J. Astrophys. Astr. (2016) 37: 22
DOI: 10.1007/s12036-016-9400-2

Velocity Distributions of Runaway Stars Produced by Supernovae in the Galaxy

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Received 9 April 2016; accepted 29 July 2016

Abstract. Using a method of population synthesis, we investigate the runaway stars produced by disrupted binaries via asymmetric core collapse supernova explosions (CC-RASs) and thermonuclear supernova explosions (TN-RASs). We find the velocities of CC-RASs in the range of about 30–100 km s^{-1}. The runaway stars observed in the galaxy are possibly CC-RASs. Due to differences in stellar chemical components and structures, TN-RASs are divided into hydrogen-rich TN-RASs and helium-rich TN-RASs. The velocities of the former are about 100–500 km s^{-1}, while the velocities of the latter are mainly between 600 and 1100 km s^{-1}. The hypervelocity stars observed in the galaxy may originate from thermonuclear supernova explosions. Our results possibly cover the US 708 which is a compact helium star and travels with a velocity of 1157 ± 53 km s^{-1} in our galaxy.

Key words. Binaries: close—stars: evolution—supernovae: general.

1. Introduction

Space velocities of the runaway stars are assumed to be greater than 30 km s^{-1} (Eldridge *et al.* 2011). The first report of the runaway stars was given in Blaauw (1961). Most of observed runaway stars are spectral types O and B, massive, early type stars, generally observed in high galactic latitude, with velocities up to 300 km s^{-1} (Blaauw 1961; Hoogerwerf *et al.* 2001; Mdzinarishvili & Chargeishvili 2005). Hypervelocity stars are runaway stars which travel with high velocities. Hills (1988) suggested that the hypervelocity stars traveling at a speed of $\sim$1000 km s^{-1} are one of the natural outcomes of interplay between the binary systems and massive black holes or dense stellar clusters. Wang & Han (2009) suggested that the surviving stars from the white dwarf (WD) + helium (He) star channels may be a possible origin for the hypervelocity stars. In recent years, low-mass, high velocity (about a few hundred km s^{-1}), spectral type G, K candidates of hypervelocity stars have been reported and the origins of these stars have been controversial (Palladino *et al.* 2014; Zhang *et al.* 2014; Ziegerer *et al.* 2015; Brown *et al.* 2015; Li *et al.* 2015). US 708 is a He star (Hirsch *et al.* 2005), and its galactic rest-frame velocity is $\sim$1280 km s^{-1} (Geier *et al.* 2015). Geier *et al.* (2015) suggested that the US 708 was likely to be the ejected donor remnant of a thermonuclear supernova in a binary system which was composed of WD and He star. Such high space velocities imply that these stars can escape the gravitational potential of Milky Way galaxy and travel a long distance from their birth place.

In terms of the origin of runaway stars, a few acceleration mechanisms have been discussed. Two of the most popular acceleration mechanisms are the dynamical ejection scenario and the binary supernova scenario (Blaauw 1961; Hoogerwerf *et al.* 2001; Eldridge *et al.* 2011).

In the first scenario, the runaway stars are the surviving stars in the disrupted binaries after the binary systems interact with the central massive black holes or dense stellar clusters (Poveda *et al.* 1967; Hills 1988). Galactic center is the suggested origin of these hypervelocity stars (Hills 1988; Brown *et al.* 2006). We do not discuss such runaway stars in this paper.

In the second scenario, runaway stars are produced by disrupted binaries via supernova explosions. The supernova explosions are divided into two subtypes according to the different explosion mechanisms: core collapse supernova explosions and thermonuclear supernova explosions. Because the consequences of two type supernova explosions are quite different, we split these cases into two parts:

(i) In the former, runaway stars are produced by disrupted binaries via asymmetric core collapse supernova explosions. The newborn compact objects (either black hole or neutron star) receive additional anisotropy kick velocity, and the systems may be disrupted after the asymmetric core collapse supernova explosions. Then, compact objects and their companions become runaway stars. In this paper, we only address the latter, and call them as core collapse-runaway stars (CC-RASs).

(ii) In the latter, runaway stars are produced by disrupted binaries via thermonuclear supernova explosions. Carbon oxygen white dwarfs (CO-WDs) in the binary systems accrete materials from their companions. These companions are probably main sequence stars, red giants, or naked He stars (Wang & Han 2009; Wolfgang & Laughlin 2012). When the mass of accreting CO-WD reaches the Chandrasekhar mass limit, type Ia supernova explosion (SN Ia) occurs. After CO-WD disappears, its companion becomes a runaway star. In this paper, we call such runaway stars as thermonuclear-runaway stars (TN-RASs).

Wang & Han (2009) have studied the properties of the companions of CO-WD + He star channel at the moment of supernova explosions. They have obtained the velocity of the surviving companions to be beyond 400 km s^{-1}. Eldridge *et al.* (2011) have studied the OB runaway stars which are produced by disrupted binaries via core collapse supernova explosions in detail. They have reported that the velocity of OB runaway stars can not exceed 300 km s^{-1}. Tauris (2015) calculated the maximum speed of the hypervelocity stars ejected from disrupted binaries by asymmetric supernova explosions. He gave the maximum velocity of B-type hypervelocity stars as 770 km s^{-1}, and the velocity of the supernova shell as 11000 km s^{-1}.

The origin of runaway stars is related closely to the binary evolution. A study of runaway stars is important in understanding the binary evolution, cosmic evolution and the structure of the galaxy. This work investigates the runaway stars originating from the disrupted binaries via supernova explosion. The paper is organized as follows. In section 2, we describe our method of calculating the velocity of the CC-RASs and TN-RASs. Our results are presented in section 3 and is concluded in section 4.

2. Model

We use the rapid binary evolution code (BSE) originated from Hurley *et al.* (2002) and updated by Kiel & Hurley (2006) to simulate binary evolution. As mentioned in the Introduction, runaway stars are divided into two types: CC-RASs and TN-RASs. Their origins are different. In this section, we describe some details for calculating their velocities.

2.1 *Core collapse-runaway stars model*

The binary system is disrupted, when a core collapse supernova explosion occurs in a binary system. Brandt & Podsiadlowski (1995) gave detailed calculations for the disruption of binary systems which undergo a core collapse supernova explosion. Here, we use their model. If a binary system is disrupted, the velocities of CC-RASs depend mainly on magnitude and direction of kick velocity (ω), its mass (M_2) and initial orbit radius (r). We use the magnitude of kick velocity as 265 km s^{-1} (Hobbs *et al.* 2005) and leave the direction of kick velocity free. Tauris & Takens (1998) derived analytical formulae to calculate the velocities of stars ejected from disrupted binaries via asymmetric core collapse supernova explosions:

$$v_x = \frac{-\omega \cos\vartheta}{m_2 R} - \left(\frac{1}{m_2 R} + \frac{1+m_{\rm shell}}{1+m_{\rm shell}+m_2}\right)v, \quad (1)$$

$$v_y = \frac{\omega \sin\vartheta \cos\varphi}{m_2 S} + \left(1 - \frac{1}{m_2 S}\right)v_{\rm im} - \frac{Q\sqrt{P}}{m_2 S}v, \quad (2)$$

$$v_z = \frac{-\omega \sin\vartheta \sin\varphi}{m_2 R}, \quad (3)$$

where ω is the kick velocity, ϑ is the angle between v and ω ($0 \le \vartheta \le \pi$), v is the relative velocity given by $v = \sqrt{G(M_1+M_2)/r}$, r is the radius of the orbit, φ is the second position angle ($0 \le \varphi < 2\pi$). Here, we have introduced the notation: $m_i \equiv M_i/M_{\rm CO}$, $M_{\rm CO}$ is the mass of compact object, $M_{\rm shell} = M_1 - M_{\rm CO}$, where $M_{\rm shell}$ is the mass of the supernova shell, and P, Q, R, S is given by

$$P \equiv 1 - 2\tilde{m} + \frac{\omega^2}{v^2} + \frac{v_{\rm im}^2}{v^2} + 2\frac{\omega}{v^2}(v\cos\vartheta - v_{\rm im}\sin\vartheta\cos\varphi), \quad (4)$$

$$Q \equiv 1 + \frac{P}{\tilde{m}} - \frac{(\omega\sin\vartheta\cos\varphi - v_{\rm im})^2}{\tilde{m}v^2}, \quad (5)$$

$$R \equiv \left(\frac{\sqrt{P}}{\tilde{m}v}(\omega\sin\vartheta\cos\varphi - v_{\rm im}) - \frac{P}{\tilde{m}} - 1\right)\frac{1+m_2}{m_2}, \quad (6)$$

$$S \equiv \left(1 + \frac{P}{\tilde{m}}(Q+1)\right)\frac{1+m_2}{m_2}, \tag{7}$$

where $\tilde{m}$ is given by

$$\tilde{m} \equiv \frac{1+m_2}{1+m_{\rm shell}+m_2}. \tag{8}$$

In this work, we do not consider the consequences of shell impact on the companions. Hence, the impact velocity $v_{\rm im} = 0$. To calculate the velocity of CC-RASs, we make use of equations (1), (2) and (3) in Monte Carlo simulation.

2.2 *Thermonuclear-runaway stars model*

TN-RASs originate from SNe Ia. Their progenitors include accreting CO-WDs and main sequence, red giant or naked He star companions. There are many works reported in the literature investigating the evolution of these progenitors (see a recent review by Wang & Han 2012). The amount of matter retained by the accreting WD is critical for the success of SN Ia. For the retention efficiencies of hydrogen (H) accumulation ($\eta_{\rm H}$), we follow Hachisu *et al.* (1999) (also see Han & Podsiadlowski 2004 and Lü *et al.* 2009). When mass-accretion rate $\dot{M}_{\rm a}$ is larger than a certain critical value $\dot{M}_{\rm cr}$, the accreted H burns steadily on the surface of the CO-WD at the rate of $\dot{M}_{\rm cr}$. The critical mass-accretion rate $\dot{M}_{\rm cr}$ is given by

$$\dot{M}_{\rm cr} = 5.3 \times 10^{-7}\frac{1.7-X}{X}(M_{\rm WD} - 0.4)M_\odot\,{\rm yr}^{-1}, \tag{9}$$

where X is the H mass fraction and is 0.7 in this work. When the $\dot{M}_{\rm a}$ is between $\frac{1}{2}\dot{M}_{\rm cr}$ and $\frac{1}{8}\dot{M}_{\rm cr}$, the accreting CO-WD undergoes very weak H-shell flashes, where we assume that the processed mass can be retained. The growth rate of the mass of the He layer on top of the CO-WD can be written as

$$\dot{M}_{\rm He} = \eta_{\rm H}\dot{M}_{\rm a}, \tag{10}$$

where

$$\eta_{\rm H} = \begin{cases} \dot{M}_{\rm cr}/\dot{M}_{\rm a}, & \dot{M}_{\rm a} > \frac{1}{2}\dot{M}_{\rm cr}, \\ 1, & \frac{1}{2}\dot{M}_{\rm cr} \geq \dot{M}_{\rm a} \geq \frac{1}{8}\dot{M}_{\rm cr}, \\ 0, & \dot{M}_{\rm a} < \frac{1}{8}\dot{M}_{\rm cr}. \end{cases} \tag{11}$$

Based on the model of optically thick wind, Kato & Hachisu (2004) calculated the retention efficiencies for He accumulation ($\eta_{\rm He}$). In this work, we used their $\eta_{\rm He}$ to calculate the mass growth of the accreting CO-WD. Then the growth rate of the CO-WD mass, $\dot{M}_{\rm WD}$, is given by

$$\dot{M}_{\rm WD} = \eta_{\rm H}\eta_{\rm He}\dot{M}_{\rm a}. \tag{12}$$

When the cumulation of CO-WD's mass reaches the Chandrasekhar mass limit, it explodes as SN Ia. If the CO-WD companion is a naked He star, we assume $\eta_{\rm H} = 1.0$. The $\dot{M}_{\rm WD}$ equals $\eta_{\rm He}\dot{M}_{\rm a}$.

When SN Ia occurs, the companion of CO-WD become a runaway star. Eldridge *et al.* (2011) suggested that its velocity roughly equals its pre-SN orbit velocity which is determined by its orbit radius r. In a binary system, before SN Ia, the velocity of the CO-WD companion in the center of mass reference frame (we assumed the center of mass is at rest) is given by Tauris & Takens (1998)

$$u = \sqrt{\frac{GM_1^2}{(M_1 + M_2)r}}, \tag{13}$$

where r is the orbit radius (distance between the secondary star and the mass of center), defined as $r = \frac{M_1}{M_1+M_2}a$, where a is the binary separation. It can be seen that velocity is inversely proportional to the square root of orbital radius. We use equation (13) to calculate the velocity of TN-RASs.

2.3 *Basic parameters of Monte Carlo simulation*

In order to simulate the population of runaway stars, we use Monte Carlo method. We take the initial mass function in Miller & Scalo (1979) as the distribution of primary mass. For the distribution of mass-ratio of binary systems, we adopt the constant distribution described in Kraicheva *et al.* (1979). The separations distribution is given by

$$\log a = 5X + 1, \tag{14}$$

where a is the separation of the orbit with $R_\odot$, and the random variable X is uniformly distributed in [0,1]. We assume that all binaries have circular orbits.

3. Results

Using BSE code, we calculate the 5×10^7 binary systems. Based on equations (1)–(3) and (13), there are 4.4×10^4 and 8.6×10^4 binary systems producing CC-RASs and TN-RASs, respectively. This gives a statistical error of less than 1%. If we assume that one binary with $M_1 \geq 0.8 M_\odot$ is formed annually in the galaxy (Yungelson *et al.* 1993; Han *et al.* 1995), the galactic birth rate of CC-RASs and TN-RASs are about 8.8×10^{-4} yr^{-1} and 1.7×10^{-3} yr^{-1}, respectively.

Figure 1 shows velocity distributions of all runaway stars in our work. Most of CC-RASs have velocities with 30–100 km s^{-1} (see the left panel in Fig. 1). Our result is consistent with that in Eldridge *et al.* (2011), where it is shown that the velocity of runaway star produced by disrupted binaries via asymmetric supernova explosions cannot exceed 300 km s^{-1}. In the velocity distribution of TN-RASs, there are two regions (see the right panel in Fig. 1). The majority of TN-RASs in the left region have velocities of about 100–500 km s^{-1}, while the velocities of TN-RASs in the right region are mainly between 600 and 1000 km s^{-1}. The former originates from the progenitors of SNe Ia in which donors are main sequence stars or giant stars. These stars are H-rich stars. The latter comes from the progenitors of SNe Ia in which donors are naked He stars. These stars are He-rich stars. Based on equation (13), the velocity of TN-RASs depends on binary separations. Most of the donors in the progenitors of SNe Ia fill up their Roche lobes. The Roche lobe radius of a star is fitted by Eggleton (1993) with

$$\frac{R_\mathrm{L}}{a} = \frac{0.49q^{2/3}}{0.6q^{2/3} + \ln(1 + q^{1/3})}, \tag{15}$$

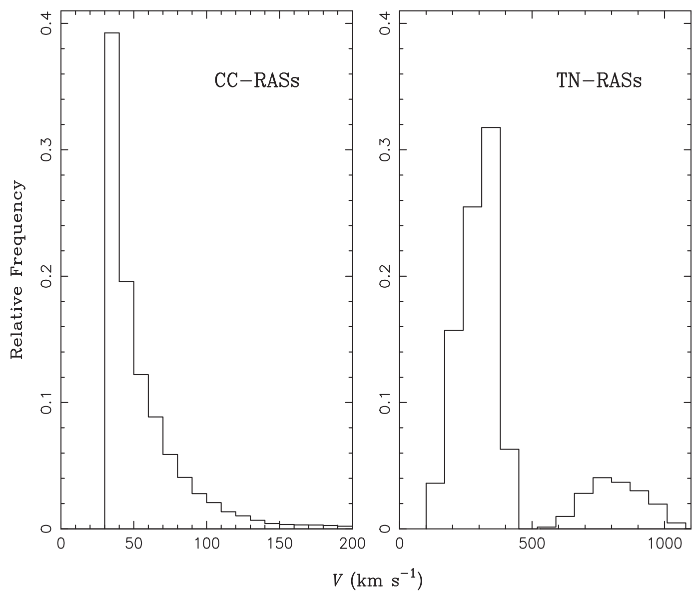

Figure 1. Velocity distributions of all the CC-RASs and the TN-RASs at the moment of supernova explosions.

where q is the mass ratio of the donor and the gainer, a is the semi-major axis of the ellipse, if binary orbit is a circle, it is binary separation. If a H-rich and a naked He donor before SNe Ia occur have the same mass, we obtain

$$\frac{R_{\rm H}}{R_{\rm He}} = \frac{R_{\rm LH}}{R_{\rm LHe}} = \frac{a_{\rm H}}{a_{\rm He}}, \tag{16}$$

i.e., donors' radii in the progenitors of SNe Ia determine the velocities of TN-RASs.

Figure 2 gives the differences of radii of H-rich and naked He stars on main sequence phase. Obviously, for a H-rich and a naked He star with the same mass, the former has about 5 times radius of the latter. Based on equation (13), the velocities of He-rich TN-RASs are about twice those of H-rich TN-RASs. Therefore, in our work, the TN-RASs are divided into two subtypes: H-rich TN-RASs and He-rich TN-RASs, written as TN-RASs(H) and TN-RASs(He), respectively.

3.1 *Core collapse – runaway stars*

According to milli-arcsecond accuracy astrometry (proper motions and parallaxes) from Hipparcos and from radio observations, Hoogerwerf *et al.* (2001) gave the space velocity of 56 runaway stars. They are O or B stars. Figure 3 gives the velocity distributions of the observed 56 runaway stars, spectral O and B type CC-RASs and non OB CC-RASs in our simulation. Obviously, most of the observed 56 runaway stars possibly are CC-RASs, because their velocity distributions are consistent with velocities below 50 km s^{-1}. But our results can not explain well what observed runaway stars with velocities above 60 km s^{-1}. It means that the runaway stars may

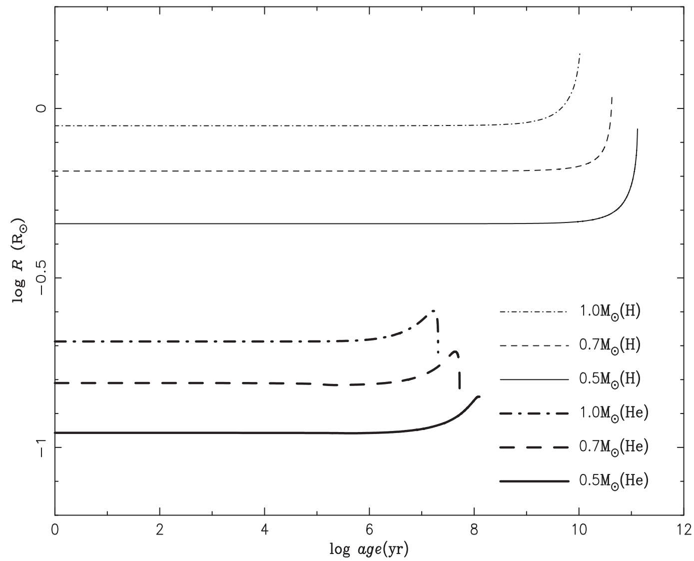

Figure 2. The radius evolution of the low-mass H-rich stars and He-rich stars. Here we only plot the radius evolution in the main sequence stage for each stars.

have other formation mechanisms, such as dynamical ejection scenario. However, they are not TN-RASs because of following two reasons:

(i) Usually, due to short orbital periods in the progenitors of SN Ia, TN-RASs have higher velocity than these runaway stars (see Fig. 1);
(ii) The O or B stars are massive stars, while the TN-RASs are low-mass stars (see the next subsection).

Hoogerwerf *et al.* (2001) gave the spectral types of the 56 runaway stars. Also using Hipparcos data, Mdzinarishvili & Chargeishvili (2005) listed the spectral types of 61 other runaway stars. These runaway stars are O or B stars. However, due to initial mass function, the majority of CC-RASs in this work are A, F, G or K stars. Figure 4 shows the distribution of mass and velocity of CC-RASs. The CC-RASs' masses have very wide distribution (from about 0.1 to $10M_{\odot}$). It is evident that the CC-RASs' masses are inversely proportional to the velocities of CC-RASs because of equations (1)–(3). Majority of CC-RASs have masses lower than $1M_{\odot}$. However, compared to O and B stars, the luminosities of these CC-RASs are very low and they are difficult to observe. We expect that more A, F, G, K runaway stars can be observed in the future. In short, the low velocity, intermediate-mass runaway stars are very likely to originate from the CC-RASs model, and they unlikely originate from the TN-RASs model.

3.2 *Thermonuclear – runaway stars*

Based on Fig. 1, significant fractions of TN-RASs are hypervelocity stars. Here we select about 73 candidates of hypervelocity stars, which may originate from the galactic disk (see Table 1). These stars are not likely to be originated from the galactic

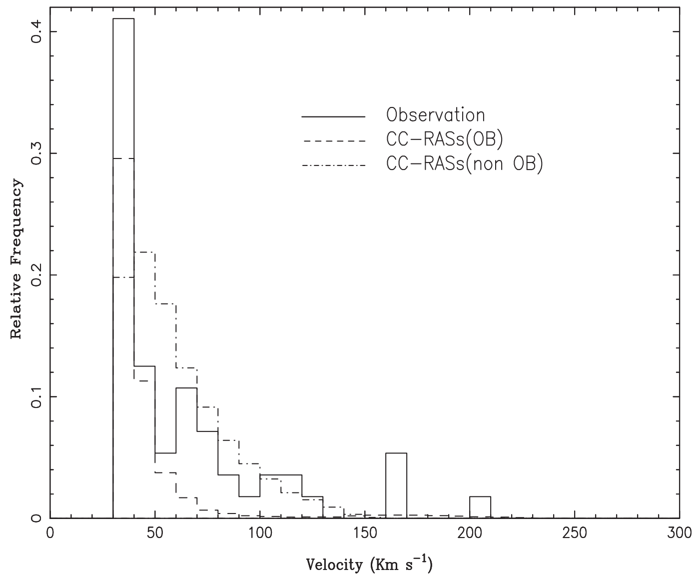

Figure 3. Velocity distributions of the spectral O and B type CC-RASs, non OB CC-RASs and the observed 56 runaway OB stars reported by Hoogerwerf *et al.* (2001).

center. Their velocity distribution is shown in Fig. 5 with those of TN-RASs(H) and TN-RASs(He) simulated by this work. The velocities of most hypervelocity star candidates are between 500 km s^{-1} and 700 km s^{-1}, which are just between TN-RASs(H) and TN-RASs(He). Liu *et al.* (2012) suggested that the kick velocity, $V_{\rm k}$, delivered by the SNe Ia, is between 51 km s^{-1} and 105 km s^{-1}. We consider the above impact, and the velocities of TN-RASs is given by $\sqrt{V^2 + V_{\rm k}^2}$. These results

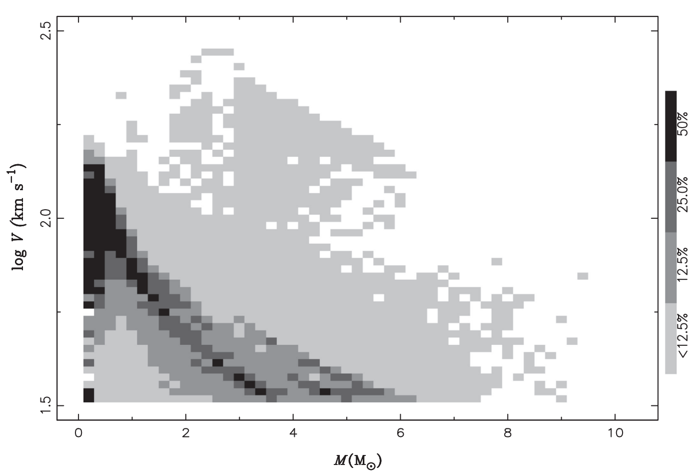

Figure 4. The distribution of mass and orbit velocity of the CC-RASs ($M_{\rm CC\text{-}RASs}$, $V_{\rm orb}$) at the moment of supernova explosions.

are shown Fig. 5 (thick line). Then, the velocity distributions of TN-RASs in our work can not cover observations well.

Wang & Han (2009) investigated the velocities of He stars after SNe Ia via the WD + He star channel. They found that the orbital velocities of most He stars are between 300 and 450 km s^{-1} at the moment of SNe Ia explosion, which are much lower than our results. The main reason is that we use different binary-evolution codes which results in different orbital periods and He star masses. In the BSE code, the equilibrium radii of donors exceed their Roche lobe by as much as a factor of 2. However, in Wang & Han (2009), the donors' radii are almost equal to their Roche lobe (private communication). Wang & Han (2009) gave the orbital periods and masses of He stars at the moment of SNe Ia explosion (see Fig. 4 in Wang & Han 2009). In their work, most of the orbital periods are between 0.05 and 0.2 days, and the masses of He stars mainly are 0.2 and $0.8M_{\odot}$. Comparison with Wang & Han (2009) shows that the lower velocity (say below 600 km s^{-1}) hypervelocity stars are better explained by Wang & Han (2009), whereas higher velocity ones are explained

Table 1. Observed 73 candidate hypervelocity stars and possible origins.

Article	*N*	Origin
Palladino *et al.* (2014)	20	Galactic disk
Zhang *et al.* (2014)	4	?
Ziegerer *et al.* (2015)	14	Galactic disk
Brown *et al.* (2015)	16	Galactic bulge/disk
Li *et al.* (2015)	19	Galactic bulge/disk

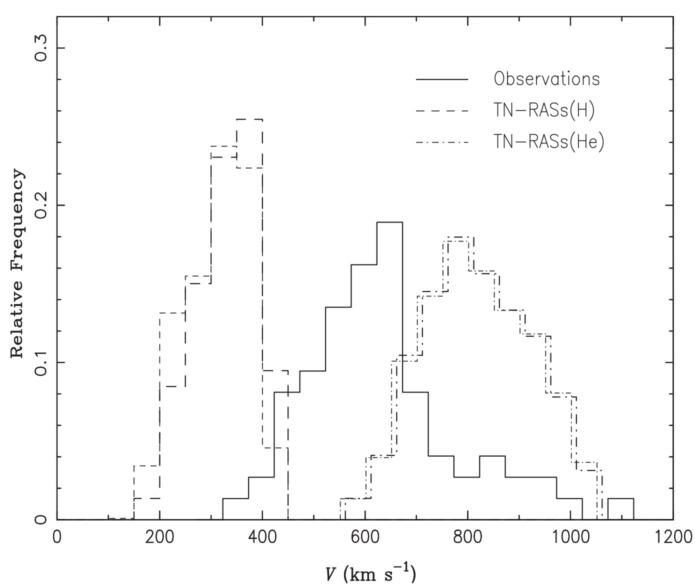

Figure 5. Velocity distributions of TN-RASs(H) and TN-RASs(He). Thick line is generated by taking $V_k = 105$ km s^{-1} in $\sqrt{V^2 + V_k^2}$ according to Liu *et al.* (2012). Observation includes 73 candidates of hypervelocity stars (see Table 1).

better in our model. Figure 6 gives the distribution of the orbital periods and masses of TN-RASs(H) and the TN-RASs(He) at the moment of SNe Ia explosions in our simulations. For TN-RASs(H), in Fig. 6(a), the distribution is split into two zones. The TN-RASs(H) in the top left zone mainly are giant or giant-like stars, while in the bottom right zone, they are main sequence stars. Compared to Fig. 4 in Wang & Han (2009), the orbital periods of TN-RASs(He) in Fig. 6(b) are shorter.

US 708, a compact He star, is travelling in our galaxy (Geier *et al.* 2015). The mass of US 708 is $\sim 0.3 M_{\odot}$ and the galactic rest-frame velocity is 1157 ± 53 km s^{-1} (Geier *et al.* 2015; Hirsch *et al.* 2005). Wang & Han (2009) were not able to reproduce such high velocities. The mass and velocity distribution of TN-RASs in shown in Fig. 7, and we can see that the velocity of TN-RASs is inversely proportional to their mass. That is, it is possible that US 708 is a TN-RAS(He).

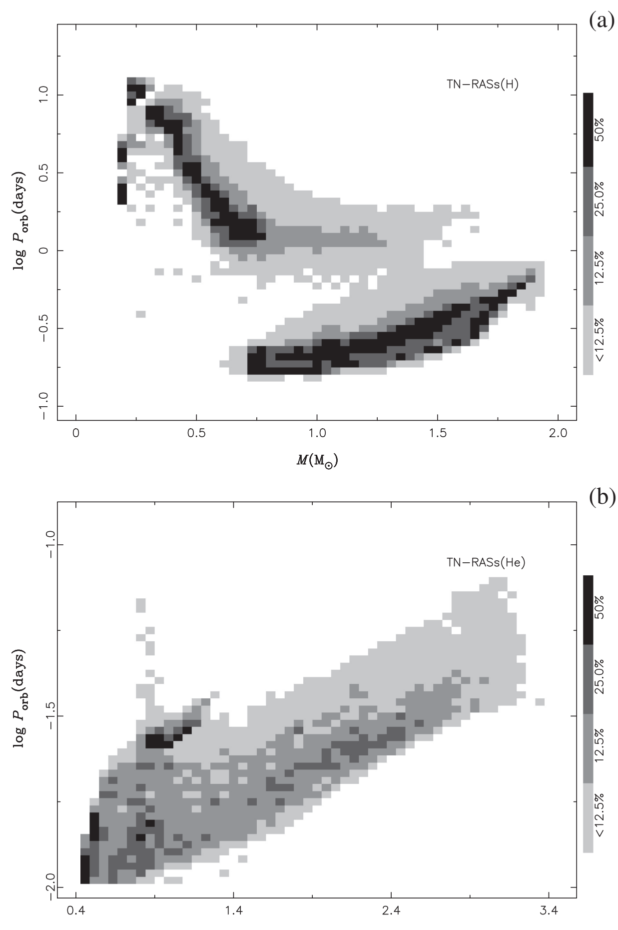

Figure 6. The distribution of mass and orbital period of the TN-RASs(H) (**a**) and TN-RASs(He) (**b**) at the moment of SNe Ia. The top portion is the giant star and the bottom portion is the main sequence star in (a).

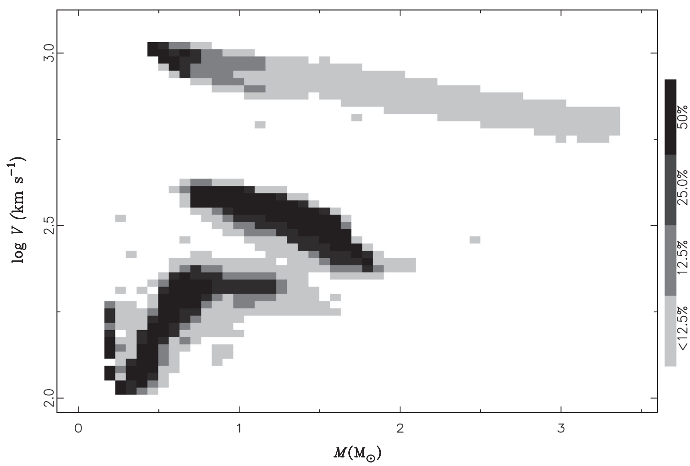

Figure 7. The distribution of mass and orbit velocity of the TN-RASs ($M_{\rm TN\text{-}RASs}$, $V_{\rm orb}$) at the moment of SNe Ia. TN-RASs(He) are in the upper region, while TN-RASs(H) at main sequence phase are in the middle region and TN-RASs(H) at the giant or giant-like phase are in the left-bottom region.

4. Conclusion

Using Monte Carlo method and BSE code, we calculate the evolution of 5×10^7 binary systems. These binary systems produce 4.4×10^4 and 8.6×10^4 CC-RASs and TN-RASs, respectively. The velocities of CC-RASs mainly are 30–100 km s^{-1}. The runaway stars observed in the galaxy possibly are CC-RASs. In the progenitors of SNe Ia, donors are H-rich or He-rich. Due to very different stellar structures between H-rich and He-rich stars, H-rich TN-RASs and He-rich TN-RASs have different velocities. The velocities of the former are 100–500 km s^{-1}, while the velocities of the latter are mainly between 600 and 1100 km s^{-1}. Therefore, the hypervelocity stars observed in the galaxy may originate from SNe Ia. Especially, US 708 which is a compact He star and travelling with a velocity of 1157 ± 53 km s^{-1} in our galaxy is possibly a He-rich TN-RAS.

Acknowledgements

This work was supported by XinJiang Science Fund for Distinguished Young Scholars under Nos 2014721015 and 2013721014, the National Natural Science Foundation of China under Nos 11473024, 11363005 and 11163005.

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