Effects of the Core-collapse Supernova Ejecta Impact on a Rapidly Rotating Massive Companion Star

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Abstract

We investigate the effects of the core-collapse supernova (CCSN) ejecta on a rapidly rotating and massive companion star. We show that the stripped mass is twice as high as that of a massive but nonrotating companion star. In close binaries with orbital periods of about 1 day, the stripped masses reach up to $\sim 1 M_\odot$. By simulating the evolutions of the rotational velocities of the massive companion stars based on different stripped masses, we find that the rotational velocity decreases greatly for a stripped mass higher than about 1 $M_\odot$. Of all the known high-mass X-ray binaries (HMXBs), Cygnus X-3 and 1WGA J0648.024418 have the shortest orbital periods, 0.2 and 1.55 days, respectively. The optical counterpart of the former is a Wolf-Rayet star, whereas it is a hot subdwarf for the latter. Applying our model to the two HMXBs, we suggest that the hydrogen-rich envelopes of their optical counterparts may have been stripped by CCSN ejecta.

Key words: binaries: close – stars: evolution – X-rays: binaries

1. Introduction

High-mass X-ray binaries (HMXBs) are composed of a compact object (CO) and a massive companion star of OB spectral type whose matter is accreted onto the CO. The CO is usually a neutron star (NS) or a black hole (BH). HMXBs are divided into BeHMXBs and sgHMXBs. In the former, the companions of accreting COs are Be stars, whereas they are supergiants in the latter. Of the 114 HMXBs known in the Galaxy (Liu et al. 2006), about 32% are sgHMXBs and more than 60% are BeHMXBs. Supergiant fast X-ray transients (SFXTs) are a subclass of sgHMXBs. They are characterized by sporadic, short, and intense X-ray flares. There are about 10 SFXTs known in the Galaxy (e.g., Romano et al. 2014). In the Small Magellanic Cloud, 148 are confirmed candidates of HMXBs (Haberl & Sturm 2016), in which only SMC X-1 belongs to sgHMXBs, while the others are BeHMXBs. Antoniou & Zezas (2016) classified 40 HMXBs in the Large Magellanic Cloud and found 33 BeHMXBs and four sgHMXBs, including two systems in which the COs may be BHs. Usually, the progenitors of HMXBs undergo core-collapse supernovae (CCSNe). When COs form, CCSN ejecta collide with their companion stars. It was shown by many works that the interaction of CCSN ejecta with the companion star may affect the evolution of the latter if the orbital periods are short enough (e.g., Wheeler et al. 1975; Hirai et al. 2014; Liu et al. 2015). Using 2D hydrodynamical simulations, Hirai et al. (2014) found that up to 25% of the companion’s mass can be stripped for the shortest binary separations, whereas Liu et al. (2015) suggested that at most 10% of the companion’s mass is removed based on 3D hydrodynamical simulations. The stripped mass depends greatly on binary separations.

Figure 1 shows the distribution of the Galactic HMXBs’ orbital periods. Obviously, there are 17 HMXBs with orbital period shorter than 10 days. In particular, the orbital period of Cygnus X-3 is only 0.2 days (Parsignault et al. 1972), and its optical counterpart, V1521 Cyg, is a Wolf-Rayet star (van Kerkwijk et al. 1992). Similarly, 1WGA J0648.024418 has an orbital period of 1.55 days (Thackeray 1970) with an optical counterpart of a hydrogen-depleted subdwarf O6 (HD 49798).

In the remaining 15 HMXBs, their optical counterparts are supergiants, that is, they are sgHMXBs (Liu et al. 2006; Romano et al. 2014). Based on Wheeler et al. (1975), Hirai et al. (2014), and Liu et al. (2015), these optical counterparts should be greatly affected by the ejecta of SNe. However, to our knowledge, the effects of CCSN ejecta on the companion star are seldom considered in previous works on HMXBs. As Shao & Li (2014) showed, the companion stars may have been spun up and become Be stars before COs were formed in HMXBs with short orbital periods. When CCSNe occur, a certain amount of mass should be removed from these Be stars. We ask the following questions: How does the surface velocity of these Be stars evolve? Will these Be stars remain Be stars after the redistributions of angular momentum?

In this paper, we investigate the impact of CCSN ejecta on their rotating massive companion stars and try to understand the optical counterparts of HMXBs. Section 2 describes the stellar model we use for simulating the evolution of rotating stars. The stripped masses from rotating massive stars during CCSNe are estimated in Section 3, and the evolutions of rotating massive stars after stripped masses are shown in Section 4. We present the main conclusions in Section 5.

2. Be Stars and the Evolution of Rotating Stars

Be stars are B-type stars with very high rotational velocity, close to the critical velocity ($V_{\text{crit}}$) where gravity is balanced by the centrifugal force. A review of Be stars can be seen in Porter & Rivinius (2003). In HMXBs, Be stars, which originate from main-sequence (MS) stars, accrete matter from their companion stars. Detailed investigations of Be stars and their properties can be found in de Mink et al. (2013), Shao & Li (2014), and Reig (2011). The range of mass distribution for Be stars in HMXBs is between 8 and 22 $M_\odot$ (Chaty 2013). For simplicity, in this work we define an MS star phenomenologically as a Be star if its mass is between 8 and 22 $M_\odot$ and its rotational velocity is higher than 80% of $V_{\text{crit}}$ (Porter & Rivinius 2003).

Rotation has significant effects on the massive stars (Maeder & Meynet 2000). Here, we use MESA (version 8118; Paxton et al. 2011, 2013, 2015) to compute the structures and
evolutions of rotating massive stars. By considering the physics of rotation, mass loss, and magnetic fields, Brott et al. (2011) gave the grids of evolutionary models for rotating massive stars. In order to compare with their results, we use similar input parameters and criteria in MESA: the Ledoux criterion is used for convection, the mixing-length parameter (\(\alpha_{\text{MLT}}\)) is taken as 1.5, and an efficiency parameter (\(\alpha_{\text{SEM}}\)) of unity is assumed for semiconvection. The metallicity (\(Z\)) of the Milky Way is taken as 0.0088 in Brott et al. (2011), which is lower than that of the Sun (\(Z_\odot = 0.012\)) found by Asplund et al. (2005).

The mass-loss rate is calculated via the model given by Vink et al. (2001). Due to rotation, the mass-loss rate is enhanced and given by (Langer 1998)

\[
\dot{M} = \left(1 - \frac{\Omega}{\Omega_{\text{crit}}}\right)^\beta \dot{M}_0,
\]

where \(\Omega\) and \(\Omega_{\text{crit}}\) are the angular velocity and the critical angular velocity, respectively, and \(\beta = 0.43\) (Langer 1998).

Rotation induces instability of various kinds, such as dynamical shear instability, Solberg–Hיסland instability, secular shear instability, Eddington–Sweet circulation, and Goldreich–Schubert–Fricke instability (e.g., Heger et al. 2000), which results in the transport of angular momentum (e.g., Endal & Sofia 1978; Pinsonneault et al. 1989; Heger et al. 2000). Following Brott et al. (2011), the ratio of the turbulent viscosity to the diffusion coefficient (\(f_t\)) is taken as 0.0228 (Heger et al. 2000), and the ratio of sensitivity to chemical gradients (\(f_g\)) as 0.1 (Yoon et al. 2006).

Figure 2 shows the evolution of a star with an initial mass of 15 \(M_\odot\) on the MS phase. It is obvious that, for the models with low initial rotational velocity (\(V_\text{f} = 223\) km s\(^{-1}\)), the results calculated by MESA and Brott et al. (2011) are in excellent agreement, although there are small differences in luminosity and radius. However, this is not the case in models for high \(V_\text{f}\) of 595 km s\(^{-1}\), where the results of MESA are quite different from those in Brott et al. (2011). Especially, when \(V_\text{f}\) increases from 223 to 595 km s\(^{-1}\), Brott et al. (2011) predicted a prolongation in the lifetime of the MS by about 30\%, whereas a prolongation of only about 10\% is predicted in MESA.

Furthermore, the rotational velocity (\(V_\text{f}\)) calculated by MESA decreases more rapidly than that using the model of Brott et al. (2011). In this work, we do not discuss the details that result in these differences, but one should note that they may lead to some large uncertainties in simulating rapidly rotating massive stars.

3. Core-collapse Supernovae

3.1. Effects of Core-collapse Supernovae on Orbital Periods

Due to an asymmetry during CCSNe, a newborn NS receives a kick velocity (\(v_\text{k}\)), which may disrupt the binary system. Brandt & Podsiadlowski (1995) systematically studied the effects of the kick velocity on the orbital periods. They found that post-CCSN distributions for binary parameters, such as orbital period and eccentricity, are determined by numerous factors, including pre-CCSN orbital period, eccentricity, and stellar masses; post-CCSN stellar masses; and the magnitude and direction of the kick velocity. As shown in Figure 1 in Belczynski et al. (2008), the pre-CCSN masses of NS progenitors are between about 6 and 10 \(M_\odot\) using the mass-loss rates in Nieuwenhuijzen & de Jager (1990), Kudritzki & Reimers (1978), and Vassiliadis & Wood (1993) for H-rich stars on MS, red giant, and asymptotic giant branches, respectively. For simplicity, we assume the pre-CCSN masses to be 8 \(M_\odot\) for all NS progenitors, and 1.4 \(M_\odot\) as the mass for all newborn NSs (Lattimer & Prakash 2007; Belczynski et al. 2008). As binary systems usually have undergone binary interaction, such as mass transfer or tidal interaction, the pre-CCSN eccentricity before CCSNe occur is taken as 0. Of course, a newborn BH also obtains a kick velocity. However, there is no observational evidence for it. Therefore, we assume that the kick velocities for BHs are similar to those of NSs. Based on Figure 1 in Belczynski et al. (2008), we take 10 \(M_\odot\) as the pre-CCSN mass for all BH progenitors, and the mass for all newborn BHs as 8 \(M_\odot\). Hence, in this paper, the binary parameters for post-CCSN systems are assumed dependent on the magnitude and direction of the kick velocity.

Based on the measured proper motions for 233 pulsars, Hobbs et al. (2005) found that the distribution of kick velocities can be perfectly described by a Maxwellian distribution

\[
P(v_k) = \frac{3}{8} \frac{v_k^2}{\sigma_k^5} e^{-v_k^2/2\sigma_k^2},
\]

with a dispersion of \(\sigma_k = 265\) km s\(^{-1}\). This implies that the direction of kick velocity is uniform over all solid angles.

For a given pre-CCSN binary, we can determine the distribution for values and directions of kick velocities using the Monte Carlo method and calculate the probability of survival for a system after CCSNe, as well as its binary parameters. A detailed description and the codes for the above calculations can be found in Hurley et al. (2002).

In this work, we use the codes provided by Hurley et al. (2002) to calculate the binary parameters of post-CCSN systems. Considering that the orbital periods of HMXBs are between 0.2 and 300 days (see Figure 1), we take a similar range for the orbital periods (\(P_i\)) of pre-CCSN systems. Figure 3 shows the percentage of bound remaining binaries after CCSNe. Here, \(\Delta \log P_i = 0.1\) days, and 10,000 binary systems are calculated for every orbital period. The results show that the larger the orbital period for a pre-CCSN binary is, the more
easily the binary is disrupted. The smaller the masses for the companions of CO progenitors in pre-CCSN binaries are, the more difficult it is for the binaries to survive. Since the masses of newborn BHs (~8 M⊙) are larger than those of newborn NSs (~1.4 M⊙), for the same orbital periods the binaries that produce BHs will remain bounded more readily than those that produce NSs.

Figure 4 gives the distribution of pre- and post-CCSN orbital periods. It is clear that the range of orbital periods in a post-CCSN binary is wider. The post-CCSN binaries with orbital periods shorter than 10 days may originate from pre-CCSN binaries with orbital periods shorter than about 30 days. By comparing the left panel to the right panel in Figure 4, the changes in orbital periods from pre- to post-CCSN are similar regardless of whether CCSN produces BHs or NSs.

3.2. Impact of Core-collapse Supernovae on Rotating Massive Stars

CCSNe not only affect the orbital periods of binaries but also have an impact on the companion stars of newborn CO progenitors (e.g., Wheeler et al. 1975; Marietta et al. 2000; Pan et al. 2012; Shappee et al. 2013; Liu et al. 2015). At the beginning of CCSN ejecta colliding with the companion stars, a shock is sent into the stellar envelope of the latter, and simultaneously, a reverse shock is sent back into the former. The shock propagates throughout the companion star, while the reverse shock turns into a bow shock around the companion star. The result of the impact of the CCSN ejecta on the companion star is that much of the shock energy is deposited in the companion’s envelope, which turns into internal energy, causing the companion star to heat up. If the internal energy of the material in the companion’s envelope is high enough, it is stripped away from the companion star.

The stripped mass is determined by local total energy given by Marietta et al. (2000),

\[ E_{\text{tot}} = E_{\text{kin}} + E_{\text{in}} + E_{\text{gr}}, \]

where \( E_{\text{kin}}, E_{\text{in}}, \) and \( E_{\text{gr}} \) are the specific kinetic energy, specific internal energy, and specific potential energy, respectively. The first and second are positive, while the third is negative. Matter is stripped if \( E_{\text{tot}} > 0 \).

Pan et al. (2012) found that the final stripped mass can be estimated using the power law given by

\[ M_{\text{st}} = A \left( \frac{a}{R_2} \right)^\eta M_2, \]

where \( R_2 \) and \( M_2 \) are the radius and mass of the companion star, respectively, and \( a \) is the binary separation. Here, \( A \) and \( \eta \) are fitting parameters whose values are dependent on the properties of CCSNe (including energy, mass, and velocity of ejecta), the structure of companion stars (including radius and density profile), and binary separations (e.g., Pan et al. 2012). Both Hirai et al. (2014) and Liu et al. (2015) estimated the stripped masses from the companion stars during CCSNe. The former focused on the red giant companion stars, while the latter investigated the MS companion stars. The detailed structures of a red giant companion star are very different from stars in the MS phase. Therefore, \( A = 0.26 \) and \( \eta = -4.3 \) are taken in Hirai et al. (2014), while they are 0.143 and −2.65, respectively, in Liu et al. (2015). Although we focus on MS stars, we take the value for fitting parameters (\( A \) and \( \eta \)) from both in Hirai et al. (2014) and Liu et al. (2015) to estimate the stripped masses, in order to discuss the effects of \( M_\text{st} \) on rotating massive stars.

Simultaneously, the shock heating can change the internal structures of the companion stars. However, it is beyond the scope of this work to calculate \( M_\text{st} \) by 2D or 3D hydrodynamical simulations and to simulate the change of stellar structures due to the shock heating. MESA cannot simulate the stripping process, but it can be used to calculate the evolution of a star with high mass-loss rate. Following Podsiałowski (2003), we assume that the impact of CCSNe on the companion star can be divided into two phases. In the first phase, the companion star loses mass at a very high rate (~10⁻²~10⁻³ M⊙ yr⁻¹) until the mass lost equals \( M_\text{st} \), given by Equation (4). This means that its thermodynamic
equilibrium is destroyed at such a high mass-loss rate. The result is that both the stellar radius and the rotational velocity at the stellar surface decrease as the stellar mass decreases. In the second phase, the mass loss stops, but the companion star is irradiated by an external heating source until $E_{\text{tot}} = 0$ at the stellar surface. In fact, similar work was done by Shappee et al. (2013) using the MESA code, but without considering the stellar rotation. Here, we must note that it is still different even when an additional heating source is introduced to simulate the shock heating due to the interaction between SN ejecta and a companion star. As shown by Pan et al. (2012), Liu et al. (2013), and Hirai et al. (2014), the internal structures of a star are strongly affected while the shock is passing through the star. However, in our model, the internal structures of massive stars are not affected by such interaction.

Figure 5 shows an example for the evolutions of an MS companion star with a mass of $10 \, M_\odot$ in the different phases mentioned above. When the central hydrogen abundance of the MS decreases to 90% of its initial value (its age is about $4.2547 \times 10^6$ yr), the impact of CCSNe begins. Based on our assumptions, the MS loses mass at a rate of $\sim 10^{-3} \, M_\odot$ yr$^{-1}$ at first. If the mass-loss rate is higher, the MESA code stops owing to the convergence problem. During this phase, the effective temperature, stellar radius, stellar luminosity, and rotational velocity drop along with the mass lost. When the stellar mass reduces to 9 $M_\odot$, the mass-loss phase stops and the MS enters the irradiated phase. In this example, a value of $10^{39}$ erg s$^{-1}$ cm$^{-2}$ is assumed for the energy flux that irradiates the MS from the heating source, which means that the power of total irradiation energy is about $4.3 \times 10^{39}$ erg s$^{-1}$ at the beginning of the irradiated phase. As Figure 5 shows, the stellar radius increases rapidly as a result of the irradiation, which leads to great enhancement on the power. With the increase of the radius and the temperature, $E_{\text{in}}$ becomes higher and higher but $|E_{\text{gr}}|$ becomes smaller and smaller around the stellar surface. After about 8000 s (equivalent to energy of about $10^{40}$ erg deposited into the stellar envelope), $E_{\text{tot}} \geq 0$ at the stellar surface and the irradiated phase stops.

According to Hirai et al. (2014) and Liu et al. (2015), the stripped mass from the companion star of the CCSN progenitor is determined by its mass, radius, rotating velocity, and binary separation. As shown in Figure 2, both the radius and rotating velocity change with stellar evolution. Therefore, the stripped masses depend indirectly on the stellar age. We use the mass fraction of central hydrogen ($X_H$) to represent the stellar age, where $X_H = 0.9X_{H_0}$ and $X_H = 0.1X_{H_0}$ represent young and old stars, respectively. Using MESA, we simulate evolution for stars with initial masses of 8, 10, 15, and 20 $M_\odot$, respectively. Their initial rotational velocities on the stellar surface are $0.95V_{\text{crit}}$, $0.85V_{\text{crit}}$, and 0. We select two points in time, at $X_H = 0.9X_{H_0}$ and $X_H = 0.1X_{H_0}$ on the MS phase for discussion of the effects of stellar evolutions. Table 1 gives the radii of the MS stars for different masses and rotation velocities at the two time points.

Assuming that the mass of the NS progenitor in CCSNe is 8 $M_\odot$, allows us to estimate the stripped masses from these stars in binary systems with different pre-CCSN orbital periods. Based on Figure 6, compared to the model for nonrotating stars, the stripped mass in the model for rapid rotation stars ($V_i = 0.95V_{\text{crit}}$) is enhanced within a factor of about 2.3. As shown in Table 1, the stellar radii of the former are about 1.3 times larger than those of the latter, which results in the increase of 1.6 and 2.3 for the fitting parameters in Liu et al. (2015) and Hirai et al. (2014), respectively (see Equation (3)). Compared to young massive stars ($X_H = 0.9X_{H_0}$) with high
rotational velocity, CCSN ejecta can strip more matter from the evolved massive stars ($XH = 0.1X_H$) because the stellar radius increases by a factor of about 2 from the time point of $XH = 0.9X_H$ to that of $XH = 0.1X_H$. According to our calculations, the stripped masses in the model with $XH = 0.1X_H$ are about 6–20 times larger than those with $XH = 0.9X_H$.

The stripped mass greatly depends on the orbital period. Figure 4 shows that HMXBs with orbital periods shorter than 10 days originate from pre-CCSN binaries with orbital periods shorter than 30 days. Based on Figure 6, we find that, regardless of whether using fitting parameters in Hirai et al. (2014) or those in Liu et al. (2015), the stripped masses from rotating massive stars in pre-CCSN binaries with orbital period shorter than 30 days are larger than $\sim 10^{-3} M_\odot$, and even up to several $M_\odot$.

### 4. Evolution of Rotating Massive Stars after the Impact

According to Hirai et al. (2014) and Liu et al. (2015), the timescale $t_{\text{ES}}$ for mass stripping during CCSNe is several hours. The distribution of angular momentum within the star may depend on the Eddington–Sweet circulation (Zahn 1992), whose timescale is given by

$$t_{\text{ES}} \sim t_{\text{KH}} \left( \frac{\Omega_{\text{crit}}}{\Omega} \right)^2,$$

where $t_{\text{KH}}$ is the local thermal timescale. It is apparent that $t_{\text{ES}} \sim t_{\text{KH}}$ for Be stars ($\Omega \sim \Omega_{\text{crit}}$). For massive stars on the MS phase, $t_{\text{KH}} \sim 10^4$–$10^5$ yr (Heger et al. 2000), which means that $t_{\text{ES}}$ is much longer than $t_{\text{KH}}$. Therefore, the internal profiles of rotational velocity and angular momentum for rotating stars do not change when their matter is stripped during CCSNe. After a certain amount of mass is stripped from a star, its thermodynamic equilibrium is disrupted. A new equilibrium will be reached after an adjustment within a thermal timescale, during which the angular momentum within the star redistributes. After the rotating star reaches a new thermodynamic equilibrium, it begins to evolve as a non-Be star.

#### 4.1. Evolution of Rotational Velocity

Figure 7 shows the internal profiles of rotational velocity and angular momentum ($J_{\text{spin}}$) from stellar surface to center. It is obvious from the figure that the rotational velocity decreases rapidly when the stellar-mass coordinates from the surface to the sub-surface. This means that the rotational velocity on the stellar surface also decreases as the stellar matter is being stripped. From the left panels in Figure 7, a rapidly rotating star ($V_\text{r} = 0.95V_{\text{crit}} \sim 600$ km s$^{-1}$) turns into a non-Be star with low rotational velocity ($V_\text{r} \sim 300$ km s$^{-1}$) even though only a mass of $10^{-3} M_\odot$ is stripped away. However, stellar rotational velocity depends on the stellar angular momentum. Comparing...
the right panel with the left panel in Figure 7, the degree of reduction in angular momentum is much lower than that in the rotational velocity if a certain mass is stripped away from a star. A problem appears: is a Be star still a Be star after a certain amount of mass is stripped?

In order to answer this problem, we investigate the rotational velocity evolution of a rotating star after a certain mass is stripped. In this work, we roughly divide the rotational velocity evolution of a rotating star’s stripped mass into three phases:

(i) Impact phase. This phase includes the stripped and the irradiated phases described in Section 3.2.

(ii) Thermally adjusting phase. After the impact, the heating source disappears, and the star undergoes adjustment to reach a new thermodynamic equilibrium. This phase lasts for a thermal timescale. According to Heger et al. (2000), the secular shear instability, Eddington–Sweet circulation, and Goldreich–Schubert–Fricke instability begin to drive the distribution of angular momentum on a thermal timescale, and they are secular processes. Therefore, during this phase, the above three instabilities do not work, but dynamical shear instability and Solberg–Hilsland instability affect the distribution of angular momentum.

(iii) Normal phase. The rotating star begins to evolve into a non-Be star after it reaches a new thermodynamic equilibrium.

Figure 8 gives the evolution of $V_0$ and $J_{\text{spin}}$ for the above three phases for a star of $10 M_\odot$ mass and a stripped mass of $1 M_\odot$. The parameters $I_\text{r}$, $\omega_\text{r}$, $R_\text{r}$, and $V_\text{r}$ are the moment of inertia, angular velocity, radius, and rotational velocity at $M_\text{r}$, respectively. The phases I, II, and III indicate the impact, thermally adjusting, and normal phases, respectively.
Due to the low mass-loss rate and the irradiation, and 25% of stellar mass is stripped. The black and red dots mean that the stars are Be stars \( V_s > 0.8V_{\text{crit}} \) and non-Be stars \( V_s < 0.8V_{\text{crit}} \), respectively. Every dot represents a model calculated by MESA.

\( R_\odot \), and 560 km s\(^{-1}\) at this time, and, based on Figure 6, it may exist in a binary system with an orbital period shorter than 1 day.

At the beginning of the impact phase, the Be star has a high mass-loss rate (about \( 10^{-2} - 10^{-3} M_\odot \text{ yr}^{-1}\)), so that the stellar angular momentum cannot be redistributed in a short timescale of about \( 10^2 - 10^3 \text{ yr} \). Therefore, \( V_s \) and \( J_{\text{spin}} \) decrease rapidly as the stripped matter increases. Meanwhile, the stellar radius also reduces quickly, enhancing the critical rotational velocity. Soon, the star is no longer a Be star but turns into a non-Be star. At the end of the stripped phase, the \( V_s \) and \( J_{\text{spin}} \) decrease from about 560 to 200 km s\(^{-1}\) and from about 1.87 \( \times \ 10^{52} \) to 1.29 \( \times \ 10^{52} \text{ g cm}^2 \text{ s}^{-1}\), respectively. Our simulation shows that the high mass-loss phase only lasts for hundreds or thousands of years. After that, the star, having been stripped of a mass of \( 1 M_\odot \), is irradiated by a heating source. Its envelope rapidly expands, and its radius sharply increases while the rotational velocity on the surface drops radically. However, as Figure 9 shows, the irradiation only affects the structure near the stellar surface.

Entering the thermally adjusting phase, the mass-loss rate reduces down to a normal value (about \( 10^{-6} M_\odot \text{ yr}^{-1}\)) and the irradiation stops. The star begins to contract, reaching a new thermodynamic equilibrium. From Figure 9, its radius reduces from about 20 to 10 \( R_\odot \). Due to the low mass-loss rate and the relatively short timescale, \( J_{\text{spin}} \) remains almost a constant, implying that the angular velocity decreases by 2.3 times. However, the star remains in the solid-body rotation because of the existence of Spruit–Tayler magnetic fields, which results in the increase of \( V_s \). This phase lasts for about \( 10^4 \text{ yr} \).

After the rapidly expanding phase, the star begins to evolve into a non-Be star. The \( J_{\text{spin}} \) and \( V_s \) decrease because of the matter lost, taking away the angular momentum. However, as the star expands, \( V_{\text{crit}} \) decreases more quickly than \( V_s \). Then, at about 1.2 \( \times \ 10^7 \text{ yr} \), when \( V_s > 0.8V_{\text{crit}} \), the star becomes a Be star.

We calculate the evolution of \( V_s \) for stars with stripped masses of \( 10^{-3} M_\odot, 10^{-2} M_\odot, 1 M_\odot, \) and 25% of stellar mass at different evolutionary ages. Compared to the old Be stars given in the right panel of Figure 10, the young Be stars in the left panel of Figure 10 are more difficult to turn into non-Be stars for the same stripped mass. The main reason is shown in the right panel of Figure 7: the ratio of the angular momentum taken away by the matter stripped near the stellar surface to the total angular momentum of the old Be stars is higher than that for the young Be stars. The same reason can also be used to explain why Be stars with higher mass are more difficult to evolve into non-Be stars than their lower-mass counterparts. In short, a Be star with a certain amount of mass stripped can hardly evolve into a non-Be star unless the stripped mass is larger than \( 1 M_\odot \), even 25% of its mass.

4.2. Discussions

As shown in Figure 6, a significant amount of mass (\( \sim \)several \( M_\odot \)) should have been stripped from the progenitors of CO companions during CCSNe for HMXBs with very short orbital periods (\( \sim 1 \text{ day} \)). Therefore, these companions may be hydrogen-depleted objects. In known HMXBs, the orbital period of Cygnus X-3 is the shortest (\( P_{\text{orb}} = 0.2 \text{ days} \)). Although the nature of its CO (NS or BH) is still under debate, its optical counterpart, V1521 Cyg, is a Wolf-Rayet star of the WN type (van Kerkwijk et al. 1992; Fermi LAT Collaboration et al. 2009). This means that V1521 Cyg is a helium-rich star. Based on the ionization structure of the wind from Cygnus X-3, Terasawa & Nakamura (1994) estimated that the mass for V1521 Cyg was about \( \sim 3 M_\odot \). Compared to the typical mass of Wolf-Rayet stars, the progenitor of V1521 Cyg must have lost an enormous amount of mass via stellar wind or Roche lobe overflow (RLOF; e.g., Lommen et al. 2005). However, in our work, its progenitor may have undergone different evolutions. As shown in Figure 4 for the changes of pre- and post-CCSN orbital periods, the progenitor system should have an orbital period shorter than \( \sim 1 \text{ day} \) in order to form an HMXB with a short orbital period similar to that of Cygnus X-3 after the CCSN explosion. We can estimate, based on Figure 6, that the stripped mass from the progenitor of V1521 Cyg could reach about \( 10 M_\odot \) during the CCSN process. Therefore, the mass of the Cyg progenitor
might be $\sim 20 M_\odot$, implying that most of its hydrogen-rich envelope might have been blown away when the CO of Cygnus X-3 was formed.

Similarly, IWGA J0648-4119 also has a very short orbital period ($P_{\text{orb}} = 1.55$ days), implying that its CO is likely an NS, but the massive white dwarf cannot be excluded (Mereghetti et al. 2016). Its optical counterpart, HD 49798, is a hot subdwarf of O6 spectral type with a mass of $1.50 M_\odot$ (Mereghetti et al. 2009). Hot subdwarfs are core helium-burning stars with a very thin hydrogen envelope whose mass is lower than 0.01 $M_\odot$ (Heber 2009). Hot subdwarfs in binary systems originate from the common-envelope ejection or stable RLOF (Han et al. 2002). Based on Figure 4, our models predict that several $M_\odot$ was stripped away from the progenitor of HD 49798 when it evolved into the later phase in the MS or the Hertzsprung gap. Considering that the mass of HD 49798 is only about 1.50 $M_\odot$, we estimate that its progenitor should have a mass of about 10 $M_\odot$.

5. Conclusions

We have estimated the stripped masses from rotating stars based on the fitting formula given by Hirai et al. (2014) and Liu et al. (2015), together with the observational data for HMXB orbital periods. Our results show that the amount of mass stripped is greatly dependent on orbital period, similar to what has been argued in previous works. However, the rotational velocity introduces an uncertainty of up to a factor of about 2. We focus on the evolutions of the rotational velocities and divide the evolutions into three phases: the impact, thermally adjusting, and normal phases. We find that a Be star can evolve into a non-Be star if it is stripped of a mass higher than about 1 $M_\odot$.

Based on the observed orbital periods, we estimate that a mass of several $M_\odot$ should have been stripped from V1521 Cyg and HD 49798. They are the optical counterparts of Cygnus X-3 and IWGA J0648-4119, respectively, and both are hydrogen depleted. It is probable that the whole hydrogen-rich envelopes of their progenitors might have been stripped when the COs formed.

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