thomas M. Tauris\textsuperscript{1,2⋆},
\textsuperscript{1} Argelander-Institut für Astronomie, Universität Bonn, Auf dem Hügel 71, D-53121 Bonn, Germany
\textsuperscript{2} Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany

ABSTRACT
The recent detection of hypervelocity stars (HVSs) as late-type B-stars and HVS candidate G/K dwarfs raises the important question of their origin. In this Letter, we investigate the maximum possible velocities of such HVSs if they are produced from binaries which are disrupted via an asymmetric supernova explosion. We find that HVSs up to \( \sim 770 \) and \( \sim 1280 \, \text{km s}^{-1} \) are possible in the Galactic rest frame from this scenario for these two subclasses of HVSs, respectively. We conclude that whereas a binary origin cannot easily explain all of the observed velocities of B-type HVSs (in agreement with their proposed central massive black hole origin) it can indeed account for the far majority (if not all) of the recently detected G/K-dwarf HVS candidates.

Key words: stars: kinematics and dynamics — supernovae: general — binaries: close

1 INTRODUCTION
In recent years, a large number of hypervelocity star (HVS) candidates have been reported (e.g. Brown et al. 2005, 2006; Edelmann et al. 2005; Hirsch et al. 2005, 2012; Tillich et al. 2009; Li et al. 2012; Palladino et al. 2014; Zhong et al. 2014, and references therein). Here we define genuine HVSs only as stars which will escape the gravitational potential of our Galaxy. Depending on the location and direction of motion, this criterion typically corresponds to a stellar velocity in the Galactic rest frame \( v > 400 \, \text{km s}^{-1} \) (Kenyon et al. 2008). More than 50 stars can thus be classified as HVSs – see Fig. 1 for a subsample.

HVSs can obtain their large velocities\textsuperscript{1} from a number of different processes. Hills (1988) predicted the formation of HVSs via tidal disruption of tight binary stars by the central supermassive black hole (SMBH) of the Milky Way. In this process one star is captured by the SMBH while the other is ejected at high speed via the gravitational slingshot mechanism. Also exchange encounters in other dense stellar environments (e.g. Aarseth 1974) between hard binaries and massive stars may cause stars to be ejected and escape our Galaxy (Leonard 1991; Gvaramadze et al. 2009). A competing mechanism for producing HVSs is disruption of close binaries via supernova (SN) explosions (Blauwe 1961; Boersma 1961; Tauris & Takens 1998, Zubovas et al. 2013). As demonstrated in Tauris & Takens (1998), the runaway velocities of both ejected stars can reach large values when asymmetric SNe are considered, i.e. when the newborn neutron star (NS) receives a momentum kick at birth.

The nature of the HVSs spans a wide range of types from OB-stars, to metal-poor F-stars and G/K dwarfs. While there is evidence from many late-type B HVSs in the halo to originate from the Galactic SMBH (e.g. Brown et al. 2014) other HVSs seem to originate from the Galactic disc (e.g. Heber et al. 2008; Li et al. 2012; Palladino et al. 2014). This calls for a detailed analysis to explain the kinematic origin of, in particular, the latter group.

In this Letter, we investigate the maximum possible ejection velocities of HVSs with different masses originating from disrupted binaries via asymmetric core-collapse SNe. We use Monte Carlo techniques and perform a systematic investigation of the parameter space prior to/during the SN in order to probe the resulting velocities. The effects of SN shell impact on the companion star are included in our calculations. A particular focus is given to late-type B and G/K-dwarf HVSs. In Section 2 we briefly describe our model. Our results are presented in Section 3 and a discussion follows in Section 4. Our conclusions are summarized in Section 5.

2 MODELLING THE DYNAMICAL EFFECTS OF SNE
Tauris & Takens (1998) derived analytical formulae to calculate the velocities of stars ejected from binaries in which asymmetric SNe occur. The velocity of the ejected companion star, \( v_2 \), depends on: the pre-SN orbital separation, \( r \); its mass, \( M_2 \); the mass of the exploding star, \( M_{\text{SN}} \); the mass and the velocity of the ejected SN shell, \( M_{\text{ej}} \) and \( v_{\text{ej}} \), and the resulting impact velocity on the companion star caused by the ejected shell, \( v_{\text{im}} \) (which depends on the explosion energy, \( E_{\text{SN}} \)); and finally, the kick velocity (magnitude and direction) imparted on the newborn NS, \( \vec{w} \).

\textsuperscript{1} E-mail: tauris@astro.uni-bonn.de
\textsuperscript{⋆} Here we do not distinguish velocity from speed (magnitude of velocity).
3 RESULTS

In Fig. 1 we have plotted the resulting values of $v_2$ as a function of kick velocity magnitudes, $w$ imparted on the NS for one specific set of initial parameters applied to late-type B-star companions with an initial mass of 3.5 $M_\odot$ (top) and G/K-dwarf companions with an initial mass of 0.9 $M_\odot$ (bottom). In both cases we simulated 10$^6$ explosions using an isotropic kick distribution. All ejection velocities in this Letter ($v_2$ and $v_{\text{NS}}$) are quoted with respect to the c.m. reference frame of the pre-SN binary. It is interesting to notice that the values of $v_2^{\text{max}}$ peak when $w \approx 1000 = 1200$ km s$^{-1}$ whereas the average values, $\langle v_2 \rangle$, keep increasing with $w$ (approaching an asymptotic value as $w \to \infty$, cf. Appendix B).

It is also seen that the values of $v_2$ for G/K-dwarf stars are generally twice as large as those for the late-type B-stars. This is mainly caused by the difference in the applied pre-SN orbital separations, $r$. The G/K dwarfs are able to remain much closer to the exploding star without filling their Roche lobes ($r_{\text{min}} \approx 2.9 R_\odot$), whereas the G/K dwarfs have smaller masses, $M_2$. As a result of these effects, the G/K dwarfs have larger orbital velocities, $v_{2,\text{orb}}$, prior to the SN, explaining their larger values of $v_2$.

In Fig. 2 we plot the distribution of $v_2$ and $v_{\text{NS}}$ for the systems with ejected G/K dwarf stars plotted in the bottom panel of Fig. 1 and for which $w = 1000$ km s$^{-1}$. In this case, as a result of the shell impact, the companion star decreases its mass from 0.90 to 0.846 $M_\odot$. About 1.9 per cent of the systems survived as HVSs, with an average systemic velocity of an impressive 703 km s$^{-1}$, and 3.1 per cent of the systems merged as a result of the SN. The average velocity of the ejected G/K dwarfs is $\langle v_2 \rangle$ = 375 km s$^{-1}$. However, the entire interval of possible values of $v_2$ spans between 87 and 839 km s$^{-1}$ for this particular setup.
3.1 Dependence on kick direction

In Fig. 3 we show that the value of $v_2$ is highly dependent on the direction of the kick imparted on the NS. The white area in the middle corresponds to cases where the newborn NS is shot into the direction of the kick imparted on the NS. The white area in the top of the plot (the shape of which depends on $\theta$ and $\phi$) is determined by the spin axis of the newborn NS. While the kick angle $\phi$ is chosen randomly, the polar kick $\theta$ is chosen randomly between $3$ and $180^\circ$. The SN-induced HVSs with the largest values of $v_2$ are ejected close to the plane of the SN explosion, and only apply to cases where the explosion energy, $E_{SN}$ is quite weak. For example, using a constant $w = 1200$ km s$^{-1}$ and increasing the value of $E_{SN}$ from $1.23$ to $8$ foe, only causes $v_2^{\text{max}}$ to increase by $\sim 6$ per cent from $891$ to $943$ km s$^{-1}$. The reason for this is that $v_2^{\text{max}}$ is less important for the HVSs high in the halo and their trajectory does not point to the central SMBH, could potentially be a remnant of an early B-star, and whose trajectory to their current location.

4 DISCUSSIONS

We have investigated the maximum runaway velocities of SN-induced HVSs. However, one must bear in mind to add the Galactic rotational velocity (typically of the order of $v_{GRF}^{\text{Gal}} \approx 230$ km s$^{-1}$) at the birth location of the binary system. Hence, in the Galactic rest frame we obtain $v_{2,GRF}^{\text{max}} \approx v_2^{\text{max}} + 230$ km s$^{-1}$.

4.1 B-type HVSs

From our simulations we find that only under the most extreme favourable conditions (with respect to $r$, $w$, $\theta$, $\phi$, $M_{He}$ and $E_{SN}$) is it possible for a B-type star ($\sim 3.5 M_\odot$) to achieve $v_2^{\text{max}}$ up to $\sim 540$ km s$^{-1}$ (in those particular cases $v_{\text{amb}} = 110$ km s$^{-1}$, and the final post-ablation stellar mass is $\sim 3.24 M_\odot$). This value implies that $v_2^{\text{max}} \approx 770$ km s$^{-1}$. Therefore, any observed B-type HVS which does not exceed this velocity at its origin, and whose trajectory does not point to the central SMBH, could potentially be the result of a disrupted binary. However, we caution that the effect of adding $v_{GRF}^{\text{Gal}}$ is less important for the HVSs high in the halo and also note that these stars lose some of their kinetic energy along the trajectory to their current location.

Finally, we have investigated disrupted binaries with early, massive B-star companions ($10 M_\odot$). Here we find $v_2^{\text{max}} \sim 320$ km s$^{-1}$, corresponding to $v_{2,GRF}^{\text{max}} \sim 550$ km s$^{-1}$, a significantly lower value compared to the late-type B-stars.
4.2 G/K-dwarf HVS candidates

We can reproduce G/K-dwarf HVSs with runaway velocities up to $v_{\text{max}} \simeq 1050 \text{ km s}^{-1}$ (in those extreme cases $v_{\text{max}} \simeq 195 \text{ km s}^{-1}$, and the final post-ablation stellar mass is $\sim 0.71 M_\odot$ for a pre-SN mass of 0.90 $M_\odot$). Hence, in the Galactic rest frame $v_{\text{max}}^{\text{SGRf}} \simeq 1280 \text{ km s}^{-1}$. Such high velocities can certainly explain many, if not all, of the recently discovered G/K-dwarf HVS candidates (Palladino et al. 2014). Interestingly enough, these HVSs do not seem to originate from the centre of our Milky Way, bringing further support for a disrupted binary scenario as to their origin.

4.3 Kick velocities of newborn NSs

In this work the aim has been to calculate the maximum possible runaway velocities for HVSs ejected from disrupted binaries via asymmetric SNe. The magnitude of the kick, $w$, has been treated as a free parameter (besides the assumption of isotropy in the kick direction) and we find peak values of $v_{\text{max}}$ for $w = 1000 − 1200 \text{ km s}^{-1}$. An important question, however, is if such large kicks are realistic? Although the average kick velocities seem to be of the order $400 − 500 \text{ km s}^{-1}$ (inferred from studies of proper motions of young radio pulsars, Lyne & Lorimer 1994; Hobbs et al. 2005) there are NSs which have received significantly larger kicks. These include the radio pulsars B2011+38 and B2224+65 which (depending on their precise distances) both have 2D velocities exceeding 1500 km s$^{-1}$ (Hobbs et al. 2005). The latter pulsar is observed with a bow shock (the “guitar nebula”) which confirms that it is moving with a large velocity (Cordes et al. 1993). Another supersonic runaway pulsar with a velocity in excess of 1000 km s$^{-1}$ is IGR J11014−6103 (Tomsick et al. 2012; Pavan et al. 2014). Finally, B1508+55 has an almost perfectly measured velocity of $\sim 1100 \pm 100 \text{ km s}^{-1}$ based on VLBA measurements of its proper motion and parallax (Chatterjee et al. 2005).

Further evidence for large kicks can be found from combining simulations of the dynamical effects of SNe with future observations of X-ray binaries with large systemic velocities, following the recipe outlined by Tauris et al. (1999). Given the above-mentioned evidence for large kicks we therefore predict the existence of low-mass X-ray binaries (and binary millisecond pulsars) with peculiar systemic velocities in excess of 700 km s$^{-1}$, cf. Section 3.

Theoretical simulations of SNe (see Janka 2012 for a review) can also account for kicks in excess of 1000 km s$^{-1}$ (e.g. Scheck et al. 2006; Wongwathanarat et al. 2013). Hence, our HVS simulations presented in this Letter are based on a solid foundation of evidence for the possibility of large kicks.

5 SUMMARY

We have performed systematic Monte Carlo simulations to investigate the maximum possible runaway velocities of HVSs ejected from disrupted binaries via asymmetric SNe. For companion stars with initial masses of 0.90, 3.50 and 10 $M_\odot$ we find $v_{\text{max}}^{\text{SGRf}} = 1280$, 770 and 550 km s$^{-1}$, respectively. While a significant fraction of late B-type HVS have been shown in the literature to originate from the central SMBH (Brown et al. 2014), we have presented evidence that, in particular, the majority (if not all) of the presently observed G/K-dwarf HVS candidates could very well originate from a binary disruption scenario. However, we caution that a more robust conclusion on the rates and the distribution of $v_{2,\text{SGRf}}$ requires detailed population synthesis studies.

Finally, we note that a firm identification of a HVS being ejected from a binary via a SN is still missing, although a candidate (HD 271791) has been proposed by Przybilla et al. (2008); however, see also the interpretation of Gvaramadze (2009).

ACKNOWLEDGEMENTS

TMT cordially thanks Warren Brown and Pablo Marchant for comments and also acknowledges the receipt of DFG grant TA 964/1-1.

REFERENCES

Aarseth S. J., 1974, A&A, 35, 237
Blauw A., 1961, Bull. Astron. Inst. Netherlands, 15, 265
Boersma J., 1961, Bull. Astron. Inst. Netherlands, 15, 291
Brown W. R., Keller M. J., Kenyon S. J., 2009, ApJ, 690, 1639
Brown W. R., Keller M. J., Kenyon S. J., 2012, ApJ, 751, 55
Brown W. R., Keller M. J., Kenyon S. J., 2014, ApJ, 787, 89
Brown W. R., Keller M. J., Kenyon S. J., Kurtz M. J., 2005, ApJ, 622, L33
Brown W. R., Keller M. J., Kenyon S. J., Kurtz M. J., 2006, ApJ, 640, L35
Chatterjee S., et al., 2005, ApJ, 630, L61
Cheng A., 1974, Ap&SS, 31, 49
Cordes J. M., Romani R. W., Lundgren S. C., 1993, Nature, 362, 133
Edelmann H., NapＷitzki R., Heber U., Christlieb N., Reimers D., 2005, ApJ, 634, L181
Gvaramadze V. V., 2009, MNRAS, 395, L85
Gvaramadze V. V., Gualandris A., Portegies Zwart S., 2009, MNRAS, 396, 570
Heber U., Edelmann H., NapＷitzki R., Altmann M., Scholz R.-D., 2008, A&A, 483, L21
Hills J. G., 1988, Nature, 331, 687
Hirai R., Sawai H., Yamada S., 2014, ApJ, 792, 66
Hirsch H. A., Heber U., O’Toole S. J., Bresolin F., 2005, A&A, 444, L61
Hobbs G., Lorimer D. R., Lyne A. G., Kramer M., 2005, MNRAS, 360, 974
Ivanova N., et al., 2013, A&A Rev., 21, 59
Janka H.-T., 2012, Annual Review of Nuclear and Particle Science, 62, 407
Kenyon S. J., Bromley B. C., Keller M. J., Brown W. R., 2008, ApJ, 680, 312
Leonard P. J. T., 1991, AJ, 101, 562
Li Y., Luo A., Zhao G., Lu Y., Ren J., Zuo F., 2012, ApJ, 744, L24
Liu Z. W., Pakmor R., Röpke F. K., Edelmann P., Wang B., Kromer M., Hillebrandt W., Han Z. W., 2012, A&A, 548, A2
Lynne A. G., Lorimer D. R., 1994, Nature, 369, 127
Marietta E., Burrows A., Fryxell B., 2000, ApJS, 128, 615
Nomoto K., Thielemann F.-K., Yokoi K., 1984, ApJ, 286, 644
Pan K.-C., Ricker P. M., Taam R. E., 2012, ApJ, 750, L39
Pavan L., et al., 2014, A&A, 562, A122
Przybilla N., Nieva M. F., Heber U., Butler K., 2008, ApJ, 684, L103
Scheck L., Kifonidis K., Janka H.-T., Müller E., 2006, A&A, 457, 963
Tauris T. M., Fender R. P., van den Heuvel E. P. J., 2006, Formation and evolution of compact stellar X-ray sources. Cambridge University Press, pp 623–665
Tillich A., Przybilla N., Scholz R.-D., Heber U., 2009, A&A, 507, L37
Tomsick J. A., Bodaghee A., Rodriguez J., Chaty S., Camilo F., Fornasini F., Rahoui F., 2012, ApJ, 750, L39
Wheeler J. C., Lecar M., McKee C. F., 1975, ApJ, 200, 145
On supernova-induced hypervelocity stars

APPENDIX A: THE SUPERNOVA SHELL IMPACT

The formulae of [Tauris & Takens (1998)] include the impact of the SN shell on the companion star. This effect is significant and must be included when probing the maximum possible ejection velocities since these arise from the tightest pre-SN systems in which the companion star is relatively close to the exploding star (and hence the cross-section for absorbing momentum of the SN ejecta is relatively high). To model the SN shell impact we adopt a modified version of the analytical formulae of [Wheeler et al. (1975)], following the implementation in [Tauris & Takens (1998)]. While there are several studies published on the shell impact on the companion star in single-degenerate Type Ia SNe, no systematic studies are yet available on similar effects caused by core-collapse SNe (Type Ib/c SNe). Therefore, we use a new calibration based on more recent multidimensional hydrodynamical simulations of the impact of the ejected shell in single-degenerate Type Ia SNe systems (cf. Marietta et al. 2008, Pakmor et al. 2008, Pan et al. 2012, Liu et al. 2012).

In Figure A1 we show our calibrated fits (dashed lines) given by a slight rewriting of Wheeler et al. (1975):

\[ v_{\text{lim}} = 0.20 \frac{v_{\text{ejecta}} (R_s^2/2r)^2 (M_{\text{ejecta}}/M_2) x_{\text{crit}}^2}{1 + \ln(2 v_{\text{ejecta}}/v_{\text{esc}})} \times (A1) \]

where \( R_s \) is the radius of the companion star, \( v_{\text{esc}} = \sqrt{2GM_2/x_{\text{crit}}} \) is the surface escape velocity of the companion star (typically, 800 - 1000 km s\(^{-1}\)), and the parameter \( x_{\text{crit}} \) is a critical fraction of the radius outside of which a total mass fraction, \( F_{\text{strip}} \), is stripped and inside of which a certain fraction, \( F_{\text{ablated}} \), is ablated. The latter parameters are found from fitted functions to the tabulated values of Wheeler et al. (1975).

After the SN shell impact, the new mass of the companion star is given by:

\[ M_2' = M_2 (1 - F^*) \]

where \( F^* = (F_{\text{strip}} + F_{\text{ablate}}) \). Finally, the average ejecta velocity, \( v_{\text{ejecta}} \) (typically, 8000 - 10000 km s\(^{-1}\)) is simply estimated from \((2 E_{\text{SN}}/M_{\text{ejecta}})^{0.5}\), where \( E_{\text{SN}} \) is the explosion energy of the SN (although this expression is probably an overestimate by about 10 per cent compared to the results from hydrodynamical studies of SNe, cf. Marietta et al. 2000).

Strictly speaking, \( v_{\text{lim}} \) is an effective velocity assuming an instant addition of incident shell momentum (stripping) and subsequent momentum resulting from mass loss due to ablation of stellar material from the surface layers heated by the passing shock wave. Although in a close binary the incident energy of the SN debris may exceed the binding energy of the companion star by a few orders of magnitude, this energy is deposited in the outer layers of the star whereby a main-sequence companion star can easily survive such an impact (Cheng 1974, Wheeler et al. 1975).

APPENDIX B: A SANITY CHECK ON THE EQUATIONS

A quick sanity check on our applied equations (51–56) of Tauris & Takens (1998) is made via their equations (13) and (44–47), and reveals the results for the limiting cases with either no

\[ v_{\text{lim}} = 0.20 \frac{v_{\text{ejecta}} (R_s^2/2r)^2 (M_{\text{ejecta}}/M_2) x_{\text{crit}}^2}{1 + \ln(2 v_{\text{ejecta}}/v_{\text{esc}})} \times (A1) \]

A quick sanity check on our applied equations (51–56) of Tauris & Takens (1998) is made via their equations (13) and (44–47), and reveals the results for the limiting cases with either no
Figure A1. Estimates of impact velocity, \( v_{\text{im}} \) (top) and fractional mass loss from the companion star, \( \Delta M = \Delta M_2/M_2 \) (bottom) as a function of pre-SN orbital separation in units of the companion star radius \( (r/R_2)^2 \). Our analytical formulae (dashed lines) result from a modified prescription of Wheeler et al. (1975) calibrated on a \( 1.0 M_\odot \) main sequence star companion. The various symbols show results based on hydrodynamical simulations of \( 0.74-1.22 M_\odot \) companion stars. These calculations were based on Type Ia SNe and thus the ejecta mass, \( M_{\text{ejecta}} \sim 1.4 M_\odot \) (total disruption of a Chandrasekhar-mass white dwarf). The explosion energy is in all cases assumed to be \( 1.23 \times 10^{51} \) ergs (model W7 of Nomoto et al. 1984). The shell effects are strongly decreasing with increasing pre-SN orbital separation. The grey-shaded zone corresponds to systems where a \( 1.0 M_\odot \) companion star (the pre-SN donor star) overfills its Roche lobe in a binary with a \( 1.4 M_\odot \) accretor (as in a pre-SN Ia binary).

In addition, we have for the case of a purely symmetric SN and neglecting the shell impact (see also Tauris & Takens 1998; Gvaramadze 2009):

\[
\lim_{w,v_{\text{im}} \to 0} v_2 = \sqrt{1 - 2 M_{\text{NS}}(M_{\text{He}} + M_2)/M_{\text{He}}^2} \quad v_2,_{\text{orb}}.
\]

\[(B4)\]

Remnant mass (as in the case of SNe Ia) or an infinite high kick velocity:

\[
\lim_{M_{\text{NS}} \to 0} v_2 = \sqrt{v_{2,\text{orb}}^2 + v_{\text{im}}^2},
\]

\[(B1)\]

\[
\lim_{w \to \infty} v_2 = \sqrt{v_{2,\text{orb}}^2 + v_{\text{im}}^2} \quad \text{and} \quad \lim_{w \to \infty} v_{\text{NS}} = w,
\]

\[(B2)\]

where \( v_2 \) is the ejection velocity of the companion star and \( v_{\text{NS}} \) is the ejection velocity of the newborn NS (both in the c.m. reference frame of the pre-SN binary). As discussed in Section 3 in tight pre-SN systems \( (r \to 0) \) we have \( v_{2,\text{orb}}^2 \gg v_{\text{im}}^2 \), which yields:

\[
\lim_{w \to \infty} v_2 \simeq v_{2,\text{orb}} = M_{\text{He}} \sqrt{G/((M_{\text{He}} + M_2) r)}.
\]

\[(B3)\]